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ABSTRACT

We study the uneven effects of a commodity cycle, documenting its impact across workers based on their skill and the region where they live. To this end, we develop a dynamic quantitative model of a multi-region economy featuring spatial linkages (interregional trade and migration) and downward wage rigidity. Empirically, we focus on the experience of Brazil during the commodity boom of the 2000s and subsequent bust of the 2010s. The commodity cycle causes an important decline in the skill premium during the boom, while the extent of downward wage rigidity determines whether it reverts or maintains its decline during the bust. In addition, there is substantial heterogeneity across Brazilian states in the gains from the commodity cycle. Finally, we build counterfactuals to show that both spatial linkages (interregional migration and interregional trade) and downward wage rigidity jointly shape the impact of the commodity cycle on the skill premium, real wages, unemployment, and spatial disparities.

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1 Introduction

Fluctuations in commodity prices have a large impact on many developing countries. While the literature has focused on the macroeconomic effects of commodity cycles, there is little evidence on how they affect different groups of people within a country. In this paper, we study the uneven effects of a commodity boom and bust cycle. We focus on how the cycle impacts workers based on their skill level and the region in which they live.

To address this question, we construct a dynamic quantitative model of a country with different regions connected by interregional trade and migration. This economy faces exogenous commodity prices and trades with the rest of the world. The production structure includes a commodity, manufacturing, and service sector, as in Benguria et al. [2024]. We extend that framework allowing for a multi–region economy with interregional trade and migration, including input–output linkages, and featuring downward wage rigidity. Because workers are forward looking when deciding whether to move across sectors and regions, the model is dynamic and is solved following the approach developed by Caliendo et al. [2019].

Empirically, we focus on the experience of Brazil during the commodity boom of the 2000s and the subsequent bust of the 2010s. We consider this to be an ideal setting for several reasons. First, there is substantial variation across regions in their exposure to the commodity cycle. This variation stems from the types of commodities produced and variation in the prices of these commodities. Second, Brazil is a large country and there is variation across regions in the extent of spatial linkages through migration and interregional trade. Third, Brazil has high levels of inequality, and there was an important decline in inequality during the 2000s [Alvarez et al., 2018], so it is relevant to ask the extent to which this decline in inequality was driven by the commodity boom. Fourth, downward wage rigidity is an important feature of Brazil's labor market and the model allows us to understand how it shaped the response to the decline in commodity prices during the 2010s. Finally, Brazil produces excellent data on labor market outcomes at a high frequency, with detailed geographic information, and distinguishing between workers with different degrees of educational attainment. We leverage these data to calibrate the model.

We have the following main results. First, at the aggregate level, the commodity boom leads to a decline in the skill premium. The real wages of both skilled and unskilled workers increase due to the boom, but the wages of unskilled workers increase substantially more, because the expanding commodity sector is unskilled intensive. The model assigns a 2.5% decline in the skill premium to the commodity boom, which corresponds to 15% of the decline in the skill premium observed in Brazil during this period. During the bust, the evolution of the skill premium depends on the degree of downward wage rigidity. The skill premium increases during the bust if the wages of unskilled workers fall enough. Alternatively, it continues its decline if downward wage rigidity is restrictive enough such that the wages of unskilled workers cannot fall sufficiently during the bust. We also find substantial heterogeneity across Brazilian states in the evolution of real wages. During the boom, for example, the median state–sector reaches an increase in the average real wage of unskilled workers of 4.7%, but this ranges from 0.8% at the 10th percentile to 10.2% at the 90th percentile.

In terms of employment, we see that half the states gain employment and half see a contraction. For most states, these changes in employment are not particularly large. However, the lack of large regional adjustments in employment is not a sign that interregional migration is unimportant in shaping the effect of the commodity boom. To properly assess the impact of interregional migration, we simulate counterfactual economies shutting down interregional migration, interregional trade, or both. The reason why observing small or moderate migration flows in response to the commodity boom does not imply that migration is unimportant is straightforward: in response to changes in commodity prices, there can be an adjustment in quantities (employment) or prices (real wages). Indeed, using our counterfactual simulations, we find that spatial linkages play a substantial role in shaping the effect of the commodity boom in the economy. At the aggregate level, the decline in the skill premium during the boom would be 10% larger in an economy with no spatial linkages.

Regarding spatial disparities, an economy without spatial linkages would see narrower differences across states in the gains in real wages from the boom. Specifically, the gap between states at the 25th and 75th percentiles of the increase in the real wage of unskilled workers widens by 50% if spatial linkages are shut down. Further, we see that while the skill premium falls in all 27 states in the data and in 26 states in our baseline economy, it only falls in 14 states in the counterfactual economy without spatial linkages.

Another important finding is that downward wage rigidity generates unemployment during the bust, and spatial linkages distribute this unemployment across states. The unemployment rate by the end of the cycle depends strongly on the extent of rigidity. In addition, shutting down spatial linkages elevates the average unemployment rate among states that face unemployment.

Finally, we extend our baseline results to account for informality in Brazil's labor market. We find similar patterns in the skill premium, real wages, employment shares, and heterogeneity across states when accounting for informality.

Summing up, the literature has established that fluctuations in commodity prices are an important determinant of the macroeconomic outcomes of many emerging economies. Our work establishes that commodity cycles also have an uneven impact across workers based on their skill level and the regions in which they live. Spatial linkages and labor market frictions play an important role in shaping this uneven response.

Contribution to the literature Our paper belongs to the broad literature analyzing the consequences of commodity price super–cycles [Fernández et al., 2017, 2018, 2023, Alberola and Benigno, 2017, Drechsel and Tenreyro, 2018, Kohn et al., 2021, Benguria et al., 2024]. This literature has measured the macroeconomic impact and the transmission channels of commodity cycles. We contribute to this literature by studying the uneven gains from commodity cycles within a country, focusing on differences in terms of skill and on differences across regions. We also contribute to this literature by assessing to what extent spatial linkages (interregional migration and interregional trade) and labor market frictions (downward wage rigidity) shape the effects of the boom and bust on different groups of the population.

Our paper also connects to the literature that studies the role of spatial linkages (interregional trade and/or migration) in the adjustment to external shocks [Caliendo and Parro, 2015, Coşar and Fajgelbaum, 2016, Adão, 2016, Dix-Carneiro and Kovak, 2017, Caliendo et al., 2019, Faber and Gaubert, 2019, Tombe and Zhu, 2019, Borusyak et al., 2022, Fajgelbaum and Redding, 2022].[1] More broadly, our work is also linked to research on the dynamics of labor markets in the response to globalization [Artuç et al., 2010, Dix-Carneiro et al., 2023, Rodríguez-Clare et al., 2024]. In particular, Rodríguez-Clare et al. [2024], which studies the effect of imports from China on the US labor market, also features downward wage rigidity. Our goal, model, and context differ from this previous work as follows. First, we focus on inequality, and thus incorporate skilled and unskilled workers. Second, our work focuses on the context of Brazil's commodity boom and bust cycle during the 2000s and 2010s. Third, we use counterfactuals to understand how spatial linkages shape the impact of the commodity cycle and how spatial linkages and labor market rigidity interact.

2 Empirical patterns: Regional heterogeneity and spatial linkages

Our first step is to document patterns of regional heterogeneity that motivate and guide the quantitative model we use. In Section 2.1 we describe our data sources used to measure commodity prices and labor market outcomes. Then, in Section 2.2 we document variation across space in the employment shares of different sectors and variation in skill intensity within sec-

[1] Adão [2016] studies the distributional effects of trade in a Roy–type model with worker heterogeneity in absolute and comparative advantage. He applies it to infer the response of Brazil's labor market to fluctuations in commodity prices. Differently than Adão [2016], our model allows for spatial linkages (interregional trade and migration) which are the focus of our paper. In addition our model is dynamic, to account for forward–looking migration decisions.

tors. We also describe how integrated or isolated regions are in terms of interregional trade flows and interregional migration. Finally, we document downward wage rigidity, which is a key feature of labor markets in Brazil.

2.1 Data sources

Commodity prices We use data on 14 commodities produced in Brazil from the World Bank's Global Economic Monitor – Commodities. These include cereals, cotton, sugarcane, soybeans, citrus, coffee, cacao, bovine meat, ovine meat, poultry meat, coal, oil and gas, a basket of metallic minerals, and a basket of precious metals. Among these, the three most important commodities produced by Brazil in terms of employment are coffee, soybeans and sugarcane.

Labor market outcomes The dataset used to track labor market outcomes is RAIS (Relação Anual de Informações Sociais), an employer–employee census of the formal sector in Brazil. This dataset has key advantages. A first advantage is that it reports the educational attainment of each worker. From this, we split workers in two groups: skilled and unskilled. Skilled workers are those with at least some extent of tertiary education. A second advantage is that we can track workers over time, which allows us to compute migration flows as detailed below. Using RAIS, we construct total employment by state, sector, skill type and year. We use RAIS for 1999-2018. We have data with worker identifiers for 1999-2013 (allowing us to track workers over time) and data without worker identifiers for 2014-2018.

Sectors We define three sectors, the commodity sector (consisting of both agriculture and mining), the tradable (i.e. manufacturing) sector and the nontradable (i.e. service) sector. We exclude government and quasi–government employment from our sample.

Geographic units We divide Brazil into 27 states. We choose the state as the geographic unit of analysis because a key topic in our paper is documenting the role of spatial linkages, including interregional trade and interregional migration. Our choice is driven by the fact that interregional trade flows used to calibrate the model are observed at the state level but not at finer levels of disaggregation.

Interregional migration flows We also construct migration flows across states and sectors over time. This is possible given that RAIS tracks workers over time.

Interregional trade flows Data on interstate trade flows in Brazil is reported in Vasconcelos [2001] for 1999.

Regional commodity price index Following Benguria et al. [2024], we construct a state–level commodity price index defined as a weighted average of commodity prices, with employment weights computed in year 2000:[2]

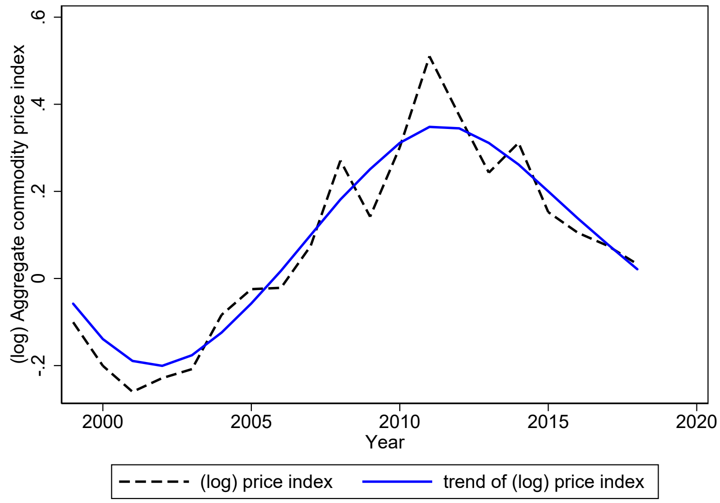
$$p_{rt} = \frac{\sum_{i \in C} p_{it} \times e_{ir}}{\sum_{i \in C} e_{ir}} \tag{1}$$

In this expression, e_{ir} corresponds to the employment in state r and commodity i and p_{it} corresponds to the price of commodity i in year t. Also following Benguria et al. [2024] we use the trend of this price index. To this end, we compute the logarithm of the price index and extract the trend using the Hodrick-Prescott filter, based on data for 1990–2018. Note that Benguria et al. [2024] derive this expression from a theoretical framework and also provide further empirical justification for this measure of regional exposure to commodity shocks.

Figure 1 shows the magnitude of the commodity cycle. It plots an aggregate commodity price index using national weights as well as its trend. The initial trough in the trend occurs in 2002 and the peak happens in 2011. Throughout the empirical analysis we refer to 2002-2011 as the boom and 2011-2018 as the bust. Appendix Figure A.1 shows changes in the state–level commodity price index between 2002-2011 and 2011-2018. The figure indicates that there is substantial variation both in the boom and bust. This variation results from the interaction of initial employment shares across different commodities and the different evolution of the price of individual commodities. The figure also shows that all states experienced an important increase in the commodity index during the boom period, ranging from 34% to 108%. The largest boom is experienced by Espírito Santo, Rondônia, and Minas Gerais. The states facing the smaller increase in commodity prices are the Distrito Federal (Federal District), Alagoas, and São Paulo. The maps in Appendix Figures A.3 and A.4 illustrate the spatial distribution of the commodity boom (2002-2011) and bust (2011-2018).

[2] Employment weights are computed using the Demographic Census of year 2000 given that it provides the most comprehensive measure of employment.

Figure 1: Commodity price cycle



Notes: This figure plots the (log) aggregate price index, based on the definition in equation (1) and using national weights. The figure also plots the trend.

2.2 Regional heterogeneity and spatial linkages

We now discuss the substantial heterogeneity across Brazilian states that motivates and guides our quantitative model. This spatial heterogeneity in the employment shares of different sectors and the skill intensity overall and within sectors, suggests that the impact of the commodity boom could differ strongly across states. In addition, we document the degree of integration or isolation of different states in terms of interregional trade flows and interregional migration, which could also shape the impact of the boom.

Employment shares and skill intensity We start by documenting differences across Brazil's five macroregions. Table 1 reports employment shares in year 2000 for each of them. First, these statistics indicate that the share of employment in the commodity sector is substantially higher in the Central–West (12.6%) region than in the rest of Brazil. The North, Northeast, and Southeast macroregions have fairly similar employment shares, while the South has a higher employment share in the tradable sector and a lower one in the nontradable sector. There are also differences across these regions in skill intensity. The share of unskilled workers is higher in the Central–West, North and Northeast macroregions, and somewhat lower in the South and then the Southeast macroregions.

Next, we focus on states, which are our regional unit of analysis throughout the paper. Figure 2 illustrates the heterogeneity across states in terms of sectoral employment shares and skill intensity in year 2000. Panel A indicates that the distribution of employment across sectors varies widely across states. For example, 25.0% of workers are employed in the commodity sector in Mato Grosso do Sul, while only 5.9% and 1.5% are found in that sector in São Paulo and the Distrito Federal, respectively. In addition, skill intensity also varies widely. Across all sectors (panel B), skill intensity is higher in the Distrito Federal (containing the capital city Brasilia) and in the wealthiest states with the largest cities: São Paulo and Rio de Janeiro. Within the commodity sector (panel C), it is generally higher in states in which the commodity sector is dominated by mining industries, and lower when agriculture accounts for a higher share of commodity employment. The share of skilled workers in the commodity sector goes from 12.9% in Acre to 1.0% in Alagoas.[3]

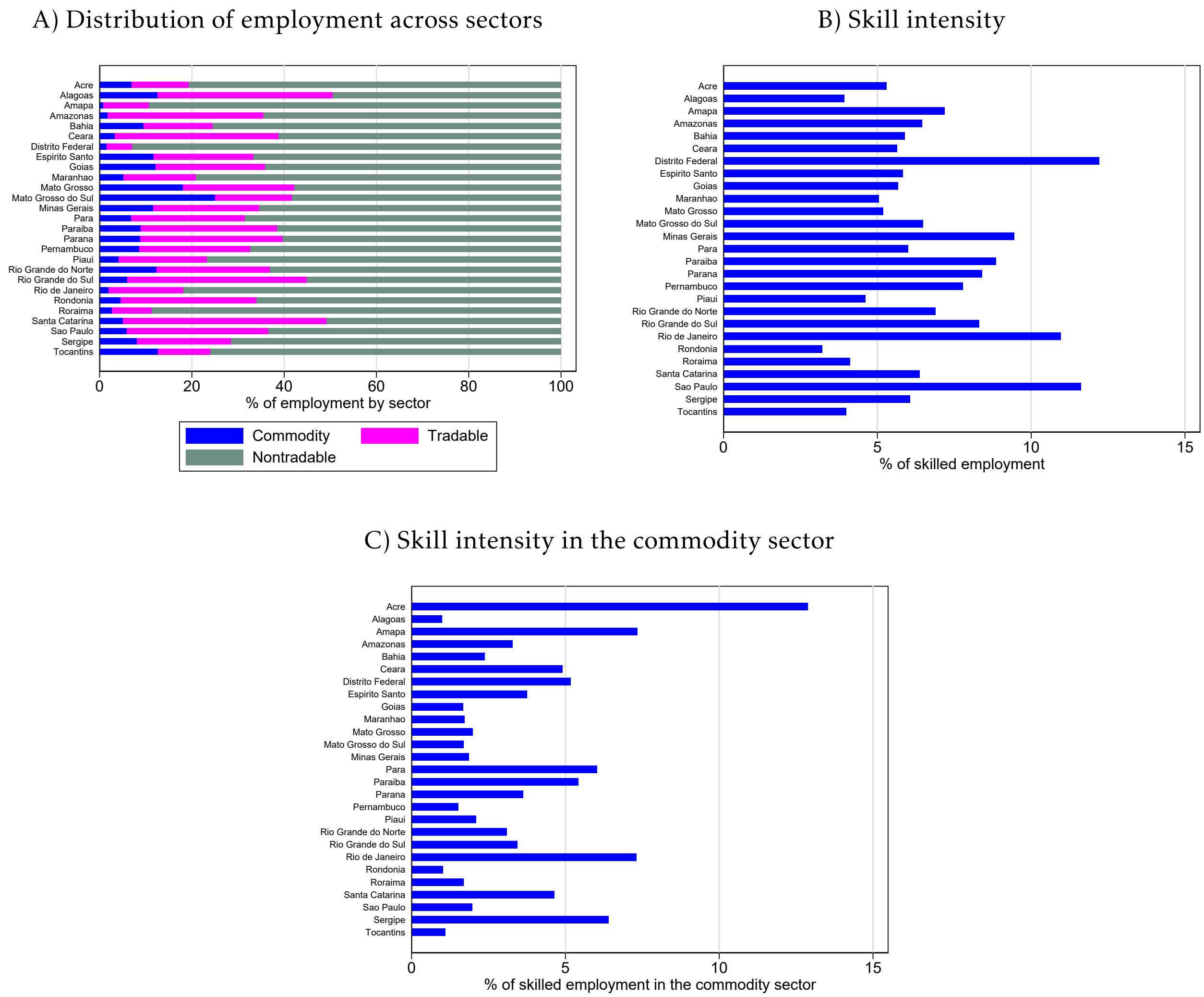
Table 1: Descriptive Statistics

Macroregion	Emp. Share Commodity	Emp. Share Tradable	Emp. Share Nontradable	Emp. Share Unskilled	Emp. Share Skilled
Central-West	12.6	17.8	69.5	92.6	7.4
North	5.4	25.3	69.3	94.4	5.6
Northeast	8.1	23.8	68.0	93.7	6.3
South	6.7	37.5	55.8	92.2	7.8
Southeast	6.6	26.2	67.2	89.1	10.9

Notes: This table shows employment shares by sector and by skill share in each state in year 2000.

[3] Appendix Table A.1 tabulates state–level statistics.

Figure 2: Heterogeneity in state characteristics: Sectoral employment shares and skill intensity

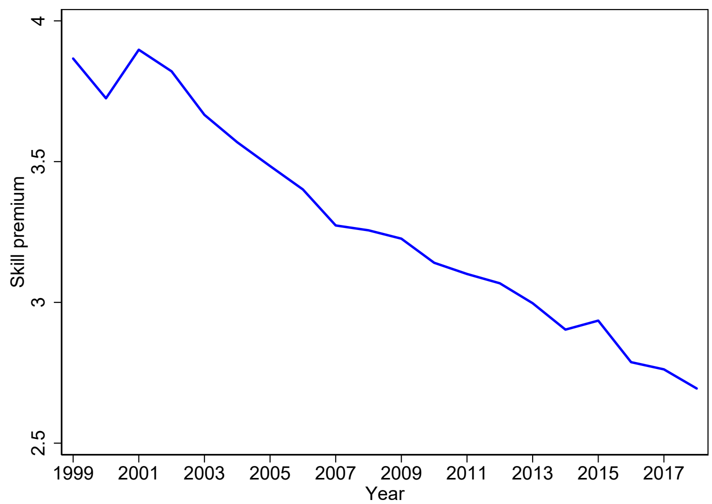


Notes: Panel A reports the share of employment by sector for each state. Panel B reports the share of skilled employment in total employment for each state. Panel C reports the share of skilled employment in total employment in the commodity sector for each state. All figures use data for year 2000.

Trends in the skill premium During the commodity boom of the 2000's, Brazil experienced a sharp decline in the skill premium, as shown in Figure 3. The skill premium further declines during the bust years, without a reversal. There are several explanations for the decline in the skill premium in Brazil during this decade Alvarez et al. [2018], and the quantitative model will determine what portion of raw trend is driven by changes in commodity prices. The figure indicates that the skill premium, measured as the ratio between the average wage of skilled and unskilled workers, fell by 30%, from 3.9 in 1999 to 2.7 in 2018. Appendix Figure A.2

illustrates the variation across states in this regard. The skill premium declined in all 27 states both during the boom and bust.

Figure 3: Skill premium



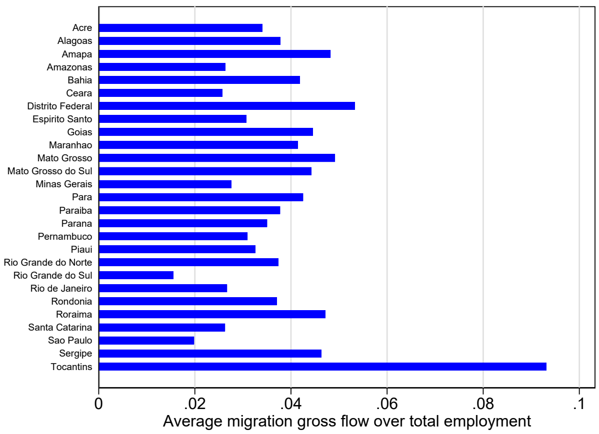
Notes: This figure plots the skill premium over time at a national level, defined as the ratio between the average wage of skilled workers and the average wage of unskilled workers.

Spatial linkages There are also differences in terms of how integrated states are with the rest of Brazil through interregional migration and interregional trade. Panel A in Figure 4 plots the average migration gross flows (the average of inflows and outflows) over total employment. This goes from 9.3% in the small state of Tocantins to 2.0% in São Paulo and 1.5% in Rio Grande do Sul. Panel B shows the share of workers who move across sectors, across states, or across both between consecutive years over 1999-2013. On average, 6.0% of individuals change sectors (but not states), 2.5% change states (but not sectors), and 0.9% change both. This increases slightly over time, with the sum of the three categories going from 8.5% at the start of the sample period to 10.2% at the end.[4] Finally, panel C illustrates the variation across states in their interstate trade linkages. It plots each state's total interstate exports as a ratio of state GDP, which goes from 96% in Amazonas to 4% in Amapá.

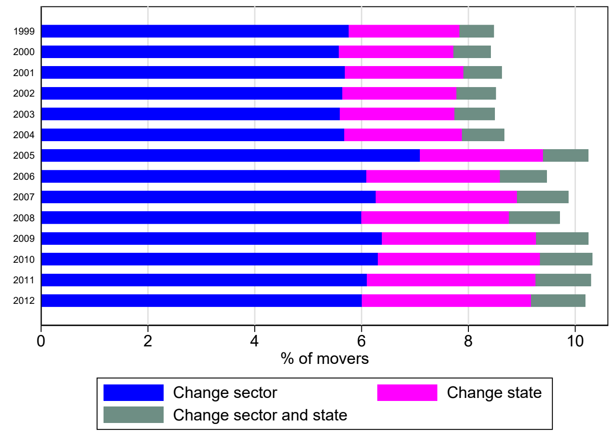
[4] Appendix Figure A.5 shows this pattern is similar for unskilled and for skilled workers.

Figure 4: Heterogeneity in state characteristics: Interregional trade and migration

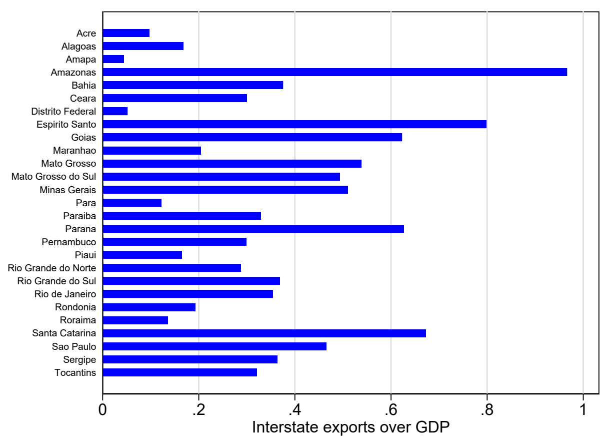
A) Average migration gross flows over total employment



B) Share of movers across sectors and/or states



C) Interstate exports over GDP



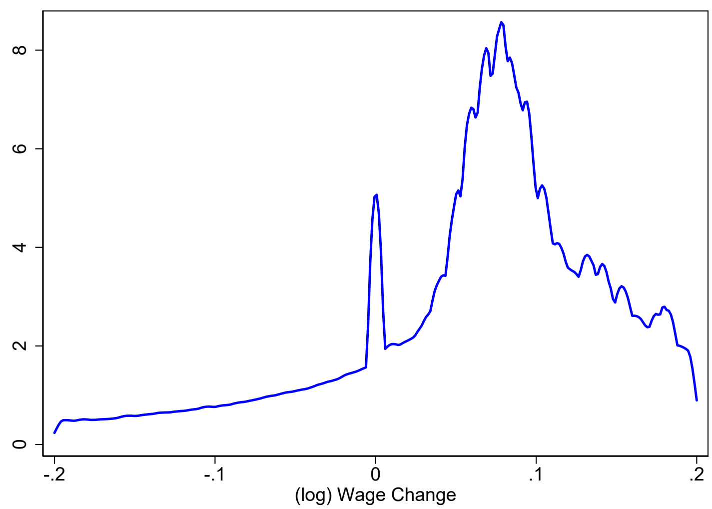
Notes: Panel A reports the average between employment inflows and outflows as a share of total employment for each state in 2000. Panel B plots the share of workers who move across sectors (but not across states), across states (but not across sectors), or across both sectors and states between consecutive years. Panel C reports total interstate exports over state GDP for each state in 1999.

Downward wage rigidity Downward wage rigidity is an important feature of labor markets in Brazil [Messina and Sanz-de Galdeano, 2014].[5] Downward wage rigidity is evident from

[5]This has historical precedents. Up until the mid-1990s, wage adjustments in Brazil were highly centralized, with adjustments for all formal sector workers set annually by law. Further, hyperinflation in the early 1990's led to indexation to the minimum wage. The period analyzed here features somewhat more flexibility. However, the labor market remains highly rigid. Campos et al. [2018] rank Brazil within the top 10% most rigid labor markets in 2000 within a sample of 144 countries. See De Barros and Corseuil [2004] and Amadeo and Camargo [1993] for details on Brazil's labor market institutions in recent decades.

examining the distribution of year-to-year wage changes. We compute the (log) wage changes for all workers in the commodities, tradable and nontradable sectors. We follow the literature [Kurmann and McEntarfer, 2019] and focus on stayers: workers that remain in the same firm from one year to the next. We pool all wage-change observations across sectors and across the period 1999-2013, and plot the kernel density estimate in Figure 5. We see that the shape of the distribution is highly asymmetric, with a large fraction of positive wage changes and few negative wage changes, which the literature interprets as a sign of downward wage rigidity.[6] In Appendix Figure A.6, we show that this distribution is very similar for both skilled and unskilled workers.

Figure 5: Downward wage rigidity: Distribution of wage changes



Notes: This figure plots a kernel density of the distribution of all nominal year-to-year wage changes pooled over 1999-2013.

3 Model

In this section, we describe the theoretical framework that we will use to analyze the uneven effect of a commodity boom on workers based on their skill type and the region in which they live. We consider an economy (Brazil) with N regions. Every region is populated by skilled and unskilled workers. In every period, workers decide whether to move across sectors and regions. Every region has a commodity sector M that produces a region-specific commodity good, a tradable sector T, and a nontradable sector N. The model features trade costs, labor mobility frictions, and downward wage rigidity, which jointly shape the propagation of the

[6] The share of wages that increase, stay constant, and fall from one year to the next is 81.3%, 2.7% and 16.0% respectively.

commodity cycle. We use j and k to index sectors, i and n to index regions, p for a worker's skill type and t for time. For conciseness, we omit time subscripts in equations that are not intertemporal.

3.1 Workers

Every region has an initial endowment of unskilled and skilled workers, $\overline{L}_i = \left\{\overline{L}_i^u, \overline{L}_i^s\right\}$. Workers of skill type p earn a wage $w_i^{j,p}$ in sector j and region i. When there is unemployment (i.e., when the downward wage rigidity constraint is binding), this wage is such that the wagebill in a region-sector-skill category is split evenly across all workers. In other words, unemployment risk is pooled. In addition, all workers – independently of their skill, region, or sector – receive an equal share of the total profits obtained from the natural resources of all regions.

Workers in region i have a period utility which is a function of a consumption bundle that is a CES aggregator over four types of goods: region–specific commodity goods, region–specific tradable goods, a region–specific nontradable good, and an imported tradable good produced in the rest of the world.

$$C_i = \left(\phi^M \left(C_i^M\right)^{\frac{\xi-1}{\xi}} + \phi^G \left(C_i^G\right)^{\frac{\xi-1}{\xi}}\right)^{\frac{\xi}{\xi-1}}, \tag{2}$$

with $\xi > 1$, $\phi^C > 0$ and $\phi^G > 0$. In this expression, C_i^M represents the consumption bundle of region–specific commodity goods and C_i^G the consumption bundle of non–commodity goods. The bundle of commodity goods C_i^M aggregates consumption of the commodities produced in every region:

$$C_i^M = \left(\sum_n \left(C_{ni}^M\right)^{\frac{\gamma_M-1}{\gamma_M}}\right)^{\frac{\gamma_M}{\gamma_M-1}}, \tag{3}$$

with $\gamma_M > 1$. In this expression, C_{ni} represents the consumption in region i of the commodity good produced in region n. We assume each region produces one specific commodity product, and we use n to denote both a region and the commodity good that the region produces. Commodity goods can be also imported from the rest of the world at the same exogenous prices of domestically–produced commodities.

The consumption bundle of non–commodity goods, in turn, aggregates the bundle of tradable goods (X) and the nontradable (N) good:

$$C_i^G = \left(\phi^X \left(C_i^X\right)^{\frac{\gamma_G-1}{\gamma_G}} + \phi^N \left(C_i^N\right)^{\frac{\gamma_G-1}{\gamma_G}}\right)^{\frac{\gamma_G}{\gamma_G-1}}, \tag{4}$$

with $\phi^X > 0$, $\phi^N > 0$ and $\gamma^G > 1$. Finally, C_i^X is a CES aggregator of the imported good (I) and the domestically– produced tradable goods (T):

$$C_i^X = \left(\phi^T \sum_n \left(C_{ni}^T\right)^{\frac{\gamma_X - 1}{\gamma_X}} + \phi^I \left(C_i^I\right)^{\frac{\gamma_X - 1}{\gamma_X}}\right)^{\frac{\gamma_X}{\gamma_X - 1}}, \tag{5}$$

where $\phi^T > 0$, $\phi^I > 0$, and $\gamma_X > 1$. In this expression, $C_i^T = \left(\sum_n (C_{ni})^{\frac{\gamma_T - 1}{\gamma_T}}\right)^{\frac{\gamma_T}{\gamma_T - 1}}$ corresponds to the consumption of region–specific tradable goods in region i, which is a CES aggregator of the tradable good produced in other regions n.

At the end of every period, workers in region i and sector j have the option to migrate to other regions and sectors. They face a time–invariant migration cost $d_{in}^{jk,p}$ which is a function of the origin and destination region pair (i,n), the origin and destination sector pair (j,k), and the skill type p. Workers have heterogeneous preferences for each region–sector pair. This is captured by an additive idiosyncratic term $\varepsilon_{i,t}^{j,p}$ in their utility function. Thus, workers in region i and sector j have the following lifetime utility from period t onward:

$$v_{i,t}^{j,p} = u\left(\widetilde{C}_{i,t}^{j,p}\right) + \max_{\{n,k\}} \left\{\rho E\left[v_{n,t+1}^{k,p}\right] - d_{in}^{jk,p} + \sigma \varepsilon_{i,t}^{j,p}\right\}. \tag{6}$$

In this expression, $\widetilde{C}_{i,t}^{j,p} = D_{i,t}^{j,p} C_{i,t}^{j,p}$ is equal to the consumption bundle multiplied by the term $D_{i,t}^{j,p}$ which captures the value of the amenities associated with working in region i and sector j for every worker of skill p. We can write $\widetilde{C}_{i,t}^{j,p} = D_{i,t}^{j,p} I_{i,t}^{j,p} / P_{i,t}$ because $I_{i,t}^{j,p}$ is the nominal wage income of a worker of skill p in region i and sector j, and $P_{i,t}$ is the ideal price index in region i. Furthermore, as in Caliendo et al. [2019], we assume a log utility function for all workers: $u(x) = \log(x)$. Finally, as in most discrete choice models, we assume the idiosyncratic preference shock $\varepsilon_{i,t}^{j,p}$ is i.i.d. over time and is drawn from a mean–zero, Type–I Extreme Value distribution. In equation (6), σ scales the variance of this idiosincratyc shock.

Migration patterns We define $V_{i,t}^{j,p} = E\left[v_{i,t}^{j,p}\right]$ as the expected lifetime utility of a worker from period t onward, with the expectation taken over the preference shock. Given the assumptions on the migration cost and preference shock, we can write:

$$V_{i,t}^{j,p} = u\left(\widetilde{C}_{i,t}^{j,p}\right) + \sigma \log\left[\sum_{n,k} \exp\left(\rho V_{n,t+1}^{k,p} - d_{in}^{jk,t}\right)^{\frac{1}{\sigma}}\right], \tag{7}$$

where consumption $\widetilde{C}_{i,t}^{j,p}$ can be re–written as:

$$\widetilde{C}_{i,t}^{j,p} = D_{i,t}^{j,p} \frac{I_{i,t}^{j,p}}{P_{i,t}} \tag{8}$$

Migration patterns are captured by the share of workers of type p that transition from region i to region n and from sector j to sector k:

$$\pi_{in,t}^{jk,p} = \frac{\exp\left(\rho V_{n,t+1}^{k,p} - d_{in}^{jk,p}\right)^{\frac{1}{\sigma}}}{\sum_{m,h} \exp\left(\rho V_{m,t+1}^{h,p} - d_{im}^{jh,p}\right)^{\frac{1}{\sigma}}}. \tag{9}$$

As a result, the labor supply of workers of type p in region i, sector j and time period $t+1$ is:

$$L_{i,t+1}^{j,p} = \sum_k \sum_n \pi_{ni,t}^{kj,p} L_{n,t}^{k,p}, \tag{10}$$

subject to a feasibility constraint such that the sum of labor across regions is equal to the (fixed) national labor force for each skill type:

$$\sum_k \sum_n L_{n,t}^{k,p} = \overline{L}^p. \tag{11}$$

3.2 Production

We now discuss the production structure in each sector of the economy.

Labor input Firms in each region i and sector j use a composite labor input combining skilled and unskilled labor according to the following CES aggregator:

$$L_i^j = \left(\phi_i^{j,u} \left(l_i^{j,u}\right)^{\frac{\eta-1}{\eta}} + \left(l_i^{j,s}\right)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}}, \tag{12}$$

with $\phi_i^{j,u} > 0$ and $\eta > 1$. We allow the skill intensity of production to vary across regions and sectors.

Commodity sector In every region i there is a representative firm producing the region–specific commodity good. This firm uses the labor input L_i^M, region–specific natural resources R_i and an intermediate input bundle X_i^M. The intermediate input bundle is obtained from a one–to–one transformation of the consumption bundle C_i. The production function is:

$$M_i = A_i^M \left(R_i^\alpha \left(L_i^M\right)^{1-\alpha}\right)^{\beta^M} \left(X_i^M\right)^{1-\beta^M}, \tag{13}$$

where A_i^M is a region–specific productivity parameter. The representative commodity producer faces an exogenous price Z_i^M, which is determined in the world market. In addition, trading commodities with the rest of the world involves a trade cost τ_{iF}^M that varies across commodity goods i.

Tradable sector In every region, the tradable sector consists of a representative firm that uses labor and an intermediate input bundle X_i^T to produce a region–specific tradable good with productivity A_i^T. The production function is:

$$T_i = A_i^T \left(L_i^T\right)^{\beta^T} \left(X_i^T\right)^{1-\beta^T}. \tag{14}$$

Tradable goods can be shipped between any two regions i and n with a bilateral iceberg–type trade cost τ_{in}. Tradable goods can also be exported to the rest of the world with trade cost τ_{iF}, which depends on the origin region.

Nontradable sector Finally, the nontradable sector consists of a representative firm in every region. It uses the labor input L_i^N and an intermediate input bundle X_i^N to produce a nontradable good that is consumed in the region in which it is produced.

$$N_i = A_i^N \left(L_i^N\right)^{\beta^N} \left(X_i^N\right)^{1-\beta^N} \tag{15}$$

In this expression, A_i^N captures the firm's productivity level.

3.3 Rest of the world

The rest of the world provides each commodity at the exogenous world price Z_i^M. It also provides a tradable foreign good at an exogenous price P^I. The foreign economy has an aggregate demand Ψ_F with the same preference structure as Brazil. This implies that for any given price of tradable goods P_{iF}^T, the demand function is given by:

$$R_{iF}^T = P_{iF}^T Q_{iF}^T = \left(\frac{P_{iF}^T}{P_F^T}\right)^{1-\gamma^T} I_F^T = \left(\frac{P_{iF}^T}{P_F^T}\right)^{1-\gamma^T} \left(\phi^T\right)^{\xi} \left(\frac{P_F^T}{P_F}\right)^{1-\xi} I_F \equiv \left(P_{iF}^T\right)^{1-\gamma^T} \Psi_F \tag{16}$$

3.4 Downward wage rigidity

We assume there is downward nominal wage rigidity. We model this in the spirit of Schmitt-Grohé and Uribe [2016] such that there is a lower bound on how much the wage of workers of any region-sector-skill in period t can fall relative to the wage in period $t-1$.

$$w_{i,t}^{j,p} \geq \chi w_{i,t-1}^{j,p}, \tag{17}$$

where $0 < \chi < 1$. When the constraint is not binding, this assumption is irrelevant. When the constraint is binding, there is unemployment. We assume that when there is unemployment, all workers within a given region-sector-skill category split wages evenly. In other words, unemployment risk is pooled across all workers.

Specifically, when the constraint binds the nominal wage is fixed at its floor $w_{i,t}^{j,p} = \chi w_{i,t-1}^{j,p}$ and employment becomes demand-determined. In this situation, firms' labor demand $l_{i,t}^{j,p}(w_{i,t}^{j,p})$ is lower than the corresponding labor supply $L_{i,t}^{j,p}$ formed from workers' migration flows. Employment and unemployment are therefore

$$l_{i,t}^{E,j,p} = \min\{L_{i,t}^{j,p}, l_{i,t}^{j,p}(w_{i,t}^{j,p})\}, \qquad u_{i,t}^{j,p} = 1 - \frac{l_{i,t}^{E,j,p}}{L_{i,t}^{j,p}} \tag{18}$$

As workers split wages evenly, the expected nominal wage income per worker is

$$\bar{w}_{i,t}^{j,p} = \frac{l_{i,t}^{E,j,p}}{L_{i,t}^{j,p}} w_{i,t}^{j,p}. \tag{19}$$

and real consumption therefore depends on

$$\widetilde{C}_{i,t}^{j,p} = D_{i,t}^{j,p} \frac{\bar{w}_{i,t}^{j,p} + \Omega_t}{P_{i,t}}. \tag{20}$$

where Ω_t is the lump-sum transfer of profits from the natural resource. Finally, note that when $\chi = 0$, the model collapses to the case with flexible wages.

3.5 Equilibrium conditions

We leave the details of the equilibrium conditions and mathematical derivations to Appendix B. Similar to Caliendo et al. [2019], the model's dynamic equilibrium is characterized by two sets of equilibrium conditions. First, a set of intertemporal conditions determines the worker migration patterns across periods. These conditions stem from workers optimally choosing in which region and sector to work in the following time period to maximize their lifetime expected utility. Second, a set of intratemporal conditions determine the prices of factors (expected wages and the returns to natural resources) and goods. These conditions are obtained from production and trade decisions and from market clearing.

4 Quantitative analysis

Our goal is to use the model to understand the uneven effect of the commodity boom on different workers and to quantify how spatial linkages shape this impact. To this end, we first describe the computation of counterfactuals, then discuss our calibration strategy, and finally present our quantitative results.

4.1 Solution algorithm and calibration

We use the "dynamic hat algebra" method to compute the counterfactual equilibrium.[7] The group of within–period equilibrium conditions are shown in Appendix B. Here, we focus on the sequential equilibrium.

Assume there is a commodity shock captured by a change in the commodity prices Z_i^M. We define the change of any variable x between two time periods as $\widehat{x_t} = \frac{x_{t+1}}{x_t}$. Based on equation (9), the share of workers that move across regions and sectors is:

$$\widehat{\pi}_{in,t+1}^{jk,p} = \frac{\exp\left(V_{n,t+2}^{k,p} - V_{n,t+1}^{k,p}\right)^{\frac{\rho}{\sigma}}}{\sum_{m,h} \pi_{im,t}^{jh,p} \exp\left(V_{m,t+2}^{h,p} - V_{m,t+1}^{h,p}\right)^{\frac{\rho}{\sigma}}} \tag{21}$$

Defining $Y_{i,t+1}^{j,p} = \exp\left(V_{n,t+1}^{k,p} - V_{n,t}^{k,p}\right)^{\frac{1}{\sigma}}$, we can write:

$$\widehat{\pi}_{in,t+1}^{jk,p} = \frac{\left(Y_{n,t+2}^{k,p}\right)^{\rho}}{\sum_{m,h} \pi_{im,t}^{jh,p} \left(Y_{m,t+2}^{h,p}\right)^{\rho}} \tag{22}$$

We also use the fact that taking the relative time differences of equation (7) across two time periods yields:

$$Y_{i,t+1}^{j,p} = \sum_{n,k} \mu_{in,t+1}^{jk,p} \left(Y_{n,t+2}^{k,p}\right)^{\rho} \tag{23}$$

where

[7] This method was introduced by Caliendo et al. [2019] building on Dekle et al. [2008] who analyze the static case. This method has the advantage of restricting the essential number of parameters and economic fundamentals required for calibration.

$$\mu_{in,t+1}^{jk,p} = \exp\left(\frac{u\left(\widetilde{C}_{i,t+1}^{j,p}\right) - u\left(\widetilde{C}_{i,t}^{j,p}\right)}{\sigma}\right)\pi_{in,t}^{jk,p} = \left(\frac{\widehat{D}_{i,t+1}^{j,p}\widehat{I}_{i,t+1}^{j,p}}{\widehat{P}_{i,t+1}}\right)^{\frac{1}{\sigma}}\pi_{in,t}^{jk,p} \tag{24}$$

Consequently, the evolution of labor supply is then characterized by:

$$L_{i,t+1}^{j,p} = \left(\sum_k \sum_n \pi_{ni,t}^{kj,p} L_{n,t}^{k,p}\right)\widehat{L}_{t+1}^{p}. \tag{25}$$

Counterfactuals To evaluate the impact of the commodity boom, we compare an economy facing the calibrated commodity boom against an economy in which commodity prices remain constant at the baseline level. The impact of the boom is measured as the difference between these two economies.

In other words, this counterfactual exercise measures the difference between the economies $\Omega_{1,t}^1 = \{\Gamma_0, \pi_{-1}, Z_t\}$ and $\Omega_{0,t}^1 = \{\Gamma_0, \pi_{-1}, Z_{-1}\}$ as $t \longrightarrow H$. We evaluate the dynamic model twice. In both cases, the initial fundamentals Γ_0 are the same and we assume they do not change along the transition path, i.e. $\Gamma_t = \Gamma_0$. The first economy faces the commodity shocks ($Z_t = \left\{Z_{i,t}^M\right\}$), while the second one does not ($Z_{i,t}^M = Z_{i,-1}^M$ or $\widehat{Z}_{i,t}^M = 1$). The differences in economic outcomes between these two counterfactual scenarios captures the impact of the commodity shocks along the dynamic transition.

Calibration We match the initial state of the economy in our quantitative model to Brazil in 1999. We use data on each state, sector and skill type's employment ($L_{i,0}^{j,p}$) and wages ($w_{i,0}^{j,p}$). Recall that there are 27 states, we divide the economy into three sectors (commodity, tradables, nontradables), and there are two skill groups (skilled and unskilled workers). We also use interstate aggregate trade flows to identify the within–country trade matrices $\lambda_{i,0}^T$ and $\lambda_{i,0}^M$. In addition, we use state–level data on GDP, exports and imports. We combine this with the interstate trade matrices to calculate the total expenditure in each state. The value-added shares in sectoral production β^j are inferred from the World Input-Output Database [Timmer et al., 2015]. External borrowing is then computed as the difference between state–level income and expenditure. We also use the migration flow between each sector–state pair between years 1999 and 2000 to infer migration costs. Next, we calibrate the state–level commodity prices using the regional commodity price index described in Section 2. Finally, we take the value of several structural parameters from Benguria et al. [2024] and the related literature, as described in Table 2. For the downward wage rigidity parameter (χ) our baseline calibration uses a value 0.95 but we also report results with smaller and larger values.

Table 2: Externally calibrated parameters

Parameter	Value	Description
α	0.3	Production intensity of natural resources
η	1.41	Elasticity of substitution between skilled and unskilled workers
ξ	$\frac{1}{1-0.5}$	Elasticity of substitution between commodity and noncommodity goods
γ_M	$\frac{1}{1-0.85}$	Elasticity of substitution between commodity goods
γ_G	$\frac{1}{1-0.74}$	Elasticity of substitution between tradable and nontradable goods
γ_X	$\frac{1}{1-0.85}$	Elasticity of substitution between domestic and imported tradable goods
γ_T	4	Elasticity of substitution between domestic tradable goods
ρ	0.9	Discount factor
σ	0.5	Variance of the preference shock
χ	0.93 / 0.95 / 0.97	Downward wage rigidity parameter

Notes: This table shows the value of the externally–calibrated parameters.

4.2 Quantitative results

We now use the calibrated model to analyze the uneven effects of the commodity cycle. We start by focusing on the skill premium as a key measure of inequality. We then examine the evolution of the real wages of skilled and unskilled workers, as a measure of their welfare. Our analysis starts by focusing on changes at the national level, and we then move on to discussing spatial inequality and differences in the response to the commodity cycle across states. Throughout the discussion, we measure changes either during the boom years (2002-2011), the subsequent bust (2011-2018), or the full boom-bust cycle (2002-2018).

4.2.1 Economic mechanisms

Before diving into the results, it is useful to discuss the key mechanisms in the model that shape the impact of the commodity cycle on these outcomes. These mechanisms are described in Benguria et al. [2024] and stem from Corden and Neary [1982]. However, in this paper, the framework is enriched to consider how spatial linkages and downward wage rigidity further shape the transmission of commodity cycles. In Brazil, the commodity sector is unskilled intensive compared to the rest of the economy. A boom in commodity prices raises the labor demand of the commodity sector, which raises the overall labor demand of unskilled relative to skilled workers. This lowers the skill premium. There are two mechanisms that transmit the shock to the other sectors of the economy: a cost channel and a demand channel. The cost channel refers to the fact that the increase in wages raises the labor cost to the tradable (i.e., manufacturing) and nontradable (i.e., service) sectors (as well as to the commodity sector itself). Since it is primarily unskilled wages that increase, this raises the labor cost differentially for the tradable and nontradable sectors. The tradable sector has a lower skill intensity than the nontradable sector, so it is hurt more by the cost channel than the nontradable sector. The second channel is a wealth or demand channel. Higher wages in a state due to higher commodity prices lead to higher demand for all goods. This benefits the tradable and nontradable (as well as the commodity) sectors to the extent that goods are sold in the local market. Since part of the tradable output is exported to other states or abroad, it benefits less from this channel than the nontradable sector that sells all its output locally.

Spatial linkages enrich this framework. An increase in labor demand in a state that faces booming commodity prices will attract interregional migration into the state. This will mitigate the rise in wages in the booming state. At the same time, it will raise wages in the states that lose workers. Interregional trade also shapes the transmission. As wages in a state increase, the labor cost and consequently the prices of tradable goods rise. This makes the state less competitive relative to other states. Other states then see an increased demand for their tradable goods, which in turn raises labor demand and wages there.

Downward wage rigidity further impacts the transmission of commodity price fluctuations. During the bust, as commodity prices fall, the process described above reverts. In a state facing a large decline in commodity prices the DWR constraint might bind, which generates unemployment. Spatial linkages then shape the transmission of unemployment across space. We discuss the geographic transmission of unemployment below when we present those results.

4.2.2 Aggregate outcomes

Moving on to the results, Figure 6a plots the evolution of the skill premium as a consequence of the commodity cycle. This is computed by comparing the change in this outcome in a simulation including all shocks and a simulation including all shocks except the commodity price shock. As the first row in Table 3 indicates, the skill premium declines by 2.5% during the boom years (between 2002 and 2011). This is a 15% of the 18% decline in the skill premium observed in Brazil during this period. The skill premium then reverts during the bust, increasing by 1.3% during 2011-2018. Overall, the net decline in the skill premium is 1.2% during the full cycle. In the data the skill premium declines during both the boom and bust (recall Figure 3). We later discuss how a calibration with a stronger degree of downward wage rigidity can lead to a decline in the skill premium not only during the boom but also in the bust. Regardless, other changes in the Brazilian economy beyond the commodity cycle could be reducing the skill premium.[8] The table also shows that the evolution of the skill premium varies when considering the commodity, tradable and nontradable sectors separately. Recall that the model generates sector–specific wages as a result of the frictions in moving across sectors. During the boom, the decline in the skill premium is larger in the tradable and nontradable sectors than in commodities.[9] During the bust, the skill premium increases in the tradable and nontradable sectors, while it declines in the commodity sector.

Next, we discuss the average real wages of unskilled and skilled workers, which are a measure of welfare. These are shown in Figure 6b and in the second and third rows in Table 3. Real wages are defined as the ratio between the nominal wages and the regional price index. As our goal is to capture a measure of welfare, we construct average real wages taking unemployment into account. In other words, average real wages are a weighted average between the positive real wage for the employed and the zero wage of the unemployed. For unskilled workers, we see a 3.6% increase during the boom and a 2.9% decline during the bust, with a net increase of 0.7%.[10] During the boom, commodity sector workers see much larger increases in average real wages than those in other sectors, but they also face a larger decline during the bust. For skilled workers, the pattern is similar, yet movements in average real wages are milder than for unskilled workers.

Figure 6c illustrates the extent of sectoral reallocation at the national level. Between 2002 and 2018, the commodity cycle leads to a 3.4 percentage point (p.p.) increase in the share of employment in the commodity sector, a 1.1 p.p, decline in the nontradable sector, and a 2.4 p.p. decline in the tradable sector. Similarly, we can examine the reallocation of workers across space. Figure 6d examines employment across Brazil's five macroregions and indicates that changes in their employment shares are relatively small. The Central-West region sees a 1.5 p.p. increase in its national employment share, while the Southeast faces an equivalent 1.1 p.p. decline and other regions lie in between. The figure also shows persistence in migration decisions, unlike sectoral employment shares that revert during the bust. Even though changes in employment shares across space are not particularly large, we will show later in our counterfactual analysis that migration can lead to relevant changes in average real wages and the skill premium.

[8] See Alvarez et al. [2018] for a broader discussion of the recent decline in inequality in Brazil.

[9] There are several mechanisms that could explain this difference. One possibility is that skilled workers face a higher cost of moving to the booming commodity sector, which could occur, for example, if there are geographically farther away from the expanding commodity production.

[10] The fact that the overall change in the unskilled average real wage is less than that in each sector suggests that sectoral shares tilt toward lower wage sectors as a result of the cycle.

4.2.3 Spatial disparities

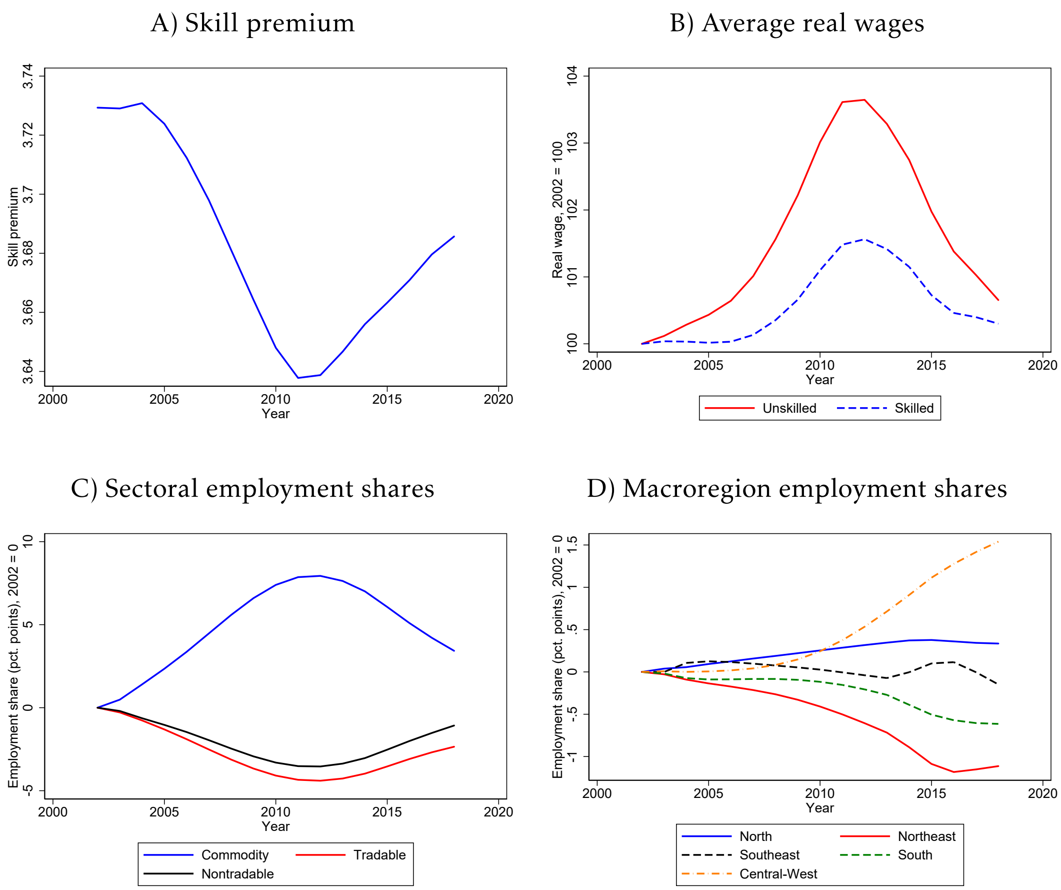
Beyond the aggregate effect of the commodity cycle, the histograms in Appendix Figure A.7 show that there is substantial variation in the changes in average real wages across states and sectors. Focusing on unskilled workers, during the boom the median state–sector reaches an average real wage increase of 4.7%, but this ranges from 0.8% at the 10th percentile to 10.2% at the 90th percentile. During the full cycle, the median state–sector obtains an average real wage increase of 1.5%, going from -2.0% at the 10th percentile to 4.8% at the 90th percentile.

We delve further into this heterogeneity in Figure 7, which reports the change in the average real wage of skilled and unskilled workers by state. During the boom, the largest increases in the average real wage of unskilled workers are seen in Rondônia, Roraima and Espírito Santo, which are all relatively small states. In general, states with larger increases during the boom also see larger declines during the bust. As panel C shows, there is substantial heterogeneity when looking at the effect of the full cycle, with twenty states seeing an increase in the averge real wage of unskilled workers and seven facing a decline. Finally, skilled wages are fairly correlated with unskilled wages, although there are eleven states for which they move in opposite directions when considering the full cycle.

We also examine the variation across states in the skill premium, shown in Appendix Figure A.8. In the boom, we see a decline in the skill premium in all but three states, while in the bust, the skill premium rises in most places. Adding up boom and bust, nearly all states face a decline in the skill premium which for most states is concentrated between -1% and -5%.

In terms of employment, Appendix Figure A.9 reports changes in employment across states due to the commodity cycle. Here, there is more spatial heterogeneity. Focusing on unskilled workers, we see 13 states that gain employment and 14 states that lose it considering the full cycle. The largest changes in both directions are seen in smaller states: Mato Grosso do Sul and Amapá see the largest gains, while Roraima and Piauí faces the largest decline. There is a very high correlation of 0.96 between skilled and unskilled employment.

Figure 6: Evolution of aggregate outcomes in response to the commodity cycle



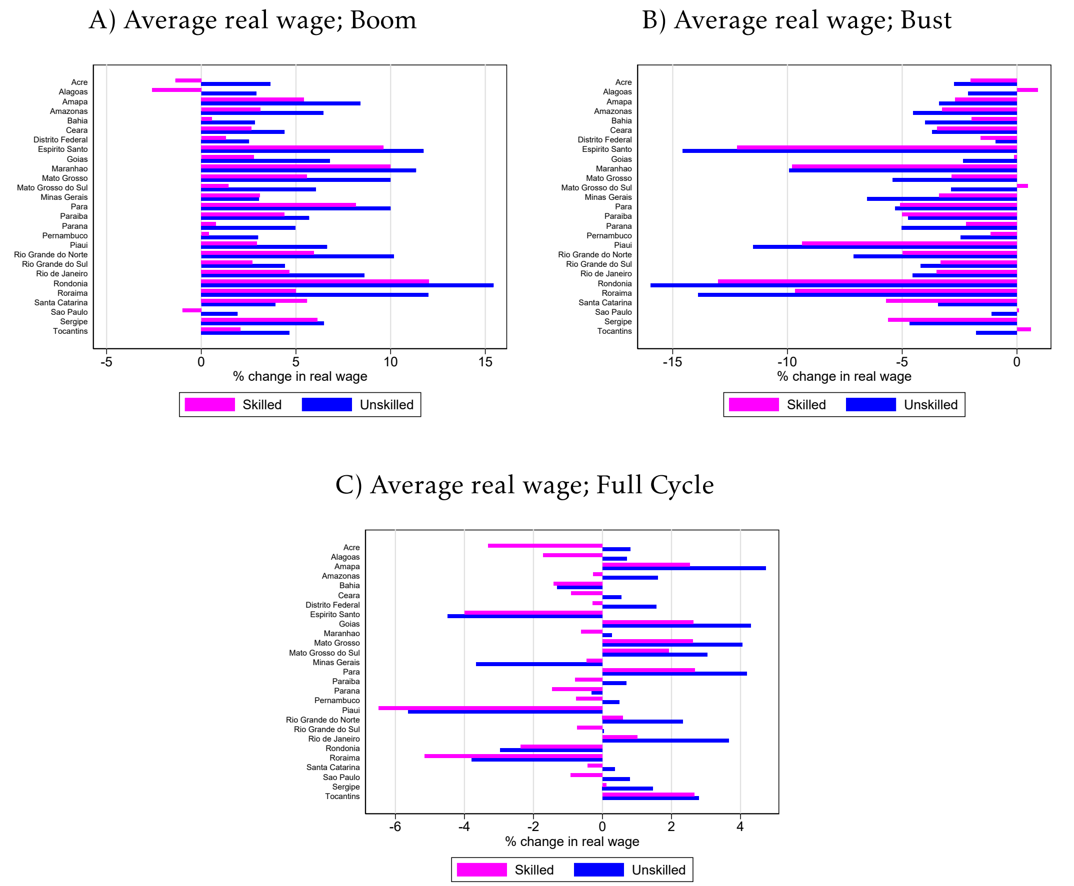
Notes: This figure shows the evolution of aggregate outcomes between 2002 and 2018. Panel A plots the skill premium, defined as the ratio between the wage of skilled workers and the wage of unskilled workers. Panel B plots the average real wage of skilled and unskilled workers, normalized to 100 in 2002. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). Panel C plots the sectoral employment shares for commodities, tradables and nontradables, all normalized to zero in 2002. Panel D plots the employment shares of Brazil's five macroregions, all normalized to zero in 2002.

Table 3: Impact of the commodity cycle on the skill premium and average real wages

	All	Commodity	Tradable	Nontradable
PANEL A: BOOM (2002-2011)				
Skill premium	-2.5%	-0.5%	-5.6%	-4.6%
Average real wage of unskilled workers	3.6%	23.2%	4.6%	6.5%
Average real wage of skilled workers	1.5%	18.8%	-0.3%	2.1%
PANEL B: BUST (2011-2018)				
Skill premium	1.3%	-0.5%	3.1%	2.4%
Average real wage of unskilled workers	-2.9%	-17.3%	-2.6%	-3.4%
Average real wage of skilled workers	-1.2%	-14.6%	-0.0%	-1.1%
PANEL C: FULL CYCLE (2002-2018)				
Skill premium	-1.2%	-1.0%	-2.7%	-2.3%
Average real wage of unskilled workers	0.7%	2.1%	1.9%	2.9%
Average real wage of skilled workers	0.3%	1.7%	-0.4%	1.0%

Notes: This table shows the percent change in the skill premium, the average real wage of unskilled workers, and the average real wage of skilled workers. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). The columns correspond to outcomes in the aggregate economy (in the first column) or by sector (next three columns). Each cell is computed as the percent change in the corresponding outcome between 2002 and 2011 (panel A), 2011-2018 (panel B) or 2002-2018 (panel C).

Figure 7: Changes in state-level outcomes in response to the commodity cycle



Notes: This figure shows the percent change in the average real wage of unskilled and skilled workers by state during the boom (2002-2011, panel A), bust (2011-2018, panel B) and full-cycle (2002-2018, panel C). Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

4.3 Assessing the role of spatial linkages and downward wage rigidity

We now use the model to assess the role of spatial linkages (interregional trade and interregional migration) and downward wage rigidity in shaping the uneven gains from the commodity cycle. In our simulations, we are able to shut down each of these channels separately or all at once, and to compare the gains from the cycle across these scenarios. This also allows us to assess how both elements (spatial linkages and labor market flexibility) interact in shaping the effects of the commodity cycle. Like before, we first focus on outcomes at the national level and later examine the variation across states.

4.3.1 Counterfactuals and aggregate outcomes

Table 4 expands the previous Table 3 to consider changes in the skill premium and in average real wages across all the counterfactual simulations. Panel A reports results for the skill premium. We had found that in the baseline model, which features both spatial linkages and downward wage rigidity, the skill premium declines by 2.5% during the boom. Banning migration results in a smaller (2.0%) decline in the skill premium, while shutting down interregional trade results in a larger (3.0%) decline. With no spatial linkages, the decline in the skill premium is somewhat larger (2.7%) than in the baseline economy, and moving to a counterfactual economy with flexible labor markets also results in a 2.7% decline in the skill premium. When considering the bust, shutting down spatial linkages or wage rigidity also results in more amplification.

Next, panels B and C show the changes in average real wages. Like before, these take into account the possibility of unemployment. For unskilled workers (in panel B), we had found that during the boom the average real wage increases by 3.6% in the baseline scenario with spatial linkages. This is lower when shutting down spatial linkages (2.7%), and slightly higher when moving to flexible labor markets (3.7%). During the bust, the decline in unskilled wages is significantly less in the economy with a flexible labor market, consistent with the fact that rigidity causes unemployment and this measure of wages takes that into account. Appendix Table A.2 reports equivalent statistics but with real wages that are conditional on employment (i.e. without considering unemployment) and in that case the real wage of unskilled workers falls more under flexible labor markets. Finally, we find that these patterns go in the same direction for skilled workers (in panel C).

Table 4: Impact of the commodity cycle on the skill premium and average real wages: Counterfactuals

	Boom 2002-2011	Bust 2011-2018	Full Cycle 2002-2018
PANEL A: SKILL PREMIUM			
DWR	-2.5%	1.3%	-1.2%
DWR No interregional migration	-2.0%	1.2%	-0.9%
DWR No interregional trade	-3.0%	1.7%	-1.4%
DWR No spatial linkages	-2.7%	1.6%	-1.1%
Flexible	-2.7%	1.8%	-0.9%
PANEL B: AVERAGE REAL WAGE OF UNSKILLED WORKERS			
DWR	3.6%	-2.9%	0.7%
DWR No interregional migration	3.9%	-3.5%	0.3%
DWR No interregional trade	2.7%	-2.4%	0.2%
DWR No spatial linkages	2.7%	-3.0%	-0.4%
Flexible	3.7%	-2.5%	1.1%
PANEL C: AVERAGE REAL WAGE OF SKILLED WORKERS			
DWR	1.5%	-1.2%	0.3%
DWR No interregional migration	2.1%	-2.0%	0.0%
DWR No interregional trade	0.6%	-0.6%	0.0%
DWR No spatial linkages	0.8%	-1.4%	-0.6%
Flexible	1.7%	-1.1%	0.6%

Notes: The rows in panel A show the percent change in the skill premium in the baseline case (including downward wage rigidity (DWR) and spatial linkages), and in the counterfactual cases with i) DWR but no interregional migration, ii) DWR but no interregional trade, iii) DWR but no spatial linkages at all (no interregional migration and no interregional trade) and iv) no DWR (flexible wages). The rows in panels B and C correspond to each of these cases for the average real wage of unskilled and skilled workers respectively. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). The columns in each panel correspond to outcomes computed over 2002-2011, 2011-2018 and 2002-2018.

4.3.2 Counterfactuals and spatial disparities

We have previously documented substantial differences across states in the effects of the commodity cycle. We now assess the role of spatial linkages in shaping this disparity. To this end, Table 5 describes the distribution across states of the changes in average real wages of unskilled workers due to the commodity cycle. We focus first on the boom years (2002-2011) in panel A. In the baseline economy, the average real wage in the state at the 25th percentile of the distribution rises by 3.7%, while it increases by 10.0% at the 75th percentile. This 6.3 percentage point differential reflects spatial differences in the gains from the boom. We see that shutting down spatial linkages or moving to flexible labor markets both substantially narrow this measure of spatial inequality.[11]

During the bust (2011-2018), in panel B, shutting down spatial linkages widens spatial inequality, while moving to flexible labor markets still narrows it. Combining boom and bust (panel C), spatial inequality is smaller both when shutting down spatial linkages and when moving to flexible labor markets. These patterns are fairly similar for skilled workers, as shown in Appendix Table A.3.

To further visualize how spatial linkages and labor market rigidity shape regional outcomes, Appendix Figure A.10 provides a scatterplot showing changes in the average real wage of unskilled workers across states under different scenarios. In panel A, we compare the baseline economy (which includes DWR and spatial linkages) to the counterfactual economy which shuts down spatial linkages. If all the changes in the average real wages were identical under these two scenarios, all observations would be in the 45-degree line. This is not the case, and most states are to the right of it, implying a larger increase in the average real wage in the baseline economy when spatial linkages are present (in line with what we documented earlier in the aggregate). The marker size in the figure represents total initial employment in each state, and we see that this deviation is larger for smaller states. In panel B, we do the same exercise but comparing the baseline economy with the counterfactual economy with flexible labor markets. In this case, states are fairly close to the 45-degree line, implying that DWR has less of an effect than spatial linkages on spatial disparities.

Along the same lines, Appendix Figure A.11 focuses on the bust, and here we see most states facing a smaller decline in real wages absent spatial linkages. Interestingly, during the bust there is more deviation from the 45-degree line when comparing the baseline economy

[11] It might seem unintuitive at first that shutting down spatial linkages reduces spatial disparities. One might expect that if, for example, the commodity boom were concentrated in a few states, then disparities would be larger if those states were isolated from the rest of Brazil. Appendix Figure A.10, discussed in more detail later, shows the gains in the average real wage of unskilled workers during the boom, and indeed we see that the remote state of Rondônia, which benefits from a large boom, does better without spatial linkages. However, this is one mechanism but not the only one. Whether this mechanism dominates depends on the distribution of the commodity boom across states.

with the counterfactual with flexible labor markets (in panel B). In this case, may states are close to the diagonal but a fraction of them are further to the left, in line with the aggregate result discussed earlier in Table 4.

Overall, our results suggest that spatial linkages have quite an important role in understanding the effect of the commodity boom on spatial disparities.

Table 5: Spatial inequality in response to the commodity cycle: Unskilled workers

	p25	p50	p75	p75-p25
PANEL A: BOOM (2002-2011)				
DWR	3.7%	6.0%	10.0%	6.3%
DWR + No interregional migration	3.1%	5.5%	8.0%	4.9%
DWR + No interregional trade	2.5%	3.7%	5.5%	3.1%
DWR + No spatial linkages	1.8%	3.0%	4.6%	2.8%
Flexible	3.5%	5.7%	8.6%	5.1%
PANEL B: BUST (2011-2018)				
DWR	-6.5%	-4.5%	-2.7%	3.8%
DWR + No interregional migration	-7.6%	-4.0%	-1.1%	6.5%
DWR + No interregional trade	-5.1%	-3.3%	-2.0%	3.1%
DWR + No spatial linkages	-5.6%	-2.9%	-1.3%	4.3%
Flexible	-5.1%	-3.9%	-2.3%	2.7%
PANEL C: FULL CYCLE (2002-2018)				
DWR	-0.3%	0.7%	2.8%	3.1%
DWR + No interregional migration	-0.9%	-0.1%	2.5%	3.4%
DWR + No interregional trade	-1.0%	0.1%	1.7%	2.7%
DWR + No spatial linkages	-1.3%	-0.3%	1.5%	2.8%
Flexible	0.5%	1.1%	2.9%	2.4%

Notes: This table shows percentiles of the distribution across states of the percent change in the average real wage of unskilled workers as a result of the commodity cycle. Panel A corresponds to the boom (2002-2011), panel B corresponds to the bust (2011-2018), and panel C corresponds to the full cycle (2002-2018). The rows in each panel correspond to the baseline economy (with DWR and including spatial linkages), and to the counterfactual economies i) with DWR and without interregional migration, ii) with DWR and without interregional trade, iii) with DWR and without spatial linkages at all (no interregional migration and no interregional trade), and iv) with flexible labor markets. The first three columns correspond to the 25th, 50th and 75th percentiles of the distribution across states. The fourth column corresponds to the difference between the 25th and 75th percentiles, and is a measure of spatial inequality. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

4.3.3 Downward wage rigidity and unemployment

Downward wage rigidity, when binding, creates unemployment. Interregional linkages can spread unemployment across space. Counterfactuals shutting down these linkages will then involve a different distribution of unemployment over space. Table 6 speaks to this issue by reporting three outcomes, all measured in 2018 at the end of the cycle. First, the share of states with positive unemployment, second, the national unemployment rate, and third, the average unemployment rate across states conditional on having positive unemployment. We compute these outcomes over several counterfactual scenarios. We first consider our baseline economy with DWR, under which 67% of states feature unemployment. We then consider economies with lower or higher degrees of rigidity. When the rigidity parameter χ increases from the baseline 0.95 to 0.97, the share of states with unemployment at the end of the cycle reaches 100% and the national unemployment rate spikes to 11.9%. Under flexible labor markets, in the fourth row, by construction there is no unemployment. We then move on to studying different degrees of spatial linkages: shutting down only interregional migration, only interregional trade, or both. Under these different scenarios the national unemployment rate does not change much because the several of the largest states (including São Paulo and Rio de Janeiro) do not have unemployment in these cases. Nevertheless, there are changes in the number of states with positive unemployment, which speaks to the spatial spread of unemployment. This measure increases when shutting down interregional migration, and falls when shutting all spatial linkages.[12] The average unemployment rate across states with positive unemployment is substantially higher in the economy with no spatial linkages (4.9%) than in the baseline economy (2.6%).

To understand the economic mechanisms behind the geographic transmission of unemployment, consider a state that faces a large decline in its commodity price index during the bust. The decline in wages in this state can make the DWR constraint binding and create unemployment. This will lead to outmigration, which will increase the labor supply in the receiving states, lowering wages and potentially making the DWR constraint binding and triggering unemployment in them. There is also a trade channel: Lower wages in the state facing the downturn will make its tradable goods cheaper. This reduces the demand for tradable goods produced in other states, which reduces the demand for labor in those states, potentially generating unemployment there. In other words, migration spreads unemployment through labor supply, while interregional trade spreads unemployment through labor demand. In both cases described, there can also be situations in which other states have enough slack in the DWR constraint such that they could absorb workers or goods from a state facing a downturn,

[12] This change is driven by two small and isolated remote states.

and potentially eliminate unemployment in the state facing the downturn. In other words, from a theoretical standpoint the number of states facing unemployment could move in either direction when shutting down spatial linkages.

Table 6: Impact of the commodity cycle on unemployment

	Share of states with unemp.	National unemp. rate	Av. unemp. rate across states with unemp.
DWR	66.7%	1.0%	2.6%
DWR (less rigidity)	14.8%	0.1%	0.5%
DWR (more rigidity)	100.0%	11.9%	21.1%
Flexible	0.0%	0.0%	0.0%
DWR + No interregional migration	77.8%	1.1%	2.3%
DWR + No interregional trade	66.7%	1.1%	4.2%
DWR + No spatial linkages	63.0%	1.1%	4.9%

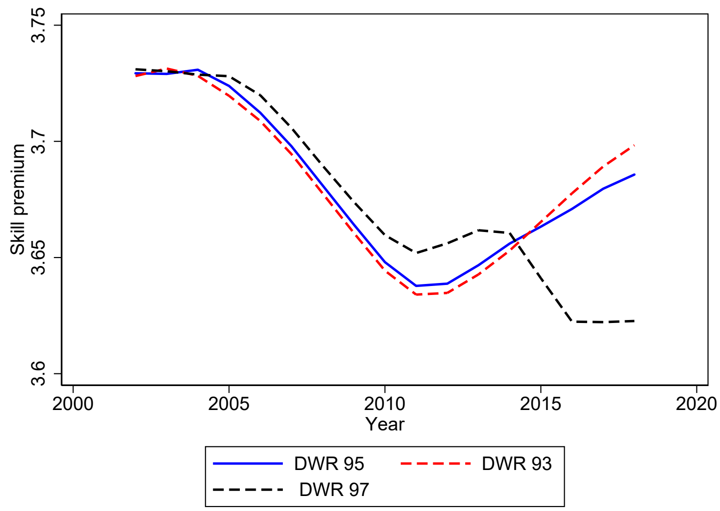
Notes: This table shows the share of states with unemployment, the national unemployment rate, and the average unemployment rate across states with positive unemployment at the end of the cycle in year 2018. The rows correspond to the baseline case (with DWR and including spatial linkages), and the counterfactual economies i) with a lower degree of rigidity (a χ parameter of 0.93), ii) with a higher degree of rigidity (a χ parameter of 0.97), iii) with flexible labor markets, iv) with DWR and without interregional migration, v) with DWR and without interregional trade, and vi) with DWR and without spatial linkages at all (no interregional migration and no interregional trade).

4.3.4 Downward wage rigidity and the skill premium

We had seen in Figure 3 that the skill premium falls continuously during both boom and bust. In contrast, with our baseline calibration we reported in Figure 6a that the skill premium falls during the boom but bounces back during the bust. It is possible that other important changes in the Brazilian economy push the skill premium down during 2011-2018 despite the decline in commodity prices. Nevertheless, it is interesting to note that with a higher degree of downward wage rigidity our model generates a path of the evolution that is closer to that observed in the data. Figure 8 plots the evolution of the skill premium with three different degrees of DWR (the baseline calibration and two cases with more and less DWR). With see that with stronger DWR ($\chi = 0.97$), the skill premium falls during both boom and bust.[13]

[13] Appendix Table A.4 reports the change over 2002-2018 in the skill premium and the average real wages of unskilled and skilled workers under different degrees of DWR.

Figure 8: Evolution of the skill premium in response to the commodity cycle: Degrees of downward wage rigidity



Notes: This figure shows the evolution of the skill premium between 2002 and 2018. The skill premium is defined as the ratio between the wage of skilled workers and the wage of unskilled workers. The blue solid line corresponds to the baseline calibration of the DWR parameter ($\chi = 0.95$). The red dashed line corresponds to a calibration with a smaller degree of DWR ($\chi = 0.93$). The black dot-dashed line corresponds to a calibration with a larger degree of DWR ($\chi = 0.97$).

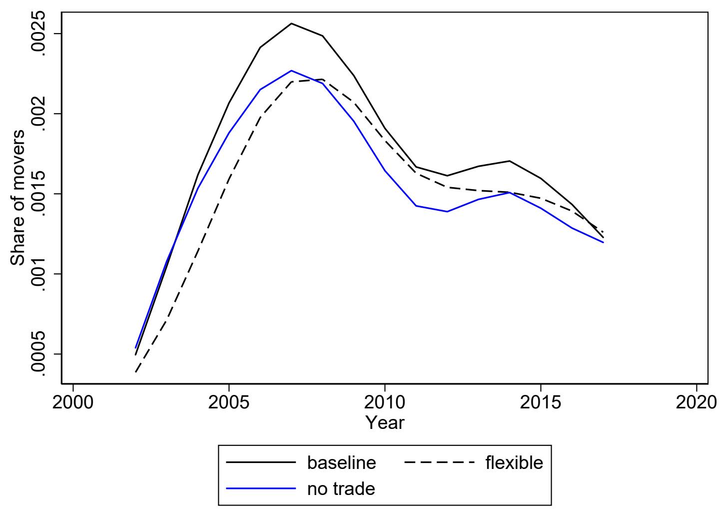
4.3.5 Downward wage rigidity, spatial linkages and migration flows

Finally, Figure 9 examines migration flows in response to the commodity cycle. It plots the total number of workers that move from one state to another in consecutive years normalized by the national population. We see that migration flows increase during the boom, given that the commodity boom raises wages in some states more than others, generating incentives to migrate. Migration flows then falls during the bust, which indicates that workers are not likely to revert their migration decisions.[14] This is consistent with the forward looking nature of workers' migration decisions during the boom. Regarding the counterfactuals, it is interesting to ask whether shutting down interregional trade leads to more or less migration. From a theoretical standpoint, interregional trade could either make regional wages converge or diverge in models with a nontradable sector.[15] In fact, we saw in Table 5 that shutting down spatial linkages narrows spatial disparities in wages during the boom (in other words, interregional trade creates wider differences in wages). This divergence in wages promotes migration. We indeed see in Figure 9 that the share of movers is lower in the counterfactual economy with

[14]This aligns with the finding on regional employment shares in Figure 6d.
[15]Wages are more likely to diverge if the states are different enough in their economic structure.

no interregional trade. A second point we in this figure is that migration is also lower in the economy with flexible labor markets. This is also consistent with Table 5, which shows that spatial disparities in wages also narrow during the boom in that case.

Figure 9: Evolution of interregional migration in response to the commodity cycle: Counterfactuals



Notes: This figure shows the evolution of interregional migration between 2002 and 2018. For each year t, we compute the total number of workers moving across regions between t and $t+1$ and normalize it by the national population in t. The solid black line corresponds to the baseline economy (with DWR and spatial linkages). The dashed black line corresponds to the counterfactual economy with flexible labor markets. The solid blue line corresponds to the counterfactual economy with DWR but no interregional trade.

4.4 The role of informality

In this section, we extend our results by considering the role of informality, a relevant feature of Brazil's labor market. Our baseline results use RAIS, which covers the formal sector. The main reason to use RAIS is that it is a longitudinal dataset: we can track workers over time to quantify transitions across regions and/or sectors. The annual household survey (PNAD) covers both the formal and informal sector, but it is not longitudinal. Given this constraint, we account for informality as follows. Using the PNAD survey of each year, we compute an "informality expansion factor" for each state, sector, and skill type. We then augment the formal sector data in RAIS using these expansion factors. Further details are provided in Appendix C.3.

With this adjustment, we obtain the following results. Appendix Figure A.12 illustrates the path of the skill premium, average real wages, and the employment shares by sector or geography. Overall, these patterns are very similar to the baseline results in Figure 6. In the case of the skill premium, we see a somewhat larger decline over the full cycle (2002-2018) of 1.4% (reported in Appendix Table A.5) compared to the 1.2% in Table 3. We also find that the evolution of sectoral employment shares and employment shares by macroregion are quite close to those using the baseline dataset.

Beyond the aggregate effects of the boom, Appendix Figure A.13 shows histograms for the change in average real wages across states and sectors for unskilled and skilled workers. For unskilled workers, for example, the average real wage change ranges from -2.1% to 4.9% at the 10th and 90th percentile. This is very close to the -2.0% and 4.8%, and the median is the same in both cases (1.5%). Thus, the informality adjustment does not have much of an impact on the distribution of the gains from the boom across state-sectors.

5 Conclusions

We have documented the uneven effects of a commodity boom on workers based on their skill type and the region where they live. We have done so combining a dynamic, quantitative, multi–region model featuring spatial linkages and downward wage rigidity and rich labor market data in the context of Brazil's commodity boom during the 2000s and the subsequent bust during the 2010s.

Our paper offers several key findings. During the 2000s, the commodity boom reduces the skill premium, accounting for 15% of the decline observed in Brazil during this period. During the bust, the skill premium reverts or maintains its decline depending on the degree of downward wage rigidity. In addition, we find a substantial degree of heterogeneity across space in the gains from the commodity cycle.

Using counterfactuals, we establish that shutting down spatial linkages (i.e., interregional trade and migration) leads to a larger decline in the skill premium. It also results in smaller spatial disparities in the gains from the commodity cycle. We also establish how downward wage rigidity generates unemployment in the bust, and how spatial linkages distribute this unemployment across space. In this regard, we find that shutting down spatial linkages elevates the average unemployment rate among states that face unemployment. More in general, we see that spatial linkages and labor market flexibility interact in shaping the effects of the commodity cycle.

6 References

R. Adão. Worker heterogeneity, wage inequality, and international trade: Theory and evidence from Brazil. *Working Paper*, 2016.

E. Alberola and G. Benigno. Revisiting the commodity curse: A financial perspective. *Journal of International Economics*, 108:S87–S106, 2017.

J. Alvarez, F. Benguria, N. Engbom, and C. Moser. Firms and the decline in earnings inequality in Brazil. *American Economic Journal: Macroeconomics*, 10(1):149–189, 2018.

E. J. Amadeo and J. M. Camargo. Labour legislation and institutional aspects of the Brazilian labour market. *Labour*, 7(1):157–180, 1993.

E. Artuç, S. Chaudhuri, and J. McLaren. Trade shocks and labor adjustment: A structural empirical approach. *American Economic Review*, 100(3):1008–1045, 2010.

F. Benguria, F. Saffie, and S. Urzúa. The transmission of commodity price super-cycles. *The Review of Economic Studies*, 91:1923–1955, 2024.

K. Borusyak, R. Dix-Carneiro, and B. Kovak. Understanding migration responses to local shocks. *Working Paper*, 2022.

L. Caliendo and F. Parro. Estimates of the trade and welfare effects of NAFTA. *The Review of Economic Studies*, 82(1):1–44, 2015.

L. Caliendo, M. Dvorkin, and F. Parro. Trade and labor market dynamics: General equilibrium analysis of the China trade shock. *Econometrica*, 87(3):741–835, 2019.

N. F. Campos, J. B. Nugent, N. Campos, P. Grauwe, and Y. Ji. The dynamics of the regulation of labour in developing and developed countries. *The Political Economy of Structural Reforms in Europe*, 75, 2018.

W. M. Corden and J. P. Neary. Booming sector and de-industrialisation in a small open economy. *The Economic Journal*, 92(368):825–848, 1982.

A. K. Coşar and P. D. Fajgelbaum. Internal geography, international trade, and regional specialization. *American Economic Journal: Microeconomics*, 8(1):24–56, 2016.

R. P. De Barros and C. H. Corseuil. The impact of regulations on brazilian labor market performance. In *Law and employment: Lessons from Latin America and the Caribbean*, pages 273–350. University of Chicago Press, 2004.

R. Dekle, J. Eaton, and S. Kortum. Global rebalancing with gravity: Measuring the burden of adjustment. *IMF Staff Papers*, 55(3):511–540, 2008.

R. Dix-Carneiro and B. K. Kovak. Trade liberalization and regional dynamics. *American Economic Review*, 107(10):2908–2946, 2017.

R. Dix-Carneiro, J. P. Pessoa, R. Reyes-Heroles, and S. Traiberman. Globalization, trade imbalances, and labor market adjustment. *The Quarterly Journal of Economics*, 138(2): 1109–1171, 2023.

T. Drechsel and S. Tenreyro. Commodity booms and busts in emerging economies. *Journal of International Economics*, 112:200–218, 2018.

B. Faber and C. Gaubert. Tourism and economic development: Evidence from mexico's coastline. *American Economic Review*, 109(6):2245–2293, 2019.

P. Fajgelbaum and S. J. Redding. Trade, structural transformation, and development: Evidence from Argentina 1869–1914. *Journal of Political Economy*, 130(5):1249–1318, 2022.

A. Fernández, S. Schmitt-Grohé, and M. Uribe. World shocks, world prices, and business cycles: An empirical investigation. *Journal of International Economics*, 108:S2–S14, 2017.

A. Fernández, A. González, and D. Rodriguez. Sharing a ride on the commodities roller coaster: Common factors in business cycles of emerging economies. *Journal of International Economics*, 111:99–121, 2018.

A. Fernández, S. Schmitt-Grohé, and M. Uribe. How important is the commodity supercycle? In *Credibility of Emerging Markets, Foreign Investors Risk Perceptions, and Capital Flows*. Banco Central de Chile, 2023.

D. Kohn, F. Leibovici, and H. Tretvoll. Trade in commodities and business cycle volatility. *American Economic Journal: Macroeconomics*, 13(3):173–208, 2021.

A. Kurmann and E. McEntarfer. Downward nominal wage rigidity in the united states: New evidence from worker-firm linked data. *Working Paper*, 2019.

J. Messina and A. Sanz-de Galdeano. Wage rigidity and disinflation in emerging countries. *American Economic Journal: Macroeconomics*, 6(1):102–133, 2014.

A. Rodríguez-Clare, M. Ulate, and J. P. Vasquez. Trade with nominal rigidities: Understanding the unemployment and welfare effects of the China shock. *Working Paper*, 2024.

S. Schmitt-Grohé and M. Uribe. Downward nominal wage rigidity, currency pegs, and involuntary unemployment. *Journal of Political Economy*, 124(5):1466–1514, 2016.

M. P. Timmer, E. Dietzenbacher, B. Los, R. Stehrer, and G. J. De Vries. An illustrated user guide to the world input–output database: the case of global automotive production. *Review of International Economics*, 23(3):575–605, 2015.

T. Tombe and X. Zhu. Trade, migration, and productivity: A quantitative analysis of China. *American Economic Review*, 109(5):1843–1872, 2019.

J. R. d. Vasconcelos. Matriz do fluxo de comércio interestadual de bens e serviços no Brasil-1999. 2001.

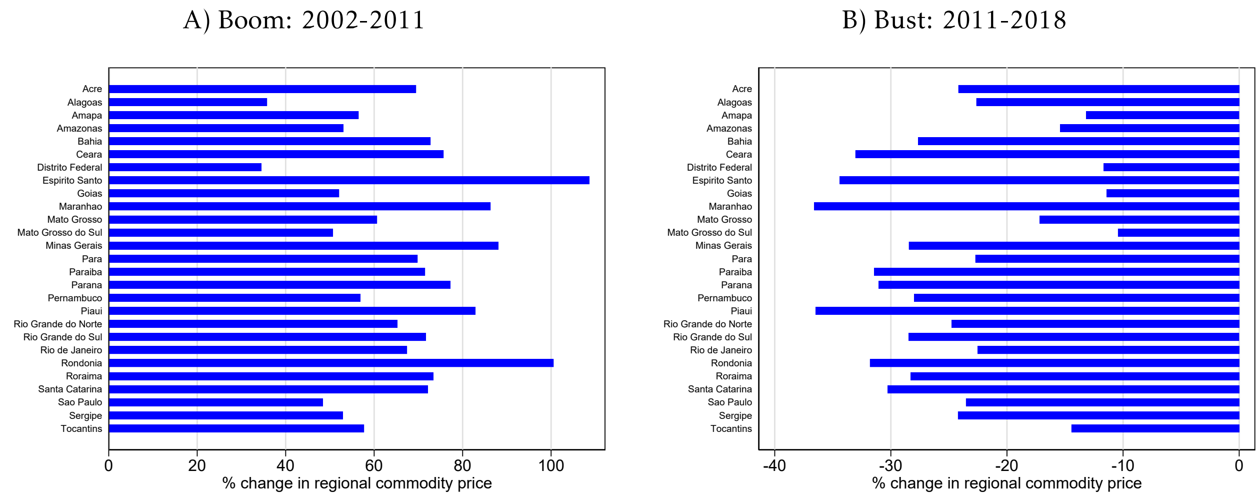
A Appendix to Section 2.1: Data

Table A.1: Descriptive statistics

Macroregion	State	State Code	Emp. Share Commodity	Emp. Share Tradable	Emp. Share Nontradable	Emp. Share Unskilled	Emp. Share Skilled
Central-West	Distrito Federal	DF	1.5	5.6	92.9	87.8	12.2
Central-West	Goiás	GO	12.2	23.7	64.1	94.3	5.7
Central-West	Mato Grosso	MT	18.1	24.2	57.8	94.8	5.2
Central-West	Mato Grosso do Sul	MS	25.0	16.7	58.3	93.5	6.5
North	Acre	AC	6.9	12.5	80.6	94.7	5.3
North	Amapá	AP	0.8	9.9	89.3	92.8	7.2
North	Amazonas	AM	1.8	33.7	64.5	93.5	6.5
North	Pará	PA	6.8	24.7	68.5	94.0	6.0
North	Rondônia	RO	4.6	29.4	66.0	96.8	3.2
North	Roraima	RR	2.7	8.6	88.7	95.9	4.1
North	Tocantins	TO	12.6	11.4	76.0	96.0	4.0
Northeast	Alagoas	AL	12.6	37.9	49.5	96.1	3.9
Northeast	Bahia	BA	9.5	14.9	75.5	94.1	5.9
Northeast	Ceará	CE	3.3	35.6	61.2	94.4	5.6
Northeast	Maranhão	MA	5.2	15.7	79.1	94.9	5.1
Northeast	Paraíba	PB	8.9	29.6	61.5	91.1	8.9
Northeast	Pernambuco	PE	8.6	24.1	67.3	92.2	7.8
Northeast	Piauí	PI	4.1	19.1	76.7	95.4	4.6
Northeast	Rio Grande do Norte	RN	12.4	24.5	63.1	93.1	6.9
Northeast	Sergipe	SE	8.1	20.4	71.5	93.9	6.1
South	Paraná	PR	8.8	30.8	60.3	91.6	8.4
South	Rio Grande do Sul	RS	6.0	39.0	55.1	91.7	8.3
South	Santa Catarina	SC	5.1	44.1	50.8	93.6	6.4
Southeast	Espírito Santo	ES	11.7	21.7	66.6	94.2	5.8
Southeast	Minas Gerais	MG	11.7	22.9	65.4	90.6	9.4
Southeast	Rio de Janeiro	RJ	2.0	16.2	81.9	89.0	11.0
Southeast	São Paulo	SP	5.9	30.7	63.4	88.4	11.6

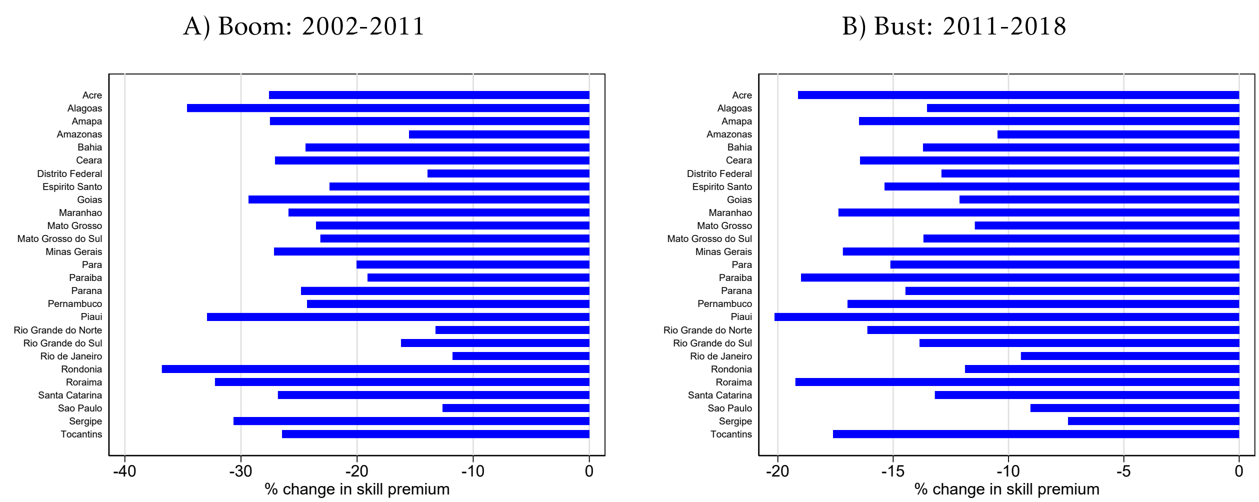
Notes: This table shows employment shares by sector and by skill share in each state in year 2000.

Figure A.1: Commodity price cycle across states



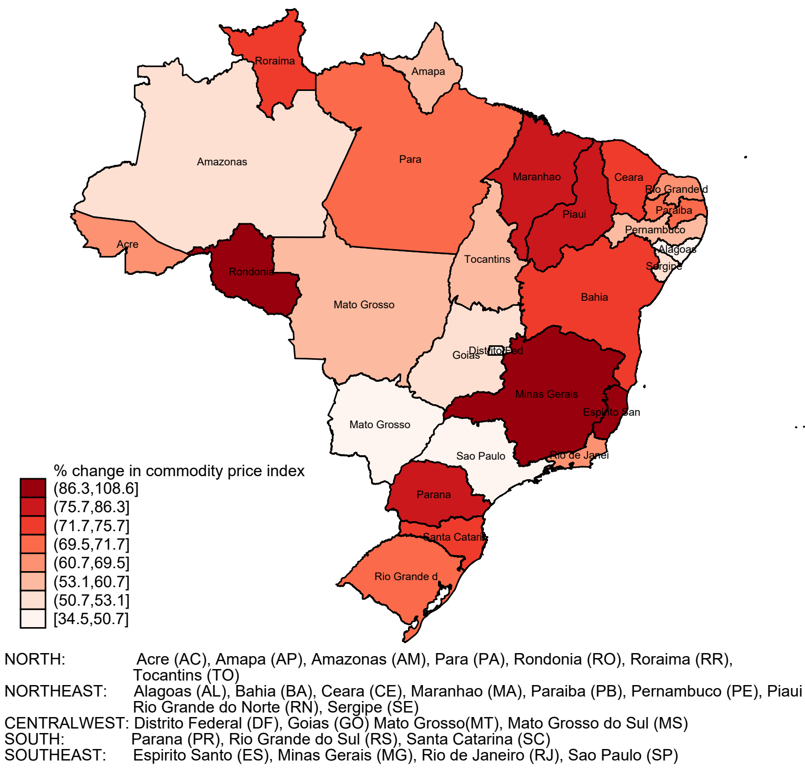
Notes: This figure plots the percent change in the state–level commodity price index between 2002 and 2011 (panel A) and 2011-2018 (panel B).

Figure A.2: Change in skill premium across states



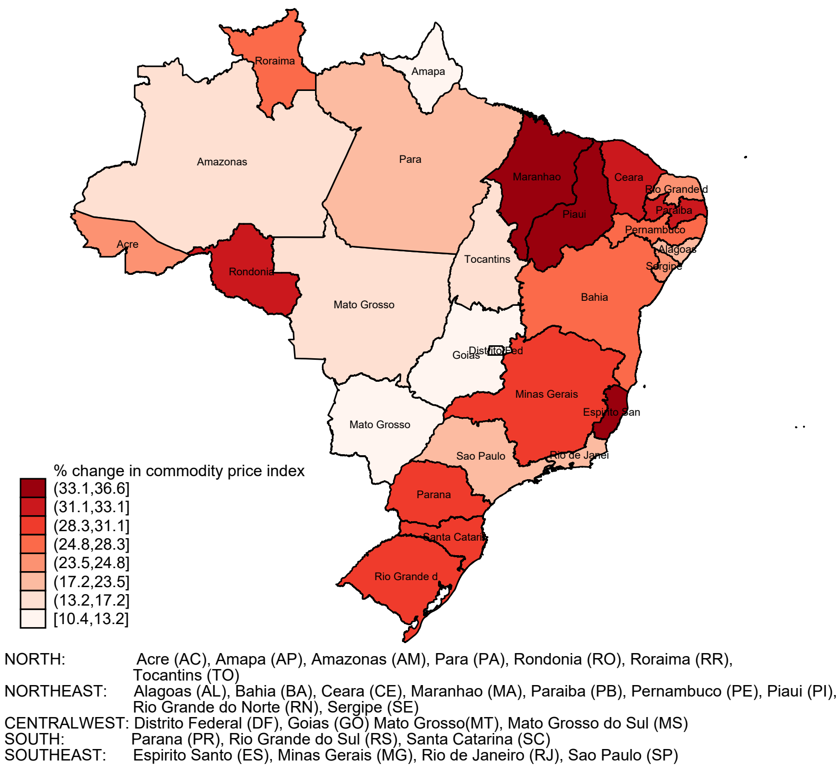
Notes: This figure plots the percent change in the skill premium between 2002 and 2011 (panel A) and 2011-2018 (panel B).

Figure A.3: Commodity boom across states



Notes: This figure shows the percent change in the state–level commodity price index between 2002 and 2011. Darker shades indicate a larger increase in the commodity price index.

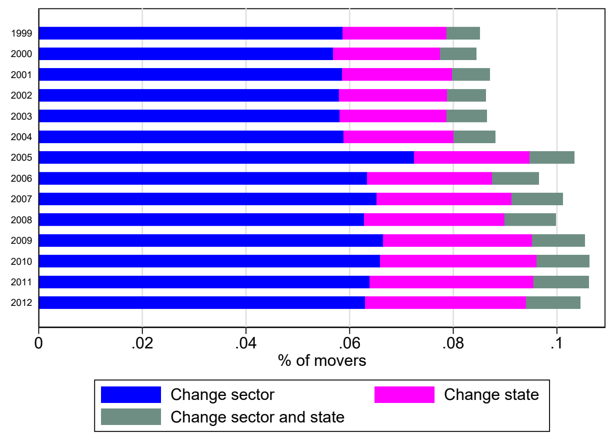
Figure A.4: Commodity bust across states



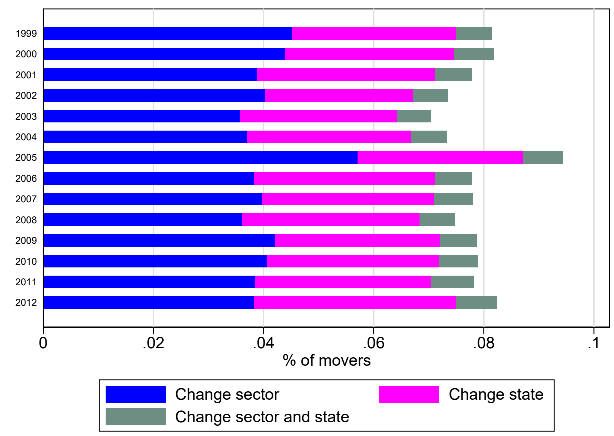
Notes: This figure shows the percent change in the state–level commodity price index between 2011 and 2018. Darker shades indicate a larger decline in the commodity price index.

Figure A.5: Share of movers across sectors and/or states by skill

A) Share of movers across sectors and/or states: Unskilled

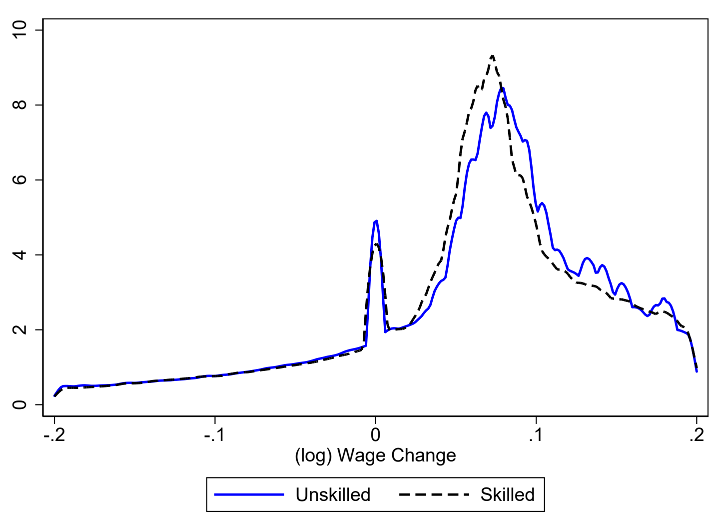


B) Share of movers across sectors and/or states: Skilled



Notes: Each panel plots the share of workers who move across sectors (but not across states), across states (but not across sectors), or across both sectors and states between consecutive years. Panel A considers unskilled workers. Panel B considers skilled workers.

Figure A.6: Downward wage rigidity: Distribution of wage changes by skill



Notes: This figure plots a kernel density of the distribution of all nominal year-to-year wage changes pooled over 1999-2013.

B Appendix to Section 3: Model

Denote $\Gamma_t = \left\{\overline{L}_t^u, \overline{L}_t^s, A_t^j, \phi_t^{j,u}, D_{i,t}^{j,p}, B_{i,t}, \tau_{in,t}, \tau_{i,F,t}, P_t^I, \Psi_{F,t}, R_{i,t}\right\}$ as the collection of exogenous fundamentals in the economy at period t, $\pi_{-1} = \left\{\pi_{in,-1}^{jk,p}\right\}$ as the initial migration pattern, and $Z_t = \left\{Z_{i,t}^M\right\}$ as the commodity price shocks at period t.

B.0.1 Within–period equilibrium

For each period t, given exogenous fundamentals Γ_t, migration patterns in period $t-1$, π_{t-1}, labor supply in each region $L_{i,t}$, nominal wage from the last period $w_{i,t-1}^{j,p}$, and commodity prices Z_t, the *within–period equilibrium* is characterized by a set of allocations and prices $\Theta_t = \left\{C_{i,t}, M_{i,t}, T_{i,t}, N_{i,t}, l_{i,t}^{j,p}, R_{iF}^T, w_{i,t}^{j,p}, P_{i,t}, r_{i,t}\right\}$ that satisfy goods and labor market clearing conditions.

Since all production and trade decisions are made within one period, we omit the time subscript for the rest of the equilibrium conditions. The sector–specific cost function for each effective labor unit and sectoral production in region i can be expressed as:

$$
\begin{aligned}
c_i^j &= \left(\left(\phi^{j,u}\right)^\eta \left(w_i^{j,u}\right)^{1-\eta} + \left(w_i^{j,s}\right)^{1-\eta}\right)^{\frac{1}{1-\eta}} \\
p_i^M &= A_i^M Z_i^M \tau_{iF}^M = \frac{1}{\left(\beta^M\right)^{\beta^M}\left(1-\beta^M\right)^{1-\beta^M}} \left(\left(\frac{r_i}{\alpha}\right)^\alpha \left(\frac{c_i^M}{1-\alpha}\right)^{1-\alpha}\right)^{\beta^M} P_i^{1-\beta^M} && \text{(A.1)} \\
p_i^j &= \frac{1}{\left(\beta^j\right)^{\beta^j}\left(1-\beta^j\right)^{1-\beta^j}} \left(c_i^j\right)^{\beta^j} P_i^{1-\beta^j} \text{ for } j = T, N && \text{(A.2)}
\end{aligned}
$$

In this expression, c_i^j is the unit cost of effective labor supply and p_i^j is the unit cost of production.

In the commodity sector, since the unit price is exogenously given, the rental rate for the natural resource would bid up to take over all the remaining profit and ensure the marginal costs equal the market prices:

$$
\begin{aligned}
L_i^M &= \left(\frac{(1-\alpha)\tau_{iF}^M Z_i^M A_i^M}{c_i^M}\right)^{\frac{1}{\alpha}} R_i \\
r_i R_i &= \frac{\alpha}{1-\alpha} c_i^M L_i^M && \text{(A.3)}
\end{aligned}
$$

On the demand side, consumers in region i will demand the same expenditure share of each commodity based on all the exogenous prices:

$$\frac{X_{in}^{M}}{X_{n}^{M}}=\frac{Z_{i}^{M}C_{in}^{M}}{I_{n}^{M}}=\lambda_{in}^{M}\equiv\lambda_{i}^{M}=\frac{\left(Z_{i}^{M}\right)^{1-\gamma_{M}}}{\sum_{k}\left(Z_{k}^{M}\right)^{1-\gamma_{M}}},\forall n \tag{A.4}$$

and $I_n^M=\sum_i Z_i^M C_{in}^M$ is the share of region n's expenditure spent on commodity goods.

The equilibrium in the tradable sector is similar to an Armington framework. Given the producer's profit maximization behavior and perfectly competitive market structure, the relation between producer prices and marginal costs is

$$P_{ii}^{T}=\frac{p_{i}^{T}}{A_{i}^{T}}, \tag{A.5}$$

and the expenditure share for tradable goods in region n can be expressed as

$$\frac{X_{in}^{T}}{X_{n}^{T}}=\frac{P_{in}^{T}C_{in}^{T}}{I_{n}^{T}}=\lambda_{in}^{T}=\frac{\left(A_{i}^{T}\right)^{\gamma_{T}-1}\left(p_{i}^{T}\tau_{in}\right)^{1-\gamma_{T}}}{\sum_{k}\left(A_{k}^{T}\right)^{\gamma_{T}-1}\left(p_{k}^{T}\tau_{kn}\right)^{1-\gamma_{T}}}, \tag{A.6}$$

where $I_n^T=\sum_i P_{in}^T C_{in}^T$.

In addition, the tradable sector can also export its goods to the foreign market, obtaining revenue

$$REV_{iF}^{T}=\left(P_{iF}^{T}\right)^{1-\gamma^{T}}\Psi_{F}=\left(\frac{p_{i}^{T}\tau_{iF}}{A_{i}^{T}}\right)^{1-\gamma^{T}}\Psi_{F}$$

The equilibrium in nontradable sector is such that prices of the nontradable goods in each region can be simply expressed as

$$P_{i}^{N}=\frac{p_{i}^{N}}{A_{i}^{N}} \tag{A.7}$$

and the consumed quantity is:

$$C_{i}^{N}=N_{i}$$

Finally, given the exogenous price P^I of imported goods, the aggregate price index in region i can be expressed as

$$P_{i}=\left[\left(\phi^{M}\right)^{\xi}\left(P^{M}\right)^{1-\xi}+\left(\phi^{G}\right)^{\xi}\left(P_{i}^{G}\right)^{1-\xi}\right]^{\frac{1}{1-\xi}}, \tag{A.8}$$

, where:

$$P^M = \left(\sum_n \left(Z_n^M\right)^{1-\gamma_M}\right)^{\frac{1}{1-\gamma_M}} \tag{A.9}$$

$$P_i^G = \left(\left(\phi^X\right)^{\gamma_G}\left(P_i^X\right)^{1-\gamma_G} + \left(\phi^N\right)^{\gamma_G}\left(P_i^N\right)^{1-\gamma_G}\right)^{\frac{1}{1-\gamma_G}} \tag{A.10}$$

$$P_i^X = \left(\left(\phi^T\right)^{\gamma_X}\left(P_i^T\right)^{1-\gamma_X} + \left(\phi^I\right)^{\gamma_X}\left(P_i^I\right)^{1-\gamma_X}\right)^{\frac{1}{1-\gamma_X}} \tag{A.11}$$

$$P_i^T = \left(\sum_n \left(P_{ni}^T\right)^{1-\gamma_T}\right)^{\frac{1}{1-\gamma_T}} = \left(\sum_n \left(\tau_{ni}\frac{p_n^T}{A_n^T}\right)^{1-\gamma_T}\right)^{\frac{1}{1-\gamma_T}} \tag{A.12}$$

and the revenues and expenditures in each sector are:

$$REV_i^M = P_i^M Q_i^M = \frac{1}{\alpha\beta^M} r_i R_i \tag{A.13}$$

$$REV_i^T = \sum_n \lambda_{in}^T \xi_n^T \left(I_n + \sum_j \left(1-\beta_n^j\right) REV_n^j\right) + REV_{iF}^T \tag{A.14}$$

$$REV_i^N = \xi_i^N \left(I_i + \sum_j \left(1-\beta^j\right) REV_i^j\right) \tag{A.15}$$

$$I_i^I = \xi_i^I I_i \tag{A.16}$$

In this expression,

$$\xi_i^M = \left(\phi^M\right)^{\xi}\left(\frac{P^M}{P_i}\right)^{1-\xi}$$

$$\xi_i^T = \left(\phi^T\right)^{\gamma_X}\left(\phi^X\right)^{\gamma_G}\left(\phi^G\right)^{\xi}\left(P_i^T\right)^{1-\gamma_X}\left(P_i^X\right)^{\gamma_X-\gamma_G}\left(P_i^G\right)^{\gamma_G-\xi}\left(P_i\right)^{\xi-1}$$

$$\xi_i^N = \left(\phi^N\right)^{\gamma_G}\left(\phi^G\right)^{\xi}\left(P_i^N\right)^{1-\gamma_G}\left(P_i^G\right)^{\gamma_G-\xi}\left(P_i\right)^{\xi-1}$$

$$\xi_i^I = \left(\phi^I\right)^{\gamma_X}\left(\phi^X\right)^{\gamma_G}\left(\phi^G\right)^{\xi}\left(P^I\right)^{1-\gamma_X}\left(P_i^X\right)^{\gamma_X-\gamma_G}\left(P_i^G\right)^{\gamma_G-\xi}\left(P_i\right)^{\xi-1}$$

The total expenditure is equal to total income plus profits and borrowing from abroad:

$$I_i = \sum_{j,p} w_i^{j,p} l_i^{j,p} + \sum_n r_n R_n \frac{L_i}{\sum_n L_n} + B_i \tag{A.17}$$

On the other hand, the labor demand for each type of worker in each sector is

$$l_i^{M,u} = \frac{\beta^M(1-\alpha)}{c_i^M}\left(\frac{\phi_i^{M,u}c_i^M}{w_i^{M,u}}\right)^\eta REV_i^M \quad , \quad l_i^{M,s} = \frac{\beta^M(1-\alpha)}{c_i^M}\left(\frac{c_i^M}{w_i^{M,s}}\right)^\eta REV_i^M \tag{A.18}$$

$$l_i^{T,u} = \frac{\beta^T}{c_i^T}\left(\frac{\phi_i^{T,u}c_i^T}{w_i^{T,u}}\right)^\eta REV_i^T \quad , \quad l_i^{T,s} = \frac{\beta^T}{c_i^T}\left(\frac{c_i^T}{w_i^{T,s}}\right)^\eta REV_i^T \tag{A.19}$$

$$l_i^{N,u} = \frac{\beta^N}{c_i^N}\left(\frac{\phi_i^{T,u}c_i^N}{w_i^{N,u}}\right)^\eta REV_i^N \quad , \quad l_i^{N,s} = \frac{\beta^N}{c_i^N}\left(\frac{c_i^N}{w_i^{N,s}}\right)^\eta REV_i^N, \tag{A.20}$$

and the labor market clearing condition with downward wage rigidity implies

$$\left(1-u_i^{j,u}\right)L_i^{j,u} = l_i^{j,u}, \left(1-u_i^{j,u}\right)L_i^{j,s} = l_i^{j,s}, \forall j, i \tag{A.21}$$

where the unemployment rate $u_i^{j,p}$ is defined according to (18). Since there is a foreign market, the total revenue of all 3 sectors in each region may not be equal to the corresponding total income and expenditure.

B.0.2 Sequential equilibrium

The *sequential equilibrium* of the economy is characterized by a set of dynamic paths $\Upsilon = \{L_t, \pi_t, V_t\}_{t=0}^{\infty}$ that satisfies: (i) Given $\{\Gamma_t, \Theta_t\}_{t=0}^{\infty}$, the evolution of $L_{i,t}^{j,p}$, $\pi_{in,t}^{jk,p}$ and $V_{i,t}^{j,p}$ is governed by conditions (21) – (25); and (ii) Given L_t, Γ_t and Z_t, Θ_t is the *within–period* equilibrium at period t.

C Appendix to Section 4: Quantitative analysis

C.1 Solution Algorithm

C.1.1 Dynamic Hat-Algebra Representation

For any variable x, define its *hat* as $\hat{x}_t \equiv x_t/x_{t-1}$. The algorithm solves for all hats relative to the previous period. The following system of equations characterizes the model equilibrium in the *dynamic hat algebra* format.

First, changes in $I_{i,t}^{j,p}$ can be expressed as changes in its components:

$$\hat{I}_{i,t+1}^{j,p} = \frac{w_{i,t}^{j,p}}{I_{i,t}^{j,p}}\hat{w}_{i,t+1}^{j,p} + \frac{rR_{i,t}}{I_{i,t}^{j,p}}\hat{rR}_{i,t+1} + \frac{B_{i,t}}{I_{i,t}^{j,p}L_{i,t}\hat{L}_{i,t+1}}\hat{B}_{i,t+1} \tag{A.22}$$

where $rR_{i,t} = \frac{\sum_n r_{n,t}R_{n,t}}{\sum_n L_{n,t}}$ is the lump sum payment each worker received from the nationwide natural resource company at period t.

In the commodity sector, changes in sourcing probability are only based on the relative changes in commodity prices:

$$\hat{\lambda}_{in,t+1}^{M} = \hat{\lambda}_{i,t+1}^{M} = \frac{\left(\hat{Z}_{i,t+1}^{M}\right)^{1-\gamma_M}}{\sum_k \lambda_{k,t}^{M}\left(\hat{Z}_{k,t+1}^{M}\right)^{1-\gamma_M}}, \forall n \tag{A.23}$$

In the tradable sector, these changes mainly depend on the changes in unit costs (if there are no changes in trade costs):

$$\hat{\lambda}_{in,t+1}^{T} = \frac{\left(\hat{p}_{i,t+1}^{T}\right)^{1-\gamma_T}}{\sum_k \lambda_{kn,t}^{T}\left(\hat{p}_{k,t+1}^{T}\right)^{1-\gamma_T}} \tag{A.24}$$

where

$$\hat{c}_{i,t+1}^{j} = \left(\omega_{i,t}^{j,u}\left(\hat{w}_{i,t+1}^{j,u}\right)^{1-\eta} + (1-\omega_{i,t}^{j,s})\left(\hat{w}_{i,t+1}^{j,s}\right)^{1-\eta}\right)^{\frac{1}{1-\eta}} \tag{A.25}$$

$$\hat{Z}_{i,t+1}^{M} = \hat{r}_{i,t+1}^{\alpha\beta^M}\left(\hat{c}_{i,t+1}^{M}\right)^{(1-\alpha)\beta^M}\hat{P}_{i,t+1}^{1-\beta^M} \tag{A.26}$$

$$\hat{p}_{i,t+1}^{j} = \left(\hat{c}_{i}^{M}\right)^{\beta^M}\hat{P}_{i}^{1-\beta^M} \text{ for } j = T, N \tag{A.27}$$

and $\omega_{i,t}^{j,u}$ is the share of wage bill towards unskilled workers in region i and sector j in period t.

Other changes in price indices and revenues can be expressed as a function of changes in unit costs:

$$\hat{P}^{M}_{i,t+1} = \left(\sum_{n} \lambda^{M}_{n,t}\left(\hat{Z}^{M}_{n,t+1}\right)^{1-\gamma_M}\right)^{\frac{1}{1-\gamma_M}} \tag{A.28}$$

$$\hat{r}_{i,t+1} = \left(\frac{\hat{Z}^{M}_{i,t+1}}{\left(\hat{c}^{M}_{i,t+1}\right)^{(1-\alpha)\beta^M}\hat{P}^{1-\beta^M}_{i,t+1}}\right)^{\frac{1}{\alpha\beta^M}} \tag{A.29}$$

$$\hat{P}^{T}_{n,t+1} = \left(\sum_{k} \lambda^{T}_{kn,t}\left(\hat{p}^{T}_{k,t+1}\right)^{1-\gamma_T}\right)^{\frac{1}{1-\gamma_T}} \tag{A.30}$$

$$\hat{P}^{N}_{n,t+1} = \hat{p}^{N}_{n,t+1} \tag{A.31}$$

$$\hat{P}^{X}_{n,t+1} = \left(S^{TX}_{n,t}\left(\hat{P}^{T}_{n,t+1}\right)^{1-\gamma_X} + \left(1-S^{TX}_{n,t}\right)\left(\hat{P}^{I}_{i,t+1}\right)^{1-\gamma_X}\right)^{\frac{1}{1-\gamma_X}} \tag{A.32}$$

$$\hat{P}^{G}_{n,t+1} = \left(S^{XG}_{n,t}\left(\hat{P}^{X}_{n,t+1}\right)^{1-\gamma_G} + \left(1-S^{XG}_{n,t}\right)\left(\hat{P}^{N}_{n,t+1}\right)^{1-\gamma_G}\right)^{\frac{1}{1-\gamma_G}} \tag{A.33}$$

$$\hat{P}_{n,t+1} = \left[S^{M}_{n,t}\left(\hat{P}^{M}_{n,t+1}\right)^{1-\xi} + \left(1-S^{M}_{n,t}\right)\left(\hat{P}^{G}_{n,t+1}\right)^{1-\xi}\right]^{\frac{1}{1-\xi}} \tag{A.34}$$

where $S^{x}_{n,t}$ is the expenditure share of type-x good in its corresponding aggregation bundle (i.e., $S^{TX}_{n,t}$ is the share of domestic tradable goods in the bundle of all tradable goods.)

Finally, changes in labor demand can be expressed as

$$\hat{l}^{j,p}_{i,t+1} = \frac{1}{\hat{c}^{j}_{i,t+1}}\left(\frac{\hat{c}^{j}_{i,t+1}}{\hat{w}^{j,p}_{i,t+1}}\right)^{\eta} R\hat{E}V^{j}_{i,t+1} \quad \text{for} \quad j = M, T, N \tag{A.35}$$

while evolution in labor supply is characterized by condition (25). As a consequence, the changes in expected wages are characterized by:

$$\widehat{\bar{w}}^{j,p}_{i,t+1} = \frac{\hat{l}^{j,p}_{i,t+1}}{\hat{L}^{j,p}_{i,t+1}}\hat{w}^{j,p}_{i,t+1}$$

and changes in real consumption can be expressed as

$$\hat{\widetilde{C}}^{j,p}_{i,t+1}\widetilde{C}^{j,p}_{i,t+1} = \frac{\widehat{\bar{w}}^{j,p}_{i,t+1}\bar{w}^{j,p}_{i,t+1} + \hat{\Omega}_{t+1}\Omega_{t+1}}{\hat{P}_{i,t+1}P_{i,t+1}}. \tag{A.36}$$

The system above can determine the equilibrium wage changes $\hat{w}^{j,p}_{n,t+1}$ as well as the state of the economy in any period $t+1$ given exogenous commodity price shocks $\hat{Z}^{M}_{i,t+1}$ and the state of the economy in the previous period t.

C.1.2 Computational Algorithm: Two-Loop Approach

This section briefly discuss how the dynamic transition path of our model is solved numerically. We adopt a two-loop approach. The inner loop solves for the within-period equilibrium with downward wage rigidity. The outer loop solves the sequential equilibrium for workers' migration decisions.

Outer loop: Sequential Equilibrium

1. Make an initial guess of $Y_{i,t+1}^{j,p}$ for $t = 0, 1, ..., H$, where H is sufficiently large to ensure the system reaches a steady state.

2. Update migration probabilities $\pi_{ni,t}^{j,p}$ and new labor supplies $L_{i,t+1}^{S,j,p}$ with conditions (22) and (25).

3. Solve the inner loop for within-period equilibrium period-by-period **forward** from $t = 0$ and get the equilibrium change in real consumption $\hat{\tilde{C}}_{i,t+1}^{j,p}$.

4. Update the guess of $Y_{i,t+1}^{j,p}$ **backward** from period $t = H$ using conditions (23) and (24).

5. Iterate the above steps until the values of $Y_{i,t+1}^{j,p}$ converge.

Inner loop: Within-period Equilibrium

1. Make initial guesses for $\hat{w}_i^{j,p}$ and $\hat{P}_i$.

2. Compute the hat-algebra equilibrium according to conditions (A.22)–(A.36) for changes in unit costs, prices, sourcing patterns, revenues, and labor supply and demand.

3. Compare relative changes in labor supply and demand, and determine whether the downward wage rigidity constraint binds.[16] If the constraint binds, update $\hat{w}_i^{j,p} = \chi$; otherwise, update $\hat{w}_i^{j,p}$ according to the excess labor demand.

4. Iterate the above steps until the values of $\hat{w}_i^{j,p}$ and $\hat{P}_i$ converge.

5. Calculate the implied real consumption change $\hat{\tilde{C}}_{i,t+1}^{j,p}$ according to condition (A.36).

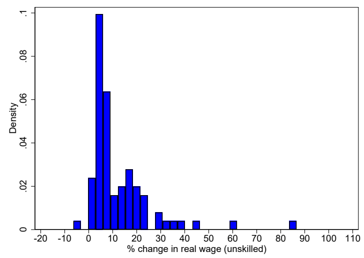
Uniqueness and stability. Monotone labor demand and CES preferences ensure a unique fixed point. Numerical stability is guaranteed by (i) damping in both loops and (ii) removing wage-floor-bound markets from the wage-clearing residual until the floor releases.

[16]When coonsidering this condition, remember it is possible that the previous period has unemployment and should be accounted for accordingly.

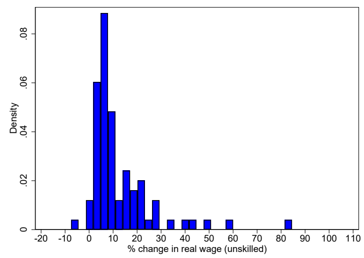
C.2 Additional results

Figure A.7: Histogram of changes in average real wages by state and sector

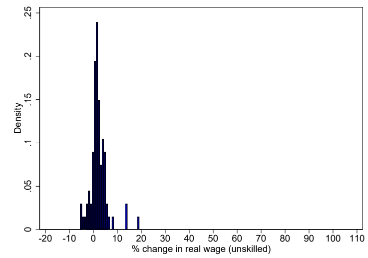
A) Unskilled workers; Boom (2002-2011)



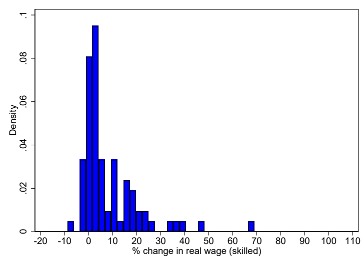
B) Unskilled workers; Bust (2011-2018)



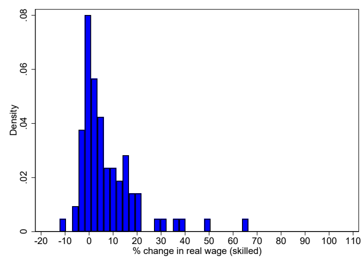
C) Unskilled workers; Full Cycle (2002-2018)



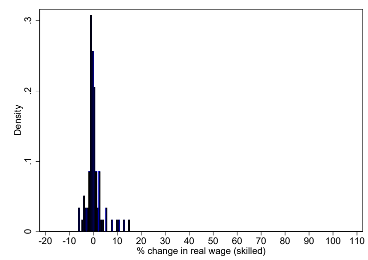
D) Skilled workers; Boom (2002-2011)



E) Skilled workers; Bust (2011-2018)



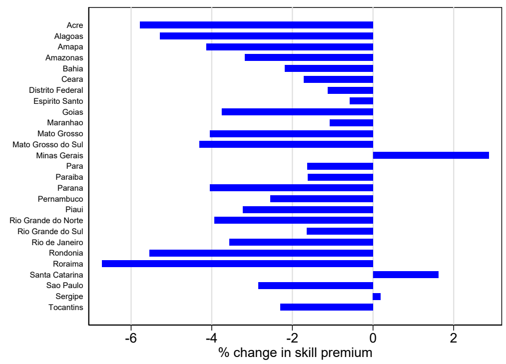
F) Skilled workers; Full Cycle (2002-2018)



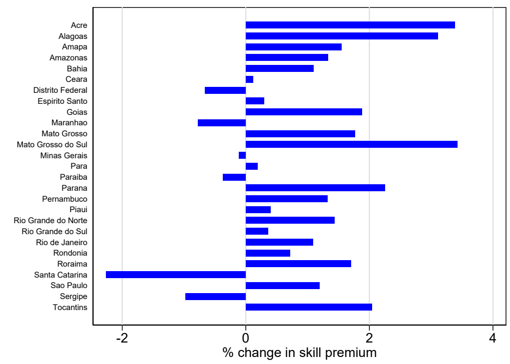
Notes: This figure shows histograms of the distribution of changes in the average real wage of unskilled workers (panels A, B, C) and skilled workers (panels D, E, F) by state and sector between 2002-2011 (panels A and D), 2011-2018 (panels B and E) and 2002-2018 (panels C and F) . Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

Figure A.8: Changes in state-level skill premium in response to the commodity cycle

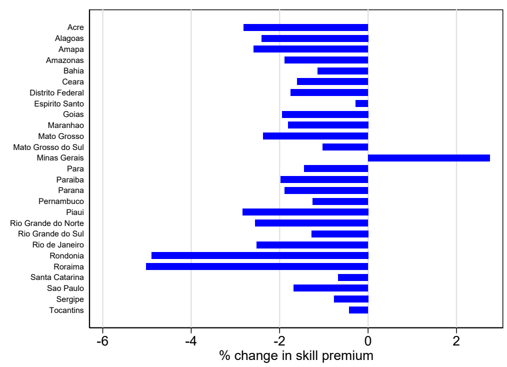
A) Skill premium; Boom



B) Skill premium; Bust

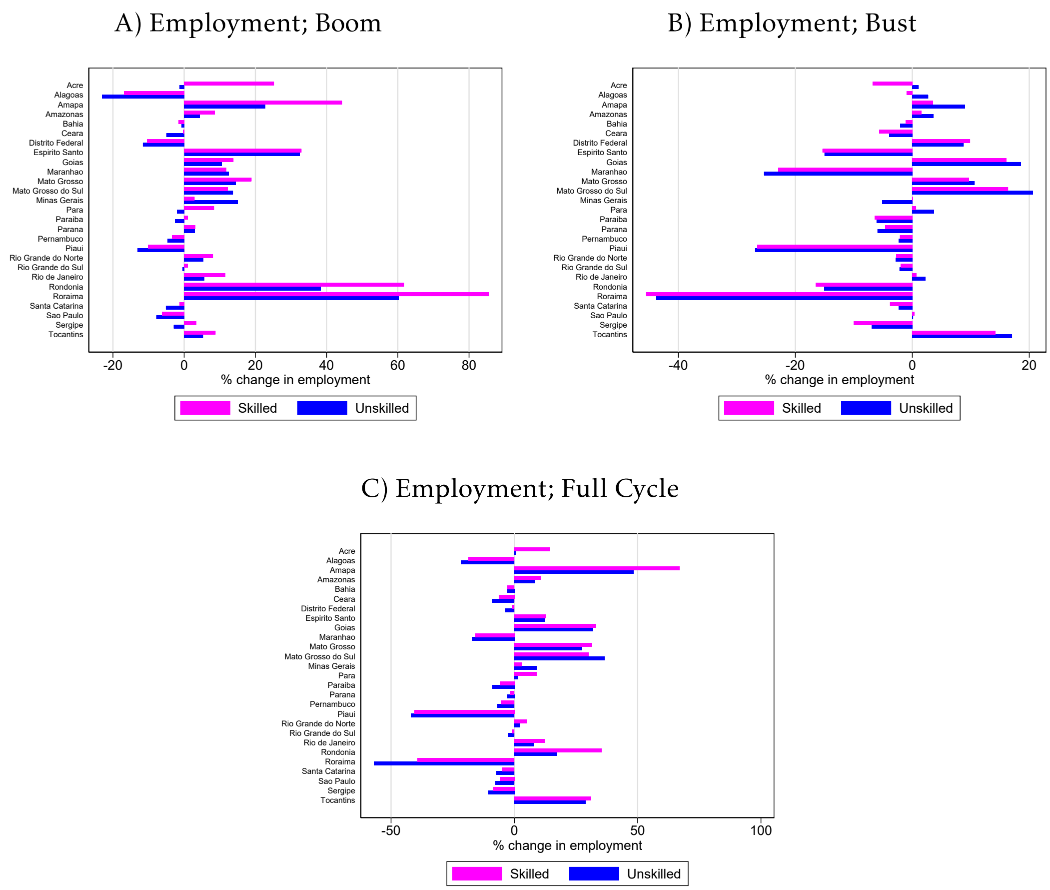


C) Skill premium; Full Cycle



Notes: This figure shows the percent change in the skill premium by state during the boom (2002-2011, panel A), bust (2011-2018, panel B) and full-cycle (2002-2018, panel C).

Figure A.9: Changes in state-level employment in response to the commodity cycle



Notes: This figure shows the percent change in the employment of skilled and unskilled workers by state during the boom (2002-2011, panel A), bust (2011-2018, panel B) and full-cycle (2002-2018, panel C).

Table A.2: Impact of the commodity cycle on the skill premium and real wages: Counterfactuals

	Boom 2002-2011	Bust 2011-2018	Full Cycle 2002-2018
PANEL A: REAL WAGE OF UNSKILLED WORKERS			
DWR	3.1%	-1.8%	1.2%
DWR + No interregional migration	3.3%	-2.3%	0.9%
DWR + No interregional trade	2.1%	-1.2%	0.9%
DWR + No spatial linkages	2.1%	-1.8%	0.2%
Flexible	3.7%	-2.5%	1.1%
PANEL B: REAL WAGE OF SKILLED WORKERS			
DWR	1.4%	-0.9%	0.4%
DWR + No interregional migration	1.9%	-1.6%	0.3%
DWR + No interregional trade	0.4%	-0.2%	0.2%
DWR + No spatial linkages	0.6%	-1.0%	-0.4%
Flexible	1.7%	-1.1%	0.6%

Notes: The rows in panels A and B show the percent change in the real wage of unskilled and skilled workers in the baseline case (including downward wage rigidity (DWR) and spatial linkages), and in the counterfactual cases with i) DWR but no interregional migration, ii) DWR but no interregional trade, iii) DWR but no spatial linkages at all (no interregional migration and no interregional trade) and iv) no DWR (flexible wages). The columns in each panel correspond to outcomes computed over 2002-2011, 2011-2018 and 2002-2018.

Table A.3: Spatial inequality in response to the commodity cycle: Skilled workers

	p25	p50	p75	p75-p25
PANEL A: BOOM (2002-2011)				
DWR	3.7%	6.0%	10.0%	6.3%
DWR + No interregional migration	3.1%	5.5%	8.0%	4.9%
DWR + No interregional trade	2.5%	3.7%	5.5%	3.1%
DWR + No spatial linkages	1.8%	3.0%	4.6%	2.8%
Flexible	3.5%	5.7%	8.6%	5.1%
PANEL B: BUST (2011-2018)				
DWR	-5.6%	-3.3%	-1.6%	4.0%
DWR + No interregional migration	-6.4%	-3.6%	-1.1%	5.3%
DWR + No interregional trade	-3.7%	-2.3%	-0.6%	3.1%
DWR + No spatial linkages	-5.3%	-2.4%	-0.7%	4.6%
Flexible	-4.7%	-2.9%	-1.5%	3.2%
PANEL B: FULL CYCLE (2002-2018)				
DWR	-1.5%	-0.6%	1.0%	2.5%
DWR + No interregional migration	-0.9%	0.1%	1.9%	2.7%
DWR + No interregional trade	-2.0%	-1.1%	0.5%	2.5%
DWR + No spatial linkages	-1.8%	-0.1%	1.5%	3.3%
Flexible	-0.5%	-0.0%	1.5%	2.0%

Notes: This table shows percentiles of the distribution across states of the percent change in the average real wage of skilled workers as a result of the commodity cycle. Panel A corresponds to the boom (2002-2011), panel B corresponds to the bust (2011-2018), and panel C corresponds to the full cycle (2002-2018). The rows in each panel correspond to the baseline economy (with DWR and including spatial linkages), and to the counterfactual economies i) with DWR and without interregional migration, ii) with DWR and without interregional trade, iii) with DWR and without spatial linkages at all (no interregional migration and no interregional trade), and iv) with flexible labor markets. The first three columns correspond to the 25th, 50th and 75th percentiles of the distribution across states. The fourth column corresponds to the difference between the 25th and 75th percentiles, and is a measure of spatial inequality. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

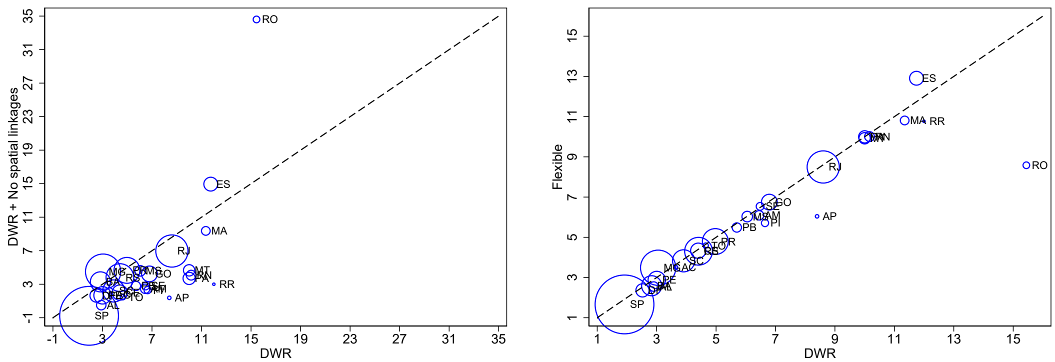
Table A.4: Impact of the commodity boom on the skill premium and average real wages

	All	Commodity	Tradable	Nontradable
Panel A: DWR parameter of 0.95 (baseline)				
Skill premium	-1.2%	-1.0%	-2.7%	-2.3%
Average real wage of unskilled workers	0.7%	2.1%	1.9%	2.9%
Average real wage of skilled workers	0.3%	1.7%	-0.4%	1.0%
Panel B: DWR parameter of 0.93 (less rigidity)				
Skill premium	-0.8%	0.0%	-2.7%	-2.4%
Average real wage of unskilled workers	0.9%	4.4%	2.1%	3.0%
Average real wage of skilled workers	0.4%	2.9%	-0.3%	1.0%
Panel C: DWR parameter of 0.97 (more rigidity)				
Skill premium	-2.9%	-1.4%	-5.4%	-2.8%
Average real wage of unskilled workers	-6.8%	-11.6%	-4.1%	-5.1%
Average real wage of skilled workers	-4.1%	-8.3%	-4.2%	-3.5%

Notes: This table shows the percent change in the skill premium, the average real wage of unskilled workers, and the average real wage of skilled workers. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). The columns correspond to outcomes in the aggregate economy (in the first column) or by sector (next three columns). Each cell is computed as the percent change in the corresponding outcome between 2002–2018. Panel A corresponds to the baseline economy (which has a DWR parameter $\chi = 0.95$). Panels B and C correspond to counterfactual economies with DWR parameters of $\chi = 0.93$ (less DWR) and $\chi = 0.97$ (more DWR) respectively.

Figure A.10: State-level changes in the average real wage of unskilled workers during the boom (2002-2011): Counterfactuals

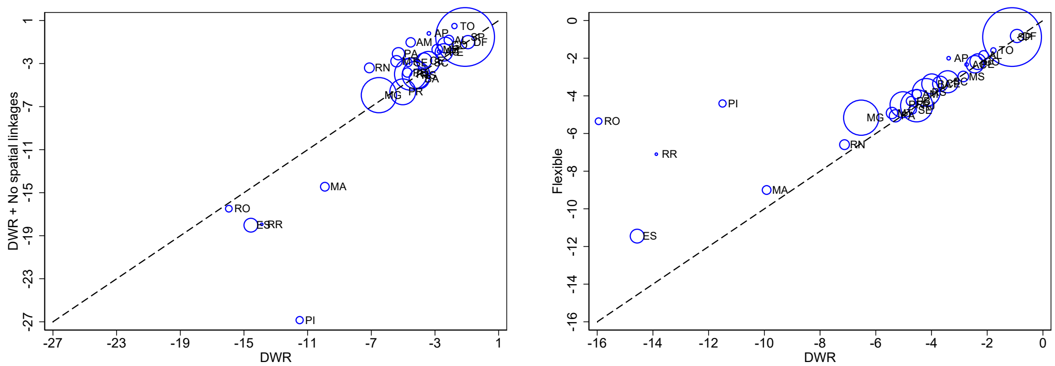
A) DWR vs. DWR without spatial linkages B) DWR vs. Flexible



Notes: Panel A shows a scatterplot with the the percent change in the average real wage of unskilled workers by state between 2002 and 2011 in both axis. The horizontal axis corresponds to the baseline economy (with DWR and spatial linkages) and the vertical axis corresponds to the counterfactual economy with DWR and no spatial linkages. In panel B the outcome is the same but with the horizontal axis corresponding to the baseline economy (with DWR and spatial linkages) and the vertical axis corresponding to the counterfactual economy with flexible labor markets (as well as spatial linkages). Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

Figure A.11: State-level changes in the average real wage of unskilled workers during the bust (2011-2018): Counterfactuals

A) DWR vs. DWR without spatial linkages B) DWR vs. Flexible



Notes: Panel A shows a scatterplot with the the percent change in the average real wage of unskilled workers by state between 2011 and 2018 in both axis. The horizontal axis corresponds to the baseline economy (with DWR and spatial linkages) and the vertical axis corresponds to the counterfactual economy with DWR and no spatial linkages. In panel B the outcome is the same but with the horizontal axis corresponding to the baseline economy (with DWR and spatial linkages) and the vertical axis corresponding to the counterfactual economy with flexible labor markets (as well as spatial linkages). Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

C.3 Informality

C.3.1 Informality: Data construction

As described in Section 4.4, we compute an informality expansion factor using Brazil's annual household survey, PNAD (Pesquisa Nacional por Amostra de Domicílios) and use it to expand the labor market outcomes in RAIS. A large change was implemented after 2015, making the survey hard to compare over time beyond this point, so we use data for 1999-2015.[17]

For each state i, sector j, skill type p and year t, we define the formality share as the ratio of formal employment (F_{ijpt}^{DC}) over formal plus informal employment ($F_{ijpt}^{DC} + I_{ijpt}^{DC}$), where the superscript $PNAD$ stands for data computed using the household survey:

$$\eta_{ijpt}^{PNAD} = \frac{F_{ijpt}^{PNAD}}{F_{ijpt}^{PNAD} + I_{ijpt}^{PNAD}} \tag{A.37}$$

Using the household survey, we can divide workers into those under formal employment, those under informal employment, and the self–employed.[18] Formal and informal employment are defined by whether the worker is in possession of a "signed work card" or not. In principle, RAIS accounts for both formal sector employment and self–employment. In practice, it is difficult to know whether self-employed individuals actually file records for RAIS or not. Our baseline choice is to define the informality share as the ratio between informal employees over formal plus informal employees. At a national level, this share is 31%. The results obtained from the model do not change much with alternative approaches.

Employment adjustment In RAIS, total employment e_{ijpt}^{R} (the sum of formal plus informal employment) would be equal to formal employment ($e_{ijpt}^{F,R}$) divided by the formal employment share (η_{ijpt}^{R}). The superscript R stands for RAIS and the superscripts F and I stand for formal and informal respectively. Of course, informal employment is not captured by RAIS.

$$e_{ijpt}^{R} = e_{ijpt}^{F,R} \cdot \frac{1}{\eta_{ijpt}^{R}} \tag{A.38}$$

We use the formality share in PNAD to replace the unobserved formality share in RAIS, so we have an expansion factor $\frac{1}{\eta_{ijpt}^{PNAD}}$.

We then augment employment in RAIS with this time–varying expansion factor. For em-

[17] This survey is not conducted in years 2000 and 2010, in which the Demographic Census takes place. We impute 2000 averarging 1999 and 2001 values and we impute 2010 values averaging 2009 and 2011 values.

[18] In few cases the survey does not have employment in a given skill-state-sector-year-formality cell. In those cases, we use the average corresponding to the macroregion in the same skill-sector-year-formality category.

ployment in period t, state i, sector j, skill type p and year t, we multiply by $\frac{1}{\eta_{ijpt}^{PNAD}}$. For the flow of labor of skill type p moving across different region–sector pairs between periods $t-1$ and t, we use the expansion factor corresponding to the origin region–sector pair. An alternative is to use the expansion factor corresponding to the destination region–sector pair. We find very similar results under that alternative.[19]

Wage adjustment To adjust wages in RAIS, we define the average wage for the formal and informal sectors as a weighted average of the average wages in each of these sectors. Recall that the informal sector is not observed in RAIS, so this equation is purely conceptual.

$$w_{ijpt}^{R} = \frac{w_{ijpt}^{F,R} \cdot e_{ijpt}^{F,R} + w_{ijpt}^{I,R} \cdot e_{ijpt}^{I,R}}{e_{ijpt}^{F,R} + e_{ijpt}^{I,R}} \tag{A.39}$$

Using the employment adjusted total employment e_{ijpt}^{R}, we define informal employment as total employment minus formal employment:

$$e_{ijpt}^{I,R} = e_{ijpt}^{R} - e_{ijpt}^{F,R} \tag{A.40}$$

Using the household survey (PNAD), we compute the ratio between the average wage for informal and formal sector workers for a given state i, sector j, skill type p and year t:

$$\nu_{ijpt}^{PNAD} = \frac{w_{ijpt}^{I,PNAD}}{w_{ijpt}^{F,PNAD}} \tag{A.41}$$

We use this ratio PNAD to replace the unobserved equivalent in RAIS and impute the average wage for informal workers based on the observed average wage for formal workers:

$$w_{ijpt}^{I,R} = \nu_{ijpt}^{PNAD} \cdot w_{ijpt}^{F,R} \tag{A.42}$$

Finally, we replace $e_{ijpt}^{I,R}$ and $w_{ijpt}^{I,R}$ in equation (A.39) to compute w_{ijpt}^{R}.

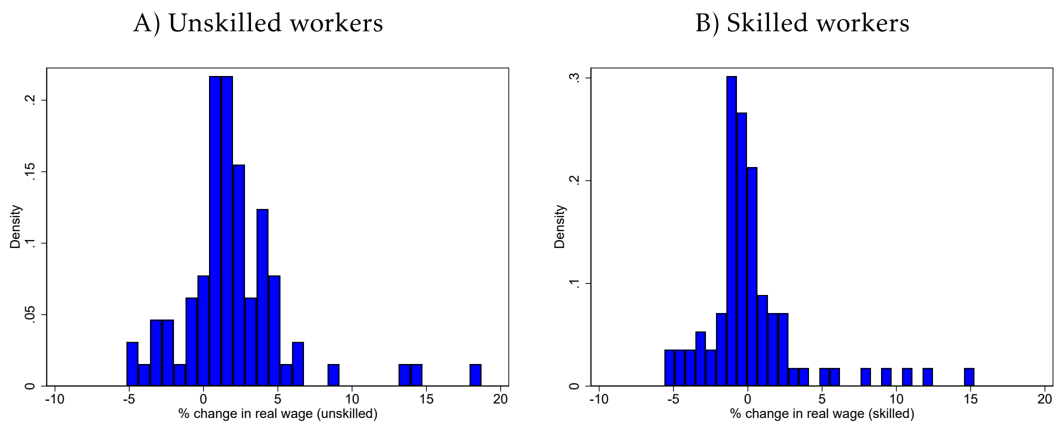
[19] By multiplying employment levels and flows by the same expansion factors, the implicit assumption is that we do use the formal sector employment levels and flows between region–sectors in RAIS, but we do not use the formal sector flows in and out of the workforce in RAIS.

C.3.2 Informality: Results

Figure A.12: Evolution of aggregate outcomes in response to the commodity cycle

Notes: This figure shows the evolution of aggregate outcomes between 2002 and 2018. Panel A plots the skill premium, defined as the ratio between the wage of skilled workers and the wage of unskilled workers. Panel B plots the average real wage of skilled and unskilled workers, normalized to 100 in 2002. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). Panel C plots the sectoral employment shares for commodities, tradables and nontradables, all normalized to zero in 2002. Panel D plots the employment shares of Brazil's five macroregions, all normalized to zero in 2002.

Figure A.13: Histogram of changes in average real wage changes by state and sector



Notes: This figure shows a histogram of the distribution of changes in the average real wage of unskilled workers (panel A) and skilled workers (panel B) by state and sector between 2002 and 2018. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed).

Table A.5: Impact of the commodity cycle on the skill premium and average real wages

	All	Commodity	Tradable	Nontradable
Panel A: Boom (2002-2011)				
Skill premium	-2.6%	-1.8%	-5.9%	-4.8%
Real wage of unskilled workers	3.3%	22.6%	4.6%	6.4%
Real wage of skilled workers	1.4%	18.5%	-0.6%	2.1%
Panel A: Bust (2011-2018)				
Skill premium	1.2%	-1.0%	3.2%	2.4%
Real wage of unskilled workers	-2.6%	-16.6%	-2.6%	-3.3%
Real wage of skilled workers	-1.2%	-14.4%	0.0%	-1.2%
Panel C: Full Cycle (2002-2018)				
Skill premium	-1.4%	-2.7%	-2.9%	-2.5%
Real wage of unskilled workers	0.6%	2.4%	2.0%	2.9%
Real wage of skilled workers	0.2%	1.6%	-0.5%	0.9%

Notes: This table shows the percent change in the skill premium, the average real wage of unskilled workers, and the average real wage of skilled workers. Average real wages account for unemployment (they are a weighted average of the positive real wage of those employed and the zero wage of those unemployed). The columns correspond to outcomes in the aggregate economy (in the first column) or by sector (next three columns). Each cell is computed as the percent change in the corresponding outcome between 2002 and 2011 (panel A), 2011-2018 (panel B) or 2002-2018 (panel C).