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ABSTRACT

We integrate the housing market and the labor market in a dynamic general equilibrium model with credit and search frictions. The model is confronted with the U.S. macroeconomic time series. Our estimated model can account for two prominent facts observed in the data. First, the land price and the unemployment rate tend to move in opposite directions over the business cycle. Second, a shock that moves the land price is capable of generating large volatility in unemployment. Our estimation indicates that a 10 percent drop in the land price leads to a 0.34 percentage point increase of the unemployment rate (relative to its steady state).

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I. INTRODUCTION

A striking feature of business cycles is that land prices and unemployment comove (Figure 1). Never is this feature more true than in the recent recession, when the collapse in the housing market was followed by sharply rising unemployment. The comovements between land prices and unemployment, along with other key business cycle variables, are quantified by a Bayesian vector autoregressions (BVAR) model. As shown in Figure 2 (solid lines and shaded areas), a negative shock to the land price leads to a simultaneous rise in unemployment and a decline in the land price, consumption, investment, total hours, and vacancies. A structural analysis of these stylized facts is essential for policy analysis as well as for understanding business cycles in general.

The goal of this paper is to deliver a structural analysis of dynamic links between land prices and unemployment and to establish the empirical relevance of this analysis. We focus on land prices because fluctuations of house prices are largely driven by those of land prices (Davis and Heathcote (2007)). To establish the links between the land price and the unemployment rate, we combine the housing market and the labor market in one unified dynamic stochastic general equilibrium (DSGE) framework. To fit the U.S. macroeconomic time series, we introduce both financial and search-matching frictions in the model.

The model consists of three types of agents: households, capitalists, and firms. The representative household consists of a continuum of workers—some are employed and others are not. All workers consume the same amount of goods and housing services, so that unemployment risks are pooled within the household. The representative capitalist owns all firms, each of which employs one worker and operates a constant-returns-to-scale technology that transforms labor, land, and capital into final consumption goods.

Capitalists' consumption, investment, and land acquisition require external financing. We assume an imperfect contract enforcement that limits the amount of loans by not only capitalists' capital value but also their land value (Kiyotaki and Moore, 1997; Iacoviello, 2005; Liu, Wang, and Zha, 2013). We model the labor market within the framework of Diamond (1982), Mortensen (1982), and Pissarides (1985) (DMP hereafter).

Econometric estimation of our structural model shows that a negative housing demand shock generates large and persistent comovements among the land price, the unemployment rate, consumption, investment, vacancies, and total hours, consistent with the styled facts revealed in Figure 2. Moreover, a shock that moves the land price is capable of generating large volatility in unemployment, as we observe in the data. These results are not only empirically important but economically substantive in several dimensions.

An important challenge for business cycle models built on the DMP theoretical framework is to generate a large volatility of the labor market (Shimer, 2005). To meet this challenge,

Hagedorn and Manovskii (2008) and Hornstein, Krusell, and Violante (2005) argue that the volatility of unemployment (relative to that of labor productivity) in DMP models can be obtained by making the replacement ratio parameter extremely high. By replacing the standard Nash bargaining problem with the “alternating offer bargaining” strategy, Christiano, Eichenbaum, and Trabandt (2013) show that their model with a lower value of the replacement ratio can account for a high volatility in the labor market according to the statistic considered by Shimer (2005)—the ratio of the standard deviation of labor market tightness to the standard deviation of aggregate labor productivity. We call this ratio “the Shimer volatility ratio.”

The original analysis of Shimer (2005) emphasizes the effects of a stationary technology shock. Our analysis focuses on a housing demand shock because this is the shock that can move the land price in a significant way. In the context of our model, therefore, the key question is whether the dynamic responses to a *housing demand shock*, without relying on an extremely high replacement ratio of income for unemployed workers, can account for not only the observed persistent fluctuations of standard macroeconomic variables but also the observed high volatility of labor-market variables. The answer is provided by Figure 2 in which the estimated responses from our DSGE model are consistent with the styled facts evinced by the BVAR model. These estimates indicate that a 10% drop in the land price would lead to an increase of the unemployment rate by 0.34 percentage points, relative to its steady state value of 5.5%.

Equally important is our finding that the dynamic responses to a housing demand shock can account for the observed high Shimer volatility ratio. In our data, the Shimer volatility ratio is 24.91; in the data used by Christiano, Eichenbaum, and Trabandt (2013), the ratio is 27.6 (see Section 6.4 and Table 6 in their paper). Using the simulated data from our estimated DSGE model with housing demand shocks, we obtain a volatility ratio of 27.47.

The transmission of housing demand shocks to fluctuations in the land price and the unemployment rate works through both the credit channel and the labor channel. The credit channel embodies the dynamic interactions between the collateral value and the value of a new employment match. A decline in housing demand lowers the equilibrium land price and thus the collateral value of land. As the borrowing capacity for the capitalist shrinks, investment spending falls as well. The decline in investment lowers future capital stock. Since capital stock and workers are complementary factors of production, a decrease in future capital stock lowers future marginal productivity of each employed worker and thus reduces the present value of a new employment match. The firm responds by posting fewer vacancies, leading to a fall in the job finding rate and a rise in the unemployment rate.

The labor channel represents endogenous wage rigidities in response to a decline in housing demand. Our model has a non-separable utility function between consumption of goods and

housing services (Piazzesi, Schneider, and Tuzel, 2007). Although consumption declines following a negative shock to housing demand, the marginal utility of consumption also declines because the shock has a direct impact on the marginal utility of consumption. *Ceteris paribus*, a reduction in the marginal utility of consumption implies an increase in the worker's reservation value when the worker bargains with the firm for a wage rate. In equilibrium, the bargained wage rate does decline because the economy contracts, but the decline is substantially dampened because of this labor channel. This leads to large responses of vacancies and unemployment.

The combination of the credit channel and the labor channel provides a statistically and economically significant mechanism that explains not only the persistent comovement between the land price and the unemployment rate but also the resultant large volatility in the labor market.

II. LITERATURE REVIEW

Our work draws on two strands of literature: one on financial frictions and the other on labor-market frictions. Since the recent recession, there has been a large and rapidly growing strand of literature on the role of financial frictions and asset prices in macroeconomic fluctuations within the general equilibrium framework. The literature is too extensive to discuss adequately. A partial list includes De Fiore and Uhlig (2005), Iacoviello (2005), Piazzesi, Schneider, and Tuzel (2007), Gilchrist, Yankov, and Zakrajsek (2009), Iacoviello and Neri (2010), Del Negro, Eggertsson, Ferrero, and Kiyotaki (2010), Hall (2011a), Jermann and Quadrini (2012), Liu, Wang, and Zha (2013), Liu and Wang (Forthcoming), and Christiano, Motto, and Rostagno (Forthcoming) (see Gertler and Kiyotaki (2010) for a survey). This literature typically builds on the financial accelerator framework originally studied by Kiyotaki and Moore (1997) and Bernanke, Gertler, and Gilchrist (1999).

The recent literature on labor-market frictions is also too large to list exhaustively. Examples are Gertler, Sala, and Trigari (2008), Lubik (2009), Justiniano and Michelacci (2011), Christiano, Trabandt, and Walentin (2011), and Christiano, Eichenbaum, and Trabandt (2013). Recent studies on potential links between financial factors and unemployment fluctuations are Chugh (2009), Davis, Fisher, and Veracierto (2010), Hall (2011b), Kocherlakota (2011), Petrosky-Nadeau (2011), Monacelli, Quadrini, and Trigari (2011), Miao, Wang, and Xu (2012), and Petrosky-Nadeau and Wasmer (2013).

Our paper places a different emphasis than the existing literature. We provide a first study that integrates the housing market and the labor market within the DSGE framework and uses the estimated structural model to account for the strong connections between land-price dynamics and large unemployment fluctuations we observe in the data.

III. THE MODEL

The economy is populated by three types of agents: households, capital producers, and firms. Each type has a continuum of agents. The representative capital producer (i.e., the capitalist) derives utility from consuming a final good produced by firms. The capitalist has access to an investment technology that transforms consumption goods into capital goods. The capitalist finances expenditures by both internal and external funds. Limited contract enforcement implies that capitalists' borrowing capacity is constrained by the value of collateral assets—the land and capital stocks held by capitalists. Capitalists own firms. A firm in an employment match hires one worker from the representative household and rents capital and land from the representative capitalist to produce the final good.

The representative household consumes both goods and housing services (by owning the land) and saves in the risk-free bond market. There is a continuum of workers within the representative household. A fraction of workers is employed and the other fraction (unemployed workers) searches for jobs in the frictional labor market. Firms post vacancies at a fixed cost. An employment match is formed according to a matching technology that combines searching workers and job vacancies to “produce” new employment matches.

III.1. Households. The representative household has the utility function

$$E \sum_{t=0}^{\infty} \beta_h^t \left[\frac{(L_{ht}^{\varphi_{Lt}} (C_{ht} - \eta_h C_{ht-1}) / Z_t^p)^{1-\gamma}}{1-\gamma} - \chi g(h_t) N_t \right], \quad g(h_t) = \frac{h_t^{1+\nu}}{1+\nu} \quad (1)$$

where $E[\cdot]$ is the expectation operator, C_{ht} denotes consumption, L_{ht} denotes the household's land holdings, h_t denotes labor hours (the intensive margin), and N_t denotes employment (the extensive margin)—the fraction of household members who is employed.

The parameter $\beta_h \in (0, 1)$ denotes the subjective discount factor, χ denotes the weight on labor disutility, η_h measures the household's habit persistence, and γ is the risk aversion parameter. Since consumption of goods grows over time while land supply and employment do not, we scale consumption by the growth factor Z_t^p (i.e., the permanent component of the technology shock) to obtain balanced growth. The variable φ_{Lt} is a housing demand shock that follows the stochastic process

$$\ln \varphi_{Lt} = (1 - \rho_L) \ln \varphi_L + \rho_L \ln \varphi_{L,t-1} + \varepsilon_{Lt}, \quad (2)$$

where $\rho_L \in (-1, 1)$ is the persistence parameter and ε_{Lt} is an i.i.d. white noise process with mean zero and variance σ_L^2 .

In the limiting case with $\gamma = 1$, the utility function (1) reduces to the standard separable preferences

$$E \sum_{t=0}^{\infty} \beta_h^t [\ln (C_{ht} - \eta_h C_{ht-1}) + \varphi_{Lt} \ln L_{ht} - \chi g(h_t) N_t]. \quad (3)$$

Following Piazzesi, Schneider, and Tuzel (2007), however, we find that maintaining non-separability in the utility function helps generate the comovement among the land price, consumption, and investment.

The household is initially endowed with $L_{h,-1}$ units of land and has no initial saving $B_{h,-1} = 0$. The household chooses consumption $\{C_{ht}\}$, land holdings $\{L_{ht}\}$, and saving $\{B_{ht}\}$ to maximize the utility function in (1) subject to the sequence of budget constraints

$$C_{ht} + \frac{B_{ht}}{R_t} + Q_{lt}(L_{ht} - L_{h,t-1}) = B_{ht-1} + W_t h_t N_t + b Z_t^p (1 - N_t) - T_t, \quad \forall t \geq 0, \quad (4)$$

where B_{ht} denotes the saving, R_t denotes the risk-free interest rate, Q_{lt} denotes the land price, W_t denotes the wage rate, N_t denotes the fraction of workers employed, b denotes the unemployment benefit, and T_t denotes lump-sum taxes. We follow Hall (2005) and scale the unemployment benefit by Z_t^p , so that the unemployment benefit relative to labor income remains stationary.

The household does not unilaterally choose h_t or N_t . Instead, as we describe below, these variables are determined in the labor market equilibrium with search and matching frictions.

III.2. Capitalists. The representative capitalist has the utility function

$$E \sum_{t=0}^{\infty} \beta_c^t \ln (C_{ct} - \eta_c C_{ct-1}), \quad (5)$$

where $\beta_c \in (0, 1)$ denotes the capitalist's subjective discount factor, C_{ct} denotes consumption, and η_c is the habit persistence parameter.

The capitalist is initially endowed with K_{-1} units of capital and $L_{c,-1}$ units of land, with no initial debt. The capitalist faces the flow-of-funds constraint

$$C_{ct} + Q_{lt}(L_{ct} - L_{c,t-1}) + I_t + \Phi(e_t) K_{t-1} + B_{c,t-1} = \frac{B_{ct}}{R_t} + R_{kt} e_t K_{t-1} + R_{lt} L_{c,t-1} + \Pi_t, \quad (6)$$

where L_{ct} , I_t , e_t , K_t , B_{ct} , R_{kt} , R_{lt} , and Π_t denote the capitalist's land holdings, investment, the capacity utilization rate, the end-of-period capital stock, the debt level, the rental rate of capital, the rental rate of land, and dividends collected from firms, respectively.

The cost of capacity utilization $\Phi(e)$ is an increasing and convex function given by

$$\Phi(e_t) = \gamma_1 (e_t - 1) + \frac{\gamma_2}{2} (e_t - 1)^2, \quad (7)$$

where the slope and curvature parameters, γ_1 and γ_2 , are both non-negative.

The capitalist finances consumption, acquisitions of new land, and investment expenditures by both internal funds and external credit. We assume that $\beta_c < \beta_h$ and the amount the capitalist can borrow is limited by a fraction of their collateral value. This assumption ensures that the borrowing constraint for the capitalist binds in a neighborhood of the deterministic steady state.

Denote by Q_{kt} the shadow price of capital (i.e., Tobin's q). The collateral constraint is given by

$$B_{ct} \leq \xi_t E_t (\omega_1 Q_{l,t+1} L_{ct} + \omega_2 Q_{k,t+1} K_t), \quad (8)$$

where ω_1 and ω_2 are the parameters that determine the weight of land and capital in the collateral value. The collateral constraint here is motivated by the limited contract enforcement problem emphasized by Kiyotaki and Moore (1997). If the capitalist fails to repay the loan, the lender can seize the collateral. Since liquidation is costly, the lender can recoup up to a fraction of the value of collateral assets, which is denoted by ξ_t . We interpret ξ_t as a collateral shock and assume that it follows the stochastic process

$$\ln \xi_t = (1 - \rho_\xi) \ln \xi + \rho_\xi \ln \xi_{t-1} + \varepsilon_{\xi t}, \quad (9)$$

where $\rho_\xi \in (-1, 1)$ is the persistence parameter and $\varepsilon_{\xi t}$ is an i.i.d. white noise process with mean zero and variance σ_ξ^2 .

The capitalist has access to an investment technology that transforms consumption goods into productive capital. In particular, given the beginning-of-period capital stock K_{t-1} , the capitalist can transform I_t units of consumption goods into K_t units of new capital. Thus, the law of motion of the capital stock is given by

$$K_t = (1 - \delta) K_{t-1} + \left[1 - \frac{\Omega}{2} \left(\frac{I_t}{I_{t-1}} - \gamma_I \right)^2 \right] I_t, \quad (10)$$

where $\delta \in (0, 1)$ denotes the depreciation rate of capital, $\Omega > 0$ is the adjustment cost parameter, and γ_I denotes the steady-state growth rate of investment.

III.3. The labor market. At the beginning of period t , there are u_t unemployed workers searching for jobs and there are v_t vacancies posted by firms. The matching technology is described by the Cobb-Douglas function

$$m_t = \varphi_{mt} u_t^a v_t^{1-a}, \quad (11)$$

where $a \in (0, 1)$ is the elasticity of job matches with respect to the number of searching workers. The variable φ_{mt} is an exogenous matching efficiency shock that follows the stochastic process

$$\ln \varphi_{mt} = (1 - \rho_m) \ln \varphi_m + \rho_m \ln \varphi_{m,t-1} + \varepsilon_{mt}, \quad (12)$$

where $\rho_m \in (-1, 1)$ is the persistence parameter and ε_{mt} is an i.i.d. white noise process with mean zero and variance σ_m^2 .

The probability that an open vacancy is matched with a searching worker, the job filling rate, is given by

$$q_t^v = \frac{m_t}{v_t}. \quad (13)$$

The probability that an unemployed and searching worker is matched with an open vacancy, the job finding rate, is given by

$$q_t^u = \frac{m_t}{u_t}. \quad (14)$$

Denote by N_{t-1} the number of employed workers at the beginning of period t . Before matching takes place, a fraction ρ of workers lose their jobs. The number of workers who survive job separations is $(1 - \rho)N_{t-1}$. Thus, the number of unemployed workers searching for jobs in period t is given by

$$u_t = 1 - (1 - \rho)N_{t-1}, \quad (15)$$

where we have assumed full labor-force participation. After matching takes place, the number of jobless workers who find jobs is m_t . Thus, aggregate employment evolves according to the law of motion

$$N_t = (1 - \rho)N_{t-1} + m_t. \quad (16)$$

Following Blanchard and Galí (2010), we assume that newly hired workers start working within the same period. Thus, the number of productive workers in period t is given by N_t .

At the end of period t , the number of unemployed workers equals those searching workers who fail to find a match. Thus, as in Blanchard and Galí (2010), the unemployment rate is given by

$$U_t = u_t - m_t = 1 - N_t. \quad (17)$$

III.4. Firms. A firm can produce only if it can be successfully matched with a worker.¹ A firm with a worker rents capital k_t and land l_{ct} from the capitalist. It produces the final consumption good using the technology

$$y_t = Z_t^{1-\alpha+\phi\alpha} \left(l_{ct}^\phi k_t^{1-\phi} \right)^\alpha h_t^{1-\alpha}, \quad (18)$$

where y_t is output, the parameters $\phi \in (0, 1)$ and $\alpha \in (0, 1)$ measure input elasticities, and Z_t is a labor augmenting technology shock, which is composed of a permanent component Z_t^p and a transitory (stationary) component Z_t^m such that $Z_t = Z_t^p Z_t^m$. The permanent component Z_t^p follows the stochastic process

$$Z_t^p = Z_{t-1}^p \lambda_{zt}, \quad \ln \lambda_{zt} = (1 - \rho_{zp}) \ln \lambda_z + \rho_{zp} \ln \lambda_{z,t-1} + \varepsilon_{zp,t}. \quad (19)$$

The stationary component follows the stochastic process

$$\ln Z_t^m = (1 - \rho_{zm}) \ln Z_{t-1}^m + \rho_{zm} \ln Z_{t-1}^m + \varepsilon_{zm,t}. \quad (20)$$

The parameter λ_z is the steady-state growth rate of Z_t^p , and the parameters ρ_{zp} and ρ_{zm} measure the degrees of persistence of Z_t^p and Z_t^m . The innovations $\varepsilon_{zp,t}$ and $\varepsilon_{zm,t}$ are i.i.d., mean-zero normal processes with standard deviations given by σ_{zp} and σ_{zm} .

¹In Appendix A we show that this setup is equivalent to an alternative setup with one large representative firm.

Denote by J_t^F the value of a new employment match. A firm matched with a worker obtains profits in the current-period production. In the next period, if the match survives (with probability $1 - \rho$), the firm continues to receive the match value; otherwise, the firm receives the value of an open vacancy (V_t). Thus, the match value is given by

$$J_t^F = \pi_t - W_t h_t + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} [(1 - \rho) J_{t+1}^F + \rho V_{t+1}], \quad (21)$$

where π_t denotes profit prior to wage payments, W_t denotes the wage rate, h_t denotes the hours worked, and Λ_{ct} denotes the marginal utility of consumption for capitalists who own the firm.

The profit π_t prior to wage payments is obtained by solving the production problem

$$\pi_t = \max_{k_t, l_{ct}} Z_t^{1-\alpha+\phi\alpha} \left(l_{ct}^\phi k_t^{1-\phi} \right)^\alpha h_t^{1-\alpha} - R_{kt} k_t - R_{lt} l_{ct}, \quad (22)$$

where the rental prices R_{kt} and R_{lt} are taken as given.

If the firm posts a job vacancy, it pays a vacancy cost κ . If the vacancy is filled (with probability q_t^v), then the firm obtains the value J_t^F . Otherwise, the firm carries the vacancy to the next period. The value of an open vacancy V_t satisfies the asset-pricing equation

$$V_t = -\kappa Z_t^p + q_t^v J_t^F + (1 - q_t^v) E_t \frac{\beta_c \Lambda_{c,t+1}}{\Lambda_{ct}} V_{t+1}. \quad (23)$$

We scale the vacancy cost by the growth factor Z_t^p to keep stationary the ratio of this cost to output.

Free entries imply that $V_t = 0$ for all t . It follows from Equation (23) that

$$J_t^F = \frac{\kappa Z_t^p}{q_t^v}. \quad (24)$$

This condition characterizes optimal vacancy posting decisions. If the firm posts a vacancy, it needs to pay the flow cost κZ_t^p . In each period, the vacancy is filled with probability q_t^v . Thus, the expected duration of the vacancy before it is filled is $1/q_t^v$. The optimal vacancy posting decision (24) equates the benefit of a new employment match to the expected cost of posting and maintaining a vacancy.

III.5. Nash bargaining. When a job match is formed, a firm and a worker bargain over wages and hours in a Nash bargaining game. The worker's surplus is the difference between the value of employment and the value of unemployment. The firm's surplus is just the value of the firm J_t^F because the value of an open vacancy V_t is driven to zero by free entries. We have specified the match value in the preceding section. We now describe the worker's value function.

If employed, the worker receives a wage payment in the current period, although suffers disutility from working. In the next period, the worker may lose the job with probability ρ and cannot find a new job with probability $1 - q_{t+1}^u$ (recall that q^u is the job finding

rate). In that event, the worker obtains the present value of unemployment. Otherwise, the worker continues to have a job and receives the employment value. Specifically, the value of employment (denoted by J_t^W) is given by

$$J_t^W = W_t h_t - \frac{\chi g(h_t)}{\Lambda_{ht}} + E_t \frac{\beta_h \Lambda_{h,t+1}}{\Lambda_{ht}} [(1 - \rho(1 - q_{t+1}^u)) J_{t+1}^W + \rho(1 - q_{t+1}^u) J_{t+1}^U], \quad (25)$$

where Λ_{ht} denotes the marginal utility of consumption for households and J_t^U denotes the value of unemployment.

An unemployed worker receives the flow benefit of unemployment b from the government. Next period, the unemployed can find a job with probability q_{t+1}^u and obtains the present value of employment. Otherwise, the worker remains unemployed. The value of unemployment is given by

$$J_t^U = bZ_t^p + E_t \frac{\beta_h \Lambda_{h,t+1}}{\Lambda_{ht}} [q_{t+1}^u J_{t+1}^W + (1 - q_{t+1}^u) J_{t+1}^U]. \quad (26)$$

The firm and the worker bargain over wages and hours. The Nash bargaining problem they face is given by

$$\max_{W_t, h_t} (J_t^W - J_t^U)^{\frac{\vartheta_t}{1+\vartheta_t}} (J_t^F)^{\frac{1}{1+\vartheta_t}}, \quad (27)$$

where ϑ_t represents a time-varying bargaining weight for the workers and it follows the stochastic process

$$\ln \vartheta_t = (1 - \rho_\vartheta) \ln \vartheta + \rho_\vartheta \ln \vartheta_{t-1} + \varepsilon_{\vartheta t}, \quad (28)$$

where ρ_ϑ measures the persistence of the bargaining shock and $\varepsilon_{\vartheta t}$ is an i.i.d. normal process with mean zero and variance σ_ϑ^2 .

It is straightforward to show that the bargaining solutions for the wage rate and labor hours satisfy the following two equations:

$$W_t h_t = \frac{\chi g(h_t)}{\Lambda_{ht}} + bZ_t^p + \vartheta_t \frac{\kappa Z_t^p}{q_t^v} - E_t \frac{\beta_h \Lambda_{h,t+1}}{\Lambda_{ht}} \left[(1 - \rho)(1 - q_{t+1}^u) \vartheta_{t+1} \frac{\kappa Z_{t+1}^p}{q_{t+1}^v} \right], \quad (29)$$

and

$$\frac{\chi g'(h_t)}{\Lambda_{ht}} = \frac{\partial y_t}{\partial h_t}. \quad (30)$$

The last equation implies that the value of the marginal product of hours is equal to the marginal rate of substitution between leisure and consumption. This condition is exactly the same as in the competitive labor market in the real business cycle literature. The condition obtains because the correct measure of the cost of hours to the firm is the marginal rate of substitution. Unlike the real business cycle literature, however, the wage rate is no longer allocative for hours due to the search and matching frictions.

III.6. **The government.** The government finances unemployment benefit payments through lump-sum taxes. We assume that the government balances the budget in each period so that

$$bZ_t^p(1 - N_t) = T_t. \quad (31)$$

We abstract from government spending for the clarity of our analysis.

III.7. **Search equilibrium.** In equilibrium, the markets for bond, housing, capital, and consumption all clear.

The bond market clearing condition is given by

$$B_{ct} = B_{ht} \equiv B_t, \quad (32)$$

where B_t denotes the equilibrium level of debt for capitalists.

The land market clearing condition is given by

$$L_{ct} + L_{ht} = 1, \quad (33)$$

where we normalize the supply of land to 1.

The capital market clearing condition is given by

$$e_t K_{t-1} = N_t k_t. \quad (34)$$

The aggregate resource constraint clears the goods market:

$$C_t + I_t + \Phi(e_t) K_{t-1} + \kappa Z_t^p v_t = Y_t, \quad (35)$$

where $C_t \equiv C_{ht} + C_{ct}$ denotes aggregate consumption and Y_t denotes aggregate output.

Aggregate output is given by

$$Y_t = Z_t^{1-\alpha+\phi\alpha} \left(l_{ct}^\phi k_t^{1-\phi} \right)^\alpha h_t^{1-\alpha} N_t = \left[(Z_t L_{c,t-1})^\phi (e_t K_{t-1})^{1-\phi} \right]^\alpha (Z_t h_t N_t)^{1-\alpha}, \quad (36)$$

where we have imposed the rental land market clearing condition that $L_{c,t} = l_{ct} N_t$.

A search equilibrium consists of sequences of prices $\{Q_{lt}, Q_{kt}, R_t, R_{kt}, R_{lt}\}$, wages $\{W_t\}$, allocations $\{C_{ht}, B_{ht}, L_{ht}\}$ for households, allocations $\{C_{ct}, B_{ct}, L_{ct}, K_t, I_t, e_t\}$ for capitalists, allocations $\{y_t, k_t, l_{ct}, h_t\}$ for each firm, and labor market variables $\{m_t, u_t, v_t, N_t, q_t^u, q_t^v\}$, such that (i) taking all prices and wages as given, households' allocations maximize their utility, (ii) taking all prices and wages as given, capitalists' allocations maximize their utility, (iii) taking all prices and wages as given, allocations for each firm with a job match maximize the firm's profit, (iv) new matches are formed based on the matching technology, with wages and labor hours determined from the bilateral bargaining between firms and workers, and (v) the land market, the capital market, the bond market, and the goods market all clear.

IV. ESTIMATION

To fit the model to the data, we first log-linearize the stationary equilibrium conditions, reported in Appendix B, around the deterministic steady state in which the collateral constraint is binding. The model with six shocks is then confronted with six quarterly U.S. time series from 1975Q1 to 2012Q4: the real land price, per capita real consumption, per capita real investment, the vacancy rate, the unemployment rate, and per capita total hours. We provide a detailed descriptions of the data and the model shocks in Appendix C.

We apply the Bayesian method to estimation of the model. Since shocks to housing demand drive almost all the fluctuations in the land price and since our paper is to study the dynamic links between the land price and the unemployment rate, our subsequent discussions revolve around understanding the macroeconomic and labor-market effects of a shock to housing demand.²

Some parameter values are fixed prior to estimation, because they are not identified within the model. Appendix D discuss what these parameters are and how they are calibrated. One parameter we highlight here is the risk aversion parameter. As the labor channel discussed in the introduction works through non-separability of the household's utility function between consumption and housing services, we set the relative risk aversion parameter $\gamma = 2$ as a benchmark to be in line with the literature (Kocherlakota, 1996; Lucas Jr., 2003).

Table 1 reports the estimated posterior mode and the 90% probability interval of each structural parameter (the last 3 columns), along with the prior distributions for comparison. The table shows that capitalists have a much stronger habit formation than households (0.98 vs. 0.22). Strong habit formation for capitalists helps smooth their consumption and amplify fluctuations in investment following a shock to housing demand. Since firms are owned by capitalists, strong habit formation implies high volatility in the stochastic discount factor for firms, which allows the model to generate large fluctuations in the value of a new employment match. Fluctuations in the match value in our model are key to generating large volatilities in job vacancies and unemployment.

The estimated value of the investment adjustment cost parameter ($\Omega = 0.14$) is very small compared to the DSGE literature without financial frictions. A small adjustment cost parameter implies low volatility in the shadow price of capital (Tobin's q). Thus, the collateral channel works mainly through interactions between debt and land value. Consistent with this finding, the estimated weight on capital value in the collateral constraint is considerably smaller than that on land value ($\omega_2 = 0.14$ vs. the normalized value of $\omega_1 = 1$).

²Appendix D provides a detailed description of prior distributions for the structural parameters and Appendix E discusses some estimation issues.

The estimated parameter values for the capacity utilization function imply a large elasticity of the capital rental rate with respect to capacity utilization (the elasticity γ_2/γ_1 is about 16 in magnitude). Since the capital rental rate does not fluctuate much in our model, the large elasticity implies small fluctuations in capacity utilization. Thus, the model does not rely on variable capacity utilization to fit the data.

The estimated curvature parameter of the disutility function of labor hours is small ($\nu = 0.027$). This finding, however, does not contradict the microeconomic evidence of a small Frisch elasticity of labor hours. In particular, in a model with credit constraints and adjustment costs, there is in general no direct mapping from the preference parameter ν to the intertemporal labor supply elasticity (Keane and Rogerson, 2011). In our model, a small value of ν allows necessary fluctuations in labor hours (the intensive margin) to prevent the model from “overshooting” the volatility of unemployment. We discuss the overshooting phenomenon in Section VI.2.

The estimates of the remaining structural parameters, δ , β_h , β_c , ϕ , λ_z , and φ_L , are broadly in line with those obtained in the literature (Iacoviello, 2005; Liu, Wang, and Zha, 2013).

Table 2 shows the prior and posterior distributions of shock parameters. We follow the DSGE literature and assume that the prior for the persistence parameters takes the beta distribution and the prior for the volatility parameters takes the inverse-gamma distribution. We select the hyperparameters for these prior distributions to obtain a reasonably broad 90% probability interval for each parameter. The posterior mode estimates indicate that the housing demand shock process is most persistent and volatile. This shock process, as we show in Section V, is most important in driving the persistent comovement between the land price and the unemployment rate as well as large fluctuations in unemployment.

V. DYNAMIC INTERACTIONS BETWEEN THE LAND PRICE AND THE LABOR MARKET

We now use the estimated model to assess the empirical importance of dynamic interactions between the land price and labor-market variables. We begin with a discussion of the macroeconomic effects of land-price dynamics. We then analyze how the labor market fluctuates with changes in the land price. We conclude by quantifying the large volatility of labor-market variables.

Figure 3 reports the impulse responses of standard macroeconomic variables in response to a negative housing demand shock. The error bands for the impulse responses are generated according to the methodology suggested by Sims and Uhlig (1991) and Sims and Zha (1999). The shock leads to a persistent decline in the land price. The decline in the land value tightens capitalists’ borrowing capacity, which in turn reduces their land acquisition, labor hours for employed workers, and business investment.

Figure 4 reports the impulse responses of labor-market variables in response to a negative housing demand shock, along with the error bands. As investment falls, the future capital stock declines and the resultant marginal product of employment (the output value of additional employment) falls. Hence, the present value of a new employment match falls, reducing the benefit of forming an employment match. Firms respond by posting fewer job vacancies. Consequently, the job finding rate for unemployed workers declines, leading to higher equilibrium unemployment as the land price declines.

To see how our structural model fits to the data, we reproduce in Figure 2 the dynamic responses to a negative housing demand shock in the estimated DSGE model (asterisk lines) against the 90% probability bands for the BVAR estimated impulse responses (shaded areas). The DSGE results fit the stylized facts surprisingly well in both dimensions: comovement and volatility. Not only does the estimated DSGE model generate the observed comovements between the land price and the standard macroeconomic and labor-market variables, but more importantly the model generates the observed large volatility in the labor market as well. Given how restrictive our DSGE model is, these results are remarkable.

Consistent with the data, fluctuations of labor-market variables in our DSGE model are large in magnitude relative to those in the land price and the standard macroeconomic variables. In particular, our impulse responses indicate that a 10% drop in the land price leads to a rise in the unemployment rate (relative to its steady state) by 0.34 percentage points.

Shimer (2005) emphasizes a special statistic for measuring the volatility of the labor market: the ratio of the standard deviation of labor market tightness (vacancies divided by unemployment) to the standard deviation of aggregate labor productivity. To compute the Shimer volatility ratio, we use the estimated model to simulate a long sequence (100,000 periods) of series. Following Shimer (2005) and Christiano, Eichenbaum, and Trabandt (2013), we first HP-filter both the simulated series and the actual data and then compute the Shimer volatility ratio. For the data set used for this paper, the ratio is 24.91. For the data set used by Christiano, Eichenbaum, and Trabandt (2013), the ratio is 27.6 (Table 6 in their paper). The Shimer volatility ratio for our simulated series is 27.47.

Both the estimated impulse responses and the computed Shimer volatility ratio evince our model's ability to account for the dynamic links between the land price and the unemployment rate as well as the large volatility of unemployment. In Section VI we explore the economic intuition behind these results.

VI. UNDERSTANDING THE ECONOMIC MECHANISM

In this section we analyze the economic mechanism behind our estimated results. We identify two key channels for the transmission and amplification of housing demand shocks to the aggregate economy and the labor market.

VI.1. The credit channel. As shown both in the data (Figure 2) and in our structural estimation (Figure 3), the fall of the land price is driven by a negative housing demand shock. Due to the credit constraint, this fall directly reduces capitalists' land value and borrowing capacity, resulting in the fall of business investment (Liu, Wang, and Zha, 2013).

We now illustrate a transmission channel through which the value of a new employment match, J_t^F , declines as a result of declining investment. We call this transmission the "credit channel." Recall the optimal equation for the value of a new employment match:

$$J_t^F = (1 - \alpha)Z_t^{1-\alpha+\alpha\phi} \left(l_{ct}^\phi k_t^{1-\phi} \right)^\alpha h_t^{1-\alpha} - W_t h_t + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} (1 - \rho) J_{t+1}^F. \quad (37)$$

The first term on the right-hand side is derived from equation (22) and can be interpreted as the marginal productivity of employed workers. Because a reduction in capitalists' investment leads to a reduction in future capital stocks, future marginal productivity of employed workers falls. For any given real wage and labor hours, the decline in future marginal productivity reduces the present value of a new employment match.³

How the fall of the new employment value is transmitted into the labor market is illustrated in Figure 5. The figure plots the Beveridge curve (the inverse relation between vacancies and unemployment derived from the matching function) and the job creation curve (the positive relation between vacancies and unemployment derived from the free-entry condition).⁴ The Beveridge curve (BC), derived from the matching function (11), implies that

$$v = \left(\frac{\rho}{\varphi_m(1 - \rho)} \frac{1 - u}{u^\alpha} \right)^{\frac{1}{1-\alpha}},$$

where we have imposed the steady-state relations that $m = \rho N$ and $1 - u = (1 - \rho)N$. The job creation curve (JCC) derived from the free-entry condition (24) implies that

$$v = \left(\varphi_m \frac{J^F}{\kappa} \right)^{\frac{1}{\alpha}} u,$$

where we have used the relation $q^v = \varphi_m \left(\frac{u}{v} \right)^\alpha$ derived from the definition of q^v and the matching function. Thus, the slope of the JCC depends positively on matching efficiency and the value of a new employment match, and negatively on vacancy costs.

³For the clarity of our argument, we postpone discussions of how the dynamics of wages and hours influence the equilibrium outcome until Section VI.2.

⁴This illustration draws from Pissarides (2000, Chapters 1 & 2). A similar graph is used by Leduc and Liu (2012), who study the macroeconomic effects of uncertainty shocks.

The intersection of the BC and the JCC determines the equilibrium vacancies and unemployment. Consider the initial equilibrium at point A, corresponding to the steady state. As discussed in the earlier part of this section, a fall of business investment in response to a negative housing demand shock causes the present value of a new employment match to fall. The decline of the match value J_t^F rotates the job creation curve downward as shown in Figure 5. The economy moves along the downward-sloping Beveridge curve to a new equilibrium, with fewer job vacancies and a higher unemployment rate (point B).

To assess the full impact of this credit channel on the labor market, we consider a counterfactual economy in which the amount of credit capitalists can obtain does not vary with their land and capital value such that their borrowing capacity remains at the steady-state level. By construction, therefore, the credit channel is muted. The dynamic responses of the key macroeconomic and labor-market variables to a negative housing demand shock in this counterfactual economy are displayed Figure 6, along with those from the estimated model.

The figure shows starkly different impulse responses to the housing demand shock between the counterfactual economy (solid lines) and the estimated economy (asterisk lines). In the counterfactual economy, capitalists' borrowing capacity is not affected by the decline in the land price driven by the housing demand shock. As land becomes cheaper, capitalists' effective resources available for purchasing investment goods actually rise. Thus, the counterfactual economy fails to generate business-cycle comovements because investment, output, and labor hours all rise whereas consumption (not shown) and the land price both decline. The effects on the value of a new employment match and thus on unemployment are muted by the absence of the credit channel.

VI.2. The labor channel. A negative shock to housing demand, through the credit channel, sparks off a simultaneous decline in the land price and business investment, which in turn reduces the value of a job match, discourages firms from posting vacancies, and thus leads to higher unemployment. But a decline in business investment alone is insufficient to produce a significant rise in unemployment. The reason is that, without wage rigidities, a drop in the wage rate would partially offset the effects of lower investment on the match value. One prominent example is a negative stationary technology shock. As Figure 7 shows, this shock in the estimated model (solid lines) leads to a large decline in business investment but fails to produce a large increase in unemployment. The result is not surprising as it confirms the finding of Shimer (2005) and others. The intuition is that real wages fall considerably, blunting the shock's impact on unemployment.

A negative shock to housing demand is capable of generating large increases in unemployment because it is channeled through a second transmission route that produces endogenous wage rigidities. We call this transmission the "labor channel." To explain how the labor

channel works, we rewrite the Nash bargained wage equation (29) as

$$W_t = \frac{\chi g(h_t)/h_t}{\Lambda_{ht}} + bZ_t^p/h_t + \frac{1}{h_t} \left[\vartheta_t J_t^F - E_t \frac{\beta_h \Lambda_{h,t+1}}{\Lambda_{ht}} ((1-\rho)(1-q_{t+1}^u) \vartheta_{t+1} J_{t+1}^F) \right].$$

A negative technology shock reduces the value of an employment match and the number of vacancy postings. The decreased job finding rate raises the unemployment duration, which weakens the workers' bargaining position and reduces the equilibrium wage rate. As shown in the Nash bargaining wage equation above, the wage rate decreases when the match value (J_t^F) falls or when the unemployment duration ($1/q^u$) rises. To be sure, a negative housing demand shock raises the unemployment duration with similar logic. But the impact works *indirectly* through the credit channel discussed in the preceding section.

The main difference, however, stems from the household side. Households' reactions to a housing demand shock differs from their reactions to a technology shock. A negative technology shock reduces consumption substantially, as shown in Figure 7. The resultant sharp increase in households' marginal utility (Λ_h) reduces the worker's reservation value and reinforces the effect of the increase in the unemployment duration. Consequently, the worker is willing to accept a lower wage offer. In equilibrium the decline in real wages limits firms' desire to contract employment, rendering the impact on unemployment small.

By contrast, a negative housing demand shock makes land less desirable for households so that they prefer to increase consumption. In the mean time, interactions between the land price and business investment amplify the impact of a housing demand shock on the land price, leading to sharp declines in the land price. As land becomes cheaper, the household would like to purchase more land and to reduce consumption. These two effects offset each other, leading to small fluctuations in consumption and in the marginal utility of consumption (Figure 7). When the utility function is non-separable, moreover, a negative housing demand shock directly lowers the marginal utility of consumption, thereby raising the workers' threat point in wage bargaining. The resultant decline in the marginal utility offsets the effect of the increase in the unemployment duration, creating less incentives for workers to accept lower wages.

As shown in Figure 7, the response of households' marginal utility to a housing demand shock (asterisk line) is an order of magnitude smaller than that to a technology shock (solid line). Consequently, the real wage does not change much following a housing demand shock while the value of a job match falls substantially. This leads to large responses of vacancies and unemployment.

While wage rigidities are crucial to the dynamic connections between the land price and the unemployment, how labor hours per employed worker (the intensive margin) adjust to changes in housing demand plays another important but different role in determining the effectiveness of the labor channel on unemployment dynamics. To see this point, consider a

counterfactual economy in which the supply of labor hours is inelastic so that equilibrium labor hours do not respond to any shocks. We compare the dynamic responses to a negative housing demand shock in this counterfactual economy to those in the estimated economy in Figure 6. In the counterfactual economy with inelastic supply of labor hours (dashed lines), the land price falls along with investment and output as in the estimated economy (asterisk lines). But both the match value and unemployment in the counterfactual economy overshoot the responses in the estimated economy. Since firms cannot reduce labor hours (the intensive margin), they rely more on adjusting employment (the extensive margin).⁵ Because firms cannot cut costs by reducing hours, the value of an employment match declines more than in the estimated economy so that firms reduce vacancy postings more aggressively. As a consequence, the responses of unemployment overshoot those in the baseline economy.

The above analysis demonstrates that the credit and labor channels reinforce each other to transmit the fluctuations in the land price into a large volatility in the labor market that is consistent with the data.

VII. CONCLUSION

The dynamic relationships between the land price and the unemployment rate are strong in the data. We construct and estimate a dynamic general equilibrium model to account for these relationships as well as those with other key macroeconomic variables. The estimated dynamic responses to a housing demand shock generate these comovements among the macroeconomic variables. More significant is our empirical finding that the dynamic response of the unemployment rate is large enough, relative to the output fluctuation, to achieve a high volatility ratio of the market tightness to labor productivity as stressed by Shimer (2005).

To understand how the DMP labor market interacts with the housing market, we focus on obtaining a transparent economic mechanism that drives our empirical results, and thus abstract from a host of other features which we could incorporate in future research. Miao, Wang, and Zha (2013), for example, provide a deeper interpretation of the housing demand shock and decompose it into three structural shocks for the purpose of explaining the wedge between the house (land) price and the rental price. Galí, Smets, and Wouters (2011) take an explicit account of labor participation dynamics in their general equilibrium model. Christiano, Eichenbaum, and Trabandt (2013) offers an alternative framework for wage negotiations and focus their analysis on how the labor market responds to technology shocks as well as monetary policy shocks. It is our hope that the economic analysis provided

⁵In the counterfactual economy, the decline of total hours is entirely driven by the decline of employment since labor hours per employed worker are fixed.

by this paper offers essential ingredients for further research on the interactions between the housing market and the labor market.

TABLE 1. Prior and posterior distributions of structural parameters

Parameter	Prior			Posterior		
	Distribution	low	high	Mode	Low	High
η_c	Beta	0.025	0.776	0.982	0.973	0.989
η_h	Beta	0.025	0.776	0.219	0.148	0.302
Ω	Gamma	0.171	10.00	0.142	0.105	0.216
γ_2	Gamma	0.171	10.00	1.009	0.537	1.498
ν	Gamma	0.086	5.000	0.027	0.013	0.049
ω_2	Gamma	0.048	2.821	0.142	0.123	0.157
$100(\lambda_z - 1)$	Gamma	0.100	1.500	0.495	0.421	0.551
δ	Simulated	0.043	0.051	0.047	0.047	0.048
β_h	Simulated	0.991	0.999	0.995	0.994	0.996
β_c	Simulated	0.968	0.997	0.989	0.989	0.989
ϕ	Simulated	0.032	0.085	0.050	0.048	0.054
γ_1	Simulated	0.060	0.064	0.063	0.063	0.063
φ_L	Simulated	0.003	0.031	0.018	0.016	0.021
χ	Simulated	0.014	0.527	0.254	0.233	0.284

Notes: “Low” and “high” denotes the bounds of the 90% probability interval for each parameter.

TABLE 2. Prior and posterior distributions of shock parameters

Parameter	Prior			Posterior		
	Distribution	low	high	Mode	Low	High
ρ_L	Beta	0.025	0.776	0.998	0.997	0.999
ρ_ϑ	Beta	0.025	0.776	0.958	0.931	0.983
ρ_m	Beta	0.025	0.776	0.990	0.972	0.997
ρ_{zp}	Beta	0.025	0.776	0.256	0.138	0.369
ρ_{zm}	Beta	0.025	0.776	0.913	0.854	0.932
ρ_ξ	Beta	0.025	0.776	0.977	0.938	0.987
σ_L	Inv-Gamma	1.00e-04	2.000	0.097	0.089	0.133
σ_ϑ	Inv-Gamma	1.00e-04	2.000	0.078	0.071	0.088
σ_m	Inv-Gamma	1.00e-04	2.000	0.019	0.017	0.021
σ_{zp}	Inv-Gamma	1.00e-04	2.000	0.012	0.010	0.013
σ_{zm}	Inv-Gamma	1.00e-04	2.000	0.014	0.013	0.016
σ_ξ	Inv-Gamma	1.00e-04	2.000	0.026	0.024	0.041

Notes: “Low” and “high” denotes the bounds of the 90% probability interval for each parameter.

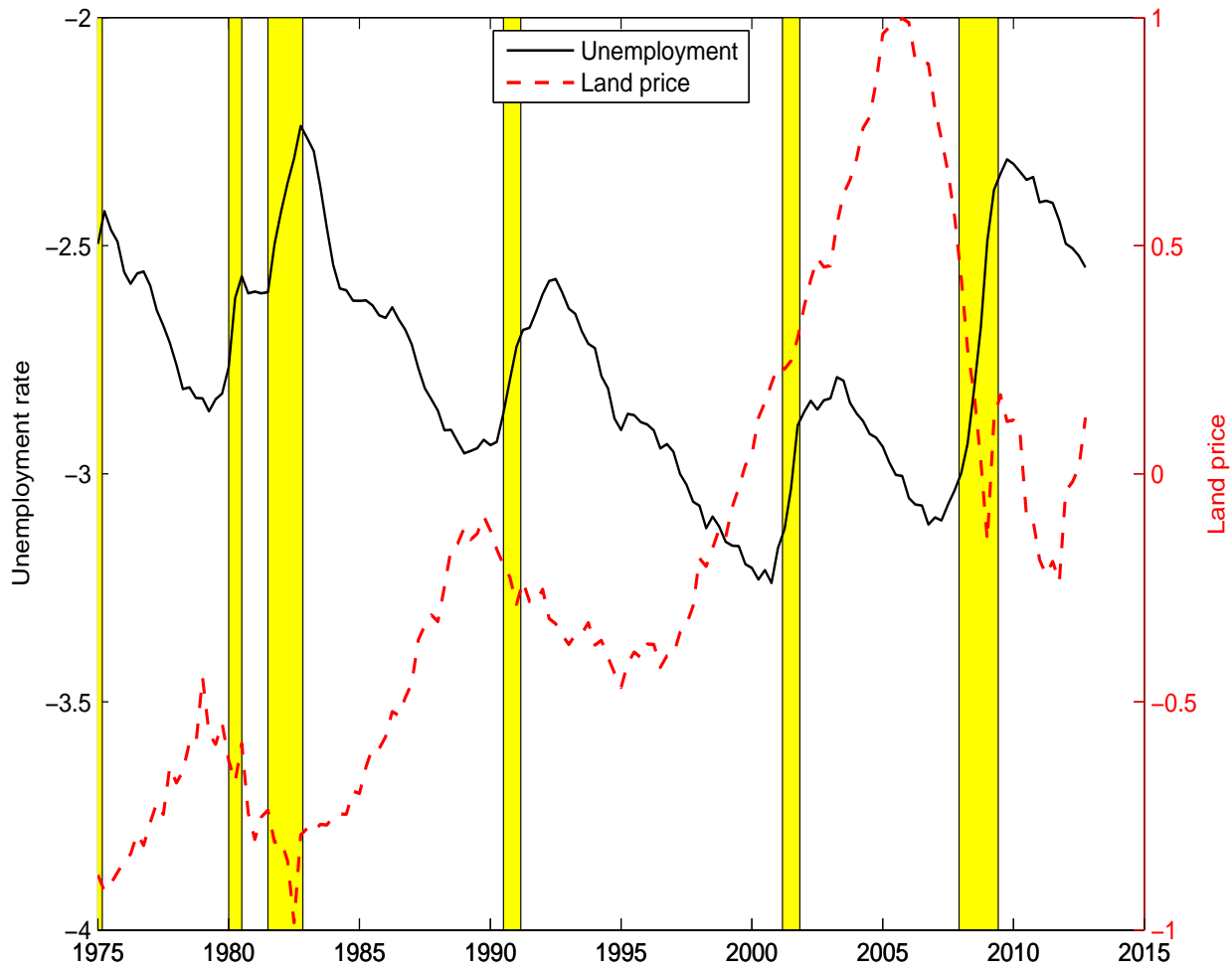


FIGURE 1. Log unemployment rate (left scale) and log real land price (right scale). The shaded bars mark the NBER recession dates.

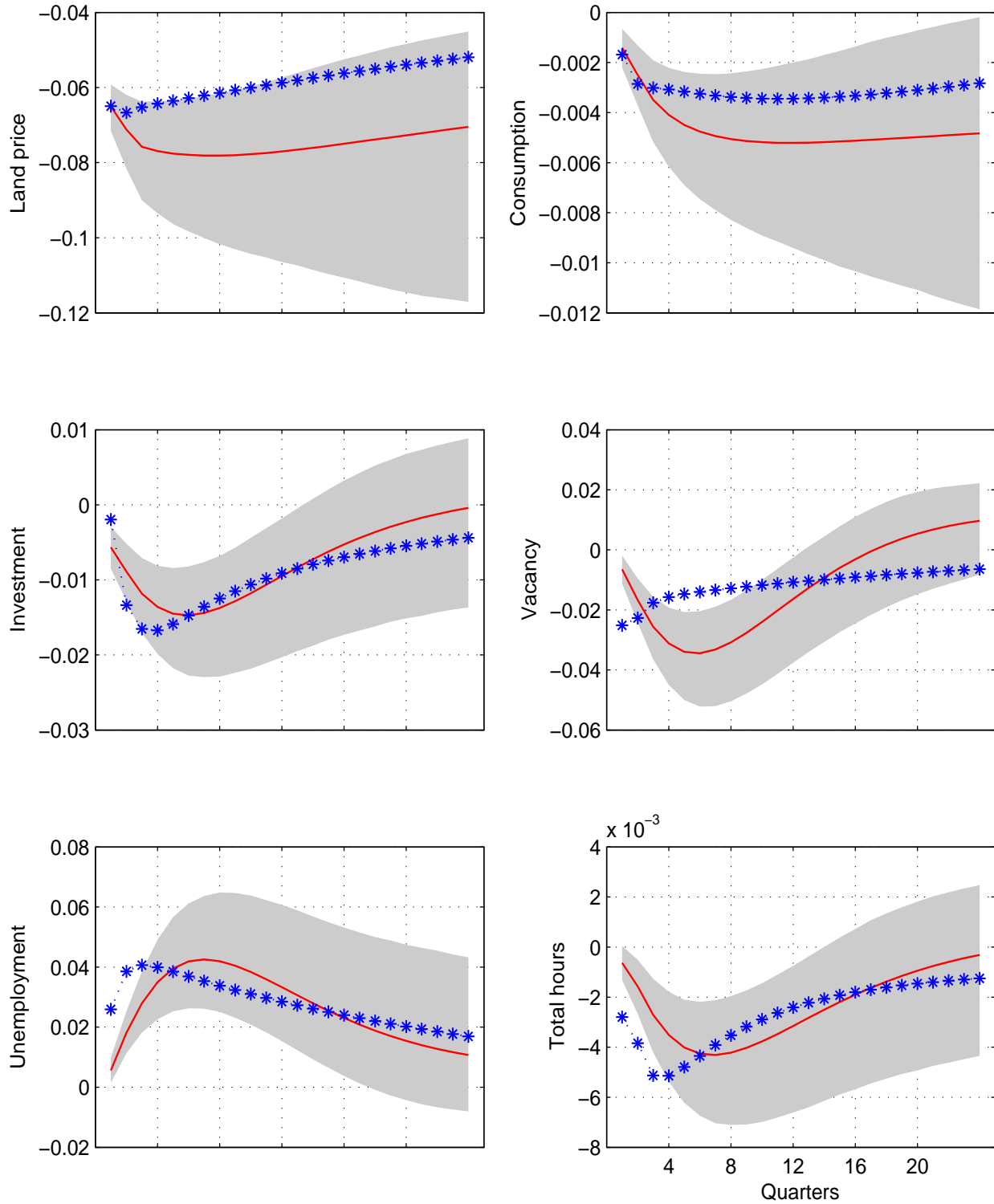


FIGURE 2. Impulse responses to a shock to the land price from a recursive BVAR model with the land price ordered first and with the Sims and Zha (1998)'s prior. All variables are in log level. Solid lines represent the estimated responses and the shaded area represents the 90% probability bands from the BVAR model. Asterisk lines represent the estimated responses to a housing demand shock in the DSGE model.

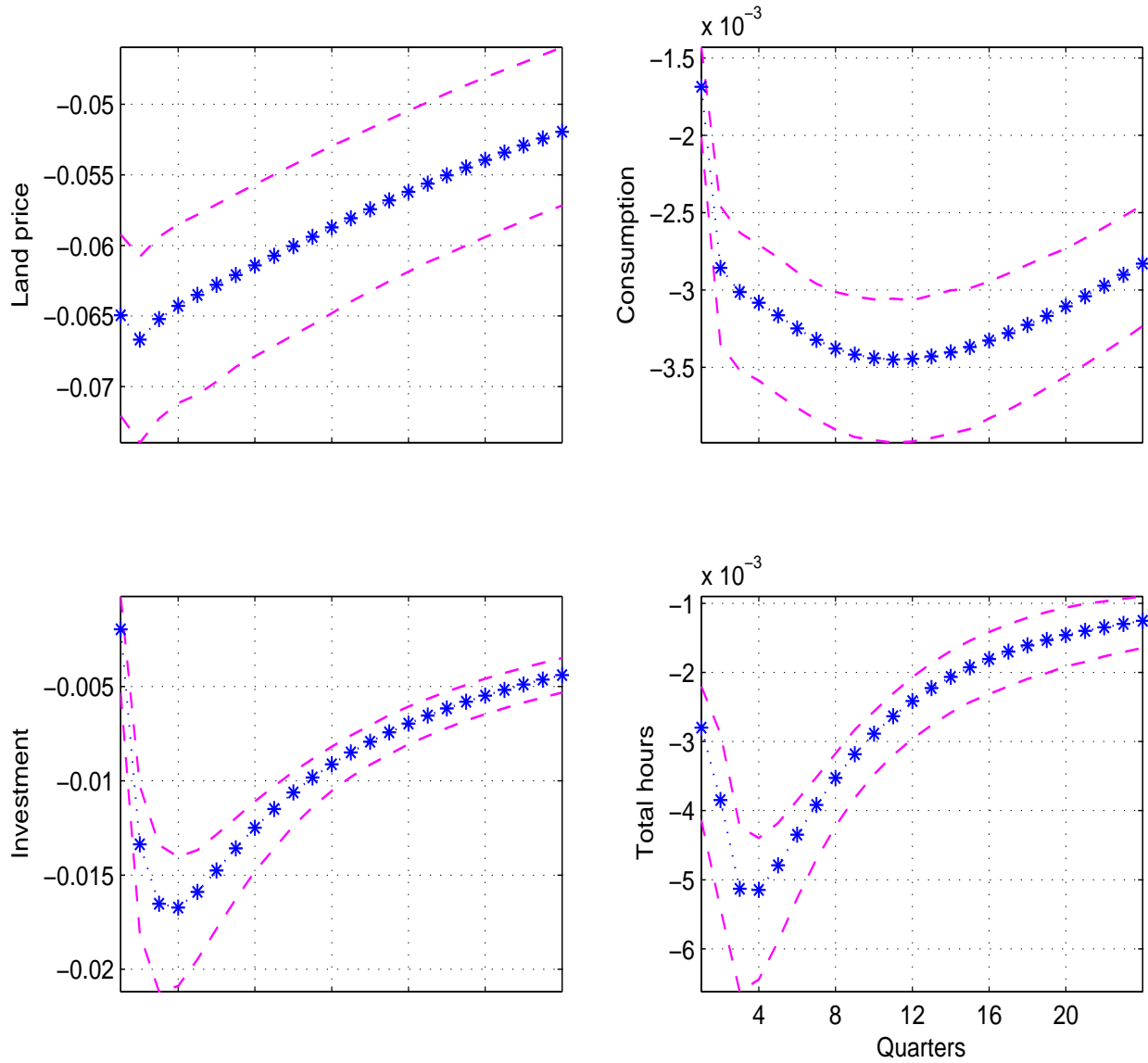


FIGURE 3. Impulse responses of standard macroeconomic variables to a negative one-standard-deviation shock to housing demand. Asterisk lines represent the estimated responses and dashed lines demarcate the 90% probability bands. Total hours is equal to $h_t N_t$.

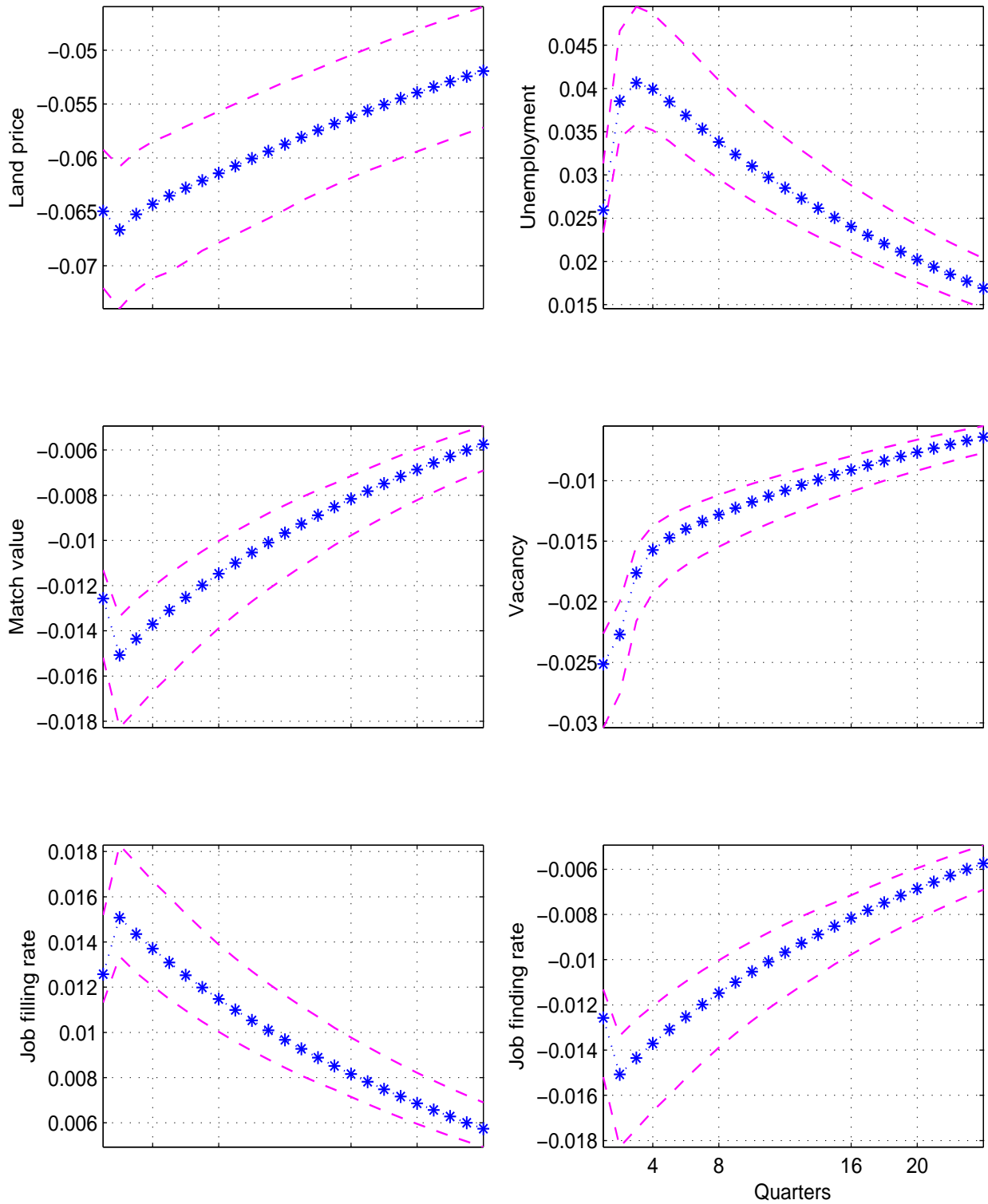


FIGURE 4. Impulse responses of labor-market variables to a negative one-standard-deviation shock to housing demand. Asterisk lines represent the estimated responses and dashed lines demarcate the 90% probability bands.

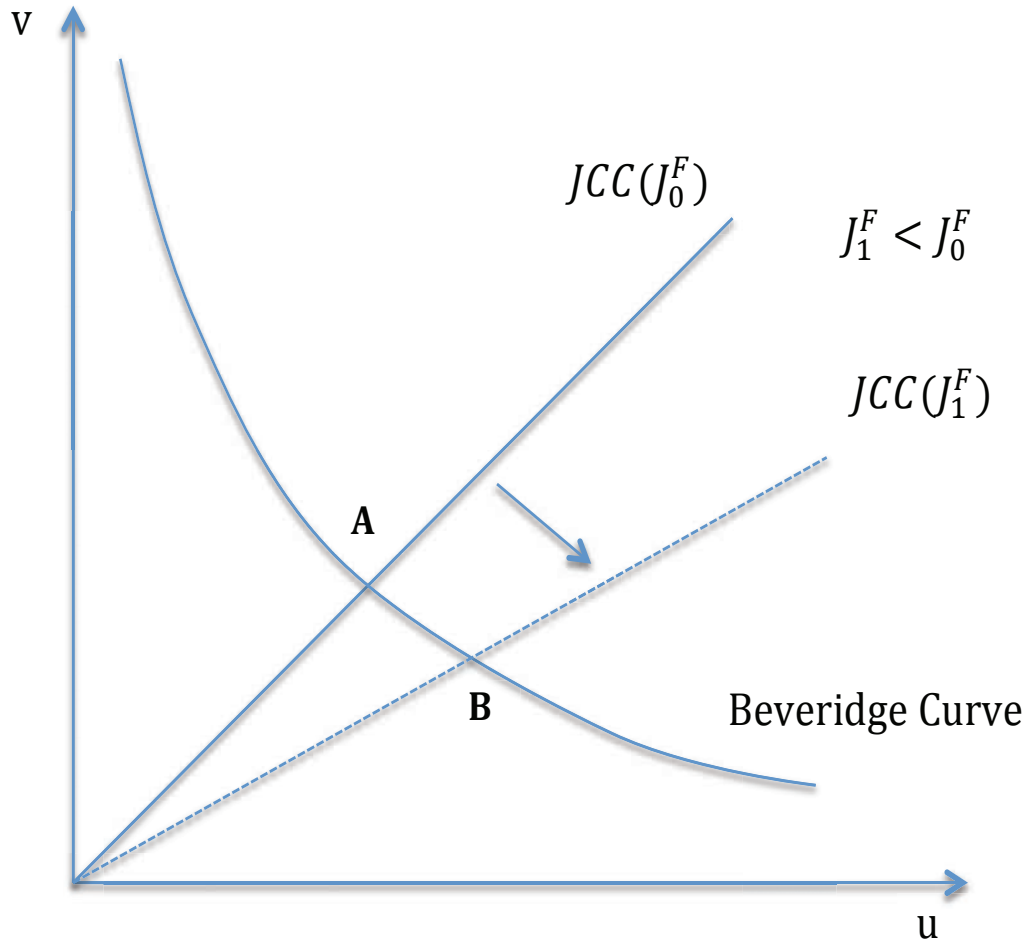


FIGURE 5. Transmission mechanism through search-matching frictions in the labor market: An illustration. JCC stands for the job creation curve and J^F is the value of a new employment match.

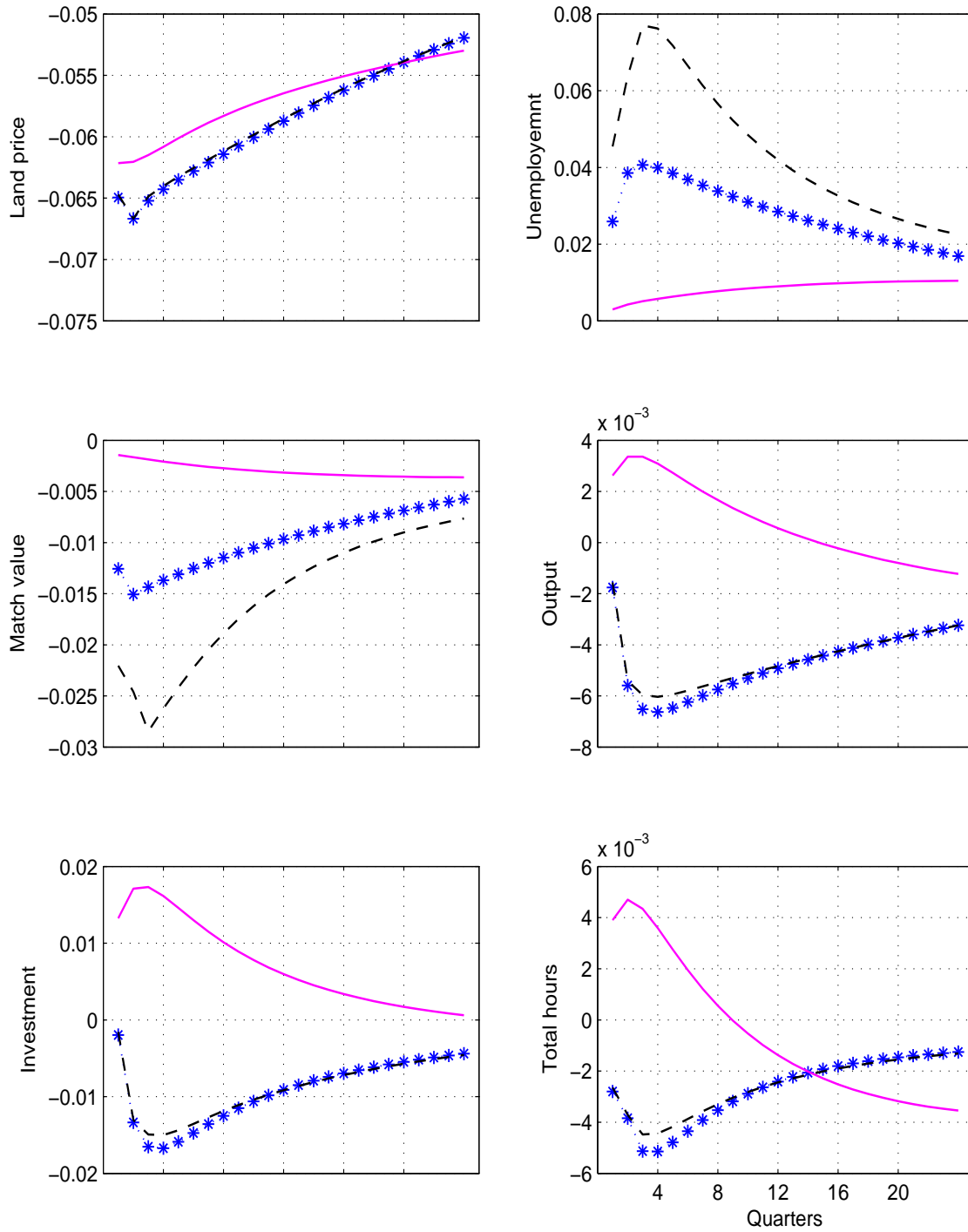


FIGURE 6. Impulse responses to a negative one-standard-deviation shock to the housing demand in the estimated model and in the two counterfactual models. Asterisk lines represent the estimated responses, solid lines represent the responses in the counterfactual economy in which credit does not respond to changes in asset values, and dashed lines represent the responses in the counterfactual economy in which each worker's hours do not adjust. Total hours are equal to $h_t N_t$.

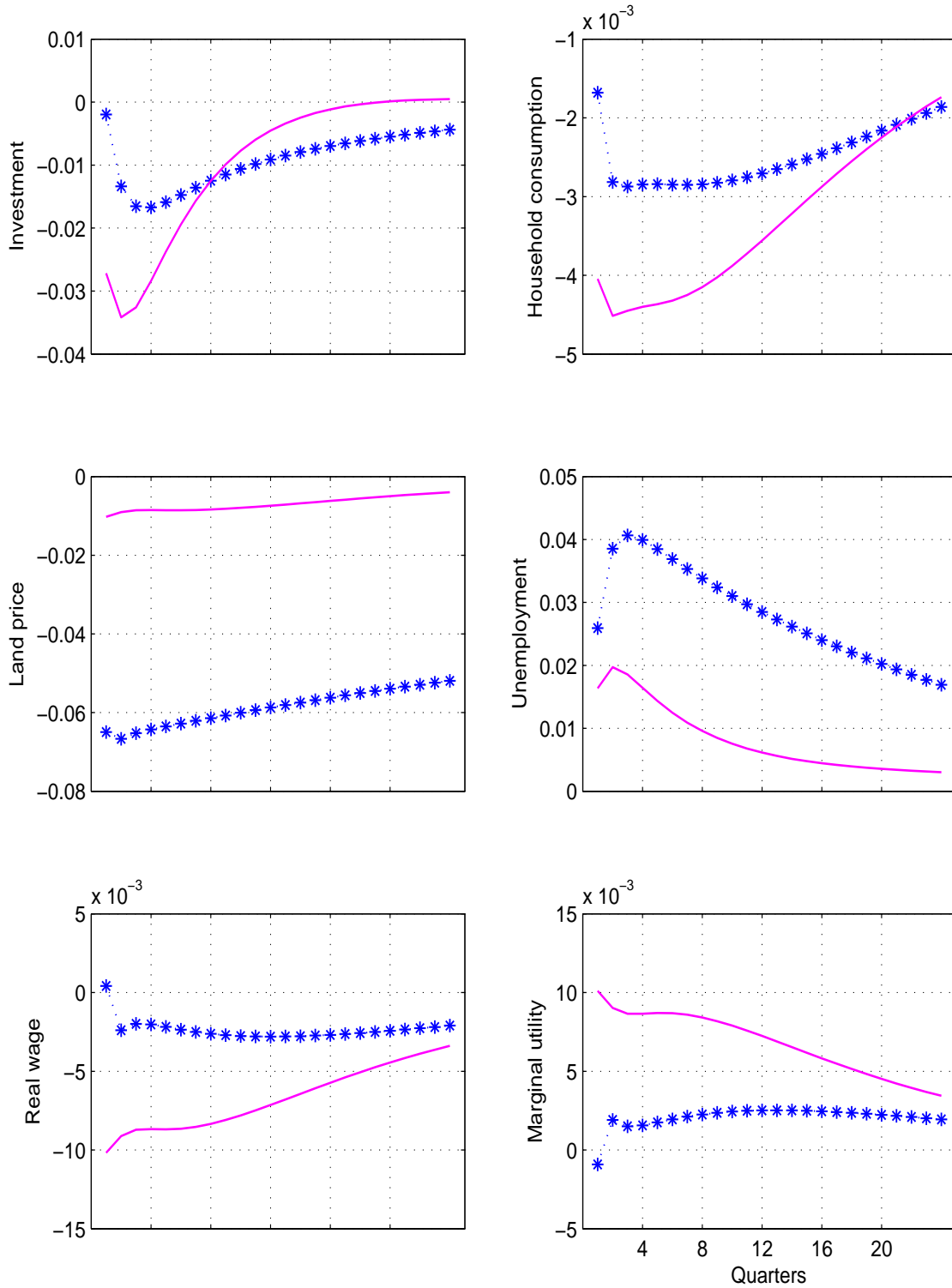


FIGURE 7. Impulse responses to a negative one-standard-deviation housing demand shock (asterisk lines) vs those to a negative stationary technology shock (solid lines). The label “Marginal utility” is the marginal utility of households’ consumption.

APPENDIX A. AN EQUIVALENT SETUP WITH THE LARGE REPRESENTATIVE FIRM

In this appendix, we show that our model in the text is equivalent to an alternative setup with one large representative firm as in the real business cycles (RBC) literature.⁶ In this alternative setup, the decision problems for households and capitalists are identical to those in the baseline model presented in the text. The environment for firms is different. Instead of the one-firm one-worker setup in the baseline model, we assume that there is one large representative firm. The firm employs N_t workers in each period, combined with capital and land to produce output. The firm bargains with the marginal worker who is seeking for a job to determine the wage rate and average hours. Once the wage rate and hours are determined, they apply to all active workers. We continue to assume that capitalists own the firm.

We begin with the representative household's problem. Denote by $V_{ht}(N_{t-1})$ the value function of the household. It satisfies the Bellman equation:

$$V_{ht}(N_{t-1}) = \max_{C_{ht}, L_{ht}, B_{ht}} \frac{(L_{ht}^{\varphi} L_t (C_{ht} - \eta_h C_{ht-1}) / Z_t^p)^{1-\gamma}}{1-\gamma} - \chi g(h_t) N_t + \beta_h E_t V_{ht+1}(N_t),$$

subject to the budget constraint (4). We define the household surplus in consumption units as

$$S_t^H \equiv \frac{1}{\Lambda_{ht}} \frac{\partial V_{ht}(N_{t-1})}{\partial N_t}. \quad (\text{A1})$$

This is the marginal value to the household when a new member is employed. Note that we consider a marginal change in N_t because a newly hired worker immediately starts working as in Blanchard and Galí (2010).

By the envelope condition,

$$\begin{aligned} \frac{\partial V_{ht}(N_{t-1})}{\partial N_t} &= \Lambda_{ht} (W_t h_t - b Z_t^p) - \chi_t g(h_t) + \beta_h E_t \frac{\partial V_{ht+1}(N_t)}{\partial N_t} \\ &= \Lambda_{ht} (W_t h_t - b Z_t^p) - \chi_t g(h_t) + \beta_h E_t \frac{\partial V_{ht+1}(N_t)}{\partial N_{t+1}} \frac{\partial N_t}{\partial N_{t+1}}, \end{aligned} \quad (\text{A2})$$

where marginal utility of consumption Λ_{ht} is equal to the Lagrange multiplier associated with the budget constraint (4).

Note that

$$\begin{aligned} N_t &= (1 - \rho) N_{t-1} + m_t \\ &= (1 - \rho) N_{t-1} + q_t^u u_t \\ &= (1 - \rho) N_{t-1} + q_t^u [1 - (1 - \rho) N_{t-1}]. \end{aligned}$$

⁶See Pissarides (2000) for a related discussion.

Since the household takes the job finding rate q_t^u as given when an additional worker is hired, one can compute that

$$\frac{\partial N_t}{\partial N_{t-1}} = (1 - \rho) - q_t^u (1 - \rho) = (1 - q_t^u) (1 - \rho). \quad (\text{A3})$$

Substituting (A1) and (A3) into (A2), we obtain

$$S_t^H = W_t h_t - b Z_t^p - \frac{1}{\Lambda_{ht}} \chi_t g(h_t) + E_t \frac{\beta_h \Lambda_{ht+1}}{\Lambda_{ht}} (1 - q_{t+1}^u) (1 - \rho) S_{t+1}^H.$$

This equation shows that S_t^H corresponds to $J_t^W - J_t^U$ in Section III.5.

Now, consider the representative firm's problem. The firm chooses capital and labor inputs and posts vacancies to maximize the present value of dividends. The flow dividend is given by

$$D_t = Y_t - R_{kt} k_t N_t - R_{lt} l_{ct} N_t - W_t h_t N_t - v_t \kappa Z_t^p,$$

where

$$Y_t = Z_t^{1-\alpha+\phi\alpha} \left(l_{ct}^\phi k_t^{1-\phi} \right)^\alpha h_t^{1-\alpha} N_t = y_t N_t.$$

The firm's value, denoted as $P_t(N_{t-1})$, satisfies the Bellman equation

$$P_t(N_{t-1}) = \max_{k_t, l_{ct}, v_t} D_t + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} P_{t+1}(N_t), \quad (\text{A4})$$

subject to

$$N_t = (1 - \rho) N_{t-1} + q_t^v v_t. \quad (\text{A5})$$

Since the firm takes q_t^v as given when choosing vacancies v_t , equation (A5) implies that

$$\frac{\partial N_t}{\partial N_{t-1}} = 1 - \rho. \quad (\text{A6})$$

The first-order conditions for k_t , l_{ct} , and v_t are given by

$$R_{kt} = \frac{\partial y_t}{\partial k_t}, \quad R_{lt} = \frac{\partial y_t}{\partial l_{ct}}, \quad \kappa Z_t^p = \frac{\partial P_t(N_t)}{\partial N_t} q_t^v. \quad (\text{A7})$$

By the envelope condition

$$\begin{aligned} \frac{\partial P_t(N_{t-1})}{\partial N_{t-1}} &= \frac{\partial N_t}{\partial N_{t-1}} \left(\frac{\partial Y_t}{\partial N_t} - W_t h_t \right) + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} \frac{\partial P_{t+1}(N_t)}{\partial N_t} \frac{\partial N_t}{\partial N_{t-1}} \\ &= \left[y_t - R_{kt} k_t - R_{lt} l_{ct} - W_t h_t + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} \frac{\partial P_{t+1}(N_t)}{\partial N_t} \right] (1 - \rho), \end{aligned}$$

where we have used equation (A6).

Define the firm surplus as

$$S_t^F \equiv \frac{\partial P_t(N_{t-1})}{\partial N_t} = \frac{\partial P_t(N_{t-1})}{\partial N_{t-1}} \frac{\partial N_{t-1}}{\partial N_t} = \frac{\partial P_t(N_{t-1})}{\partial N_{t-1}} \frac{1}{1 - \rho},$$

where we have used equation (A6) again. Combining the above two equations, we obtain

$$S_t^F = y_t - R_{kt} k_t - R_{lt} l_{ct} - W_t h_t + E_t \frac{\beta_c \Lambda_{ct+1}}{\Lambda_{ct}} (1 - \rho) S_{t+1}^F.$$

Note that S_t^F corresponds to J_t^F in Section III.5. Thus, the last equation in (A7) corresponds to the free-entry condition (24).

Wages and hours are determined by Nash bargaining between the marginal worker and the representative firm. As in the standard DMP framework, when an additional worker is hired, surplus is computed as the marginal value to the household as well as to the firm. The Nash bargaining problem is given by

$$\max_{W_t, h_t} (S_t^H)^{\frac{\vartheta_t}{1+\vartheta_t}} (S_t^F)^{\frac{1}{1+\vartheta_t}},$$

which is the same as the problem (27).

It is straightforward to show that this alternative setup of labor-market frictions produces equilibrium dynamics identical to those in the baseline model presented in Section III.

APPENDIX B. EQUILIBRIUM CONDITIONS

We summarize, below, the stationary equilibrium conditions in the baseline model described in Section III. The model features stochastic growth driven by the permanent technology shock. To obtain stationarity we transform the variables as follows:

$$\begin{aligned} \tilde{C}_{ht} &= \frac{C_{ht}}{Z_t^p}, & \tilde{C}_{ct} &= \frac{C_{ct}}{Z_t^p}, & \tilde{I}_t &= \frac{I_t}{Z_t^p}, & \tilde{K}_t &= \frac{K_t}{Z_t^p}, & \tilde{Y}_t &= \frac{Y_t}{Z_t^p}, & \tilde{B}_t &= \frac{B_t}{Z_t^p}, & \tilde{T}_t &= \frac{T_t}{Z_t^p}, \\ \tilde{Q}_{lt} &= \frac{Q_{lt}}{Z_t^p}, & \tilde{R}_{lt} &= \frac{R_{lt}}{Z_t^p}, & \tilde{W}_t &= \frac{W_t}{Z_t^p}, & \tilde{W}_t^{NB} &= \frac{W_t^{NB}}{Z_t^p}, & \tilde{S}_t &= \frac{S_t}{Z_t^p}, & \tilde{\Lambda}_{ct} &= \Lambda_{ct} Z_t^p, \\ \tilde{\Lambda}_{ht} &= \Lambda_{ht} Z_t^p, & \tilde{\mu}_t &= \mu_t Z_t^p, & \tilde{J}_t^F &= \frac{J_t^F}{Z_t^p}, & \tilde{J}_t^w &= \frac{J_t^w}{Z_t^p}, & \tilde{J}_t^u &= \frac{J_t^u}{Z_t^p}. \end{aligned}$$

The stationary equilibrium is summarized by a system of 32 equations for 32 variables. The 32 variables are $\tilde{\mu}_t, Q_{kt}, \tilde{Q}_{lt}, \tilde{B}_t, \gamma_{lt}, \tilde{I}_t, e_t, \tilde{\Lambda}_{ct}, \tilde{C}_{ht}, R_t, L_{ht}, \tilde{\Lambda}_{ht}, m_t, q_t^u, q_t^v, N_t, u_t, \tilde{Y}_t, R_{kt}, \tilde{R}_{lt}, \tilde{K}_t, \tilde{C}_t, L_{ct}, v_t, \widetilde{MUL}_t, \tilde{W}_t, \tilde{C}_{ct}, U_t, \tilde{J}_t^F, \tilde{J}_t^W, \tilde{J}_t^U$, and h_t . The 32 equations, displayed below, are in the same order as in our computer code.

(1) Capitalist's bond Euler equation:

$$\frac{1}{R_t} = E_t \beta_c \frac{\tilde{\Lambda}_{c,t+1}}{\tilde{\Lambda}_{ct} \lambda_{z,t+1}} + \frac{\tilde{\mu}_t}{\tilde{\Lambda}_{ct}}. \quad (\text{A8})$$

(2) Capitalist's capital Euler equation:

$$Q_{kt} = E_t \beta_c \frac{\tilde{\Lambda}_{c,t+1}}{\tilde{\Lambda}_{ct} \lambda_{z,t+1}} [R_{k,t+1} e_{t+1} - \Phi(e_{t+1}) + (1 - \delta) Q_{k,t+1}] + \frac{\tilde{\mu}_t}{\tilde{\Lambda}_{ct}} \omega_2 \xi_t E_t Q_{k,t+1} \quad (\text{A9})$$

(3) Capitalist's land Euler equation:

$$\tilde{Q}_{lt} = E_t \beta_c \frac{\tilde{\Lambda}_{ct+1}}{\tilde{\Lambda}_{ct}} [\tilde{Q}_{l,t+1} + \tilde{R}_{l,t+1}] + \frac{\tilde{\mu}_t}{\tilde{\Lambda}_{ct}} \omega_1 \xi_t E_t \tilde{Q}_{l,t+1} \lambda_{z,t+1}. \quad (\text{A10})$$

(4) Borrowing constraint:

$$\tilde{B}_t = \xi_t E_t \left(\omega_1 \tilde{Q}_{l,t+1} \lambda_{z,t+1} L_{ct} + \omega_2 Q_{k,t+1} \tilde{K}_t \right). \quad (\text{A11})$$

(5) Investment growth rate:

$$\frac{I_t}{I_{t-1}} \equiv \gamma_{It} = \frac{\tilde{I}_t}{\tilde{I}_{t-1}} \lambda_{zt}. \quad (\text{A12})$$

(6) Capitalist's investment Euler equation:

$$\begin{aligned} 1 &= Q_{kt} \varphi_{It} \left[1 - \frac{\Omega}{2} (\gamma_{It} - \gamma_I)^2 - \Omega (\gamma_{It} - \gamma_I) \gamma_{It} \right] \\ &+ E_t \beta_c \frac{\tilde{\Lambda}_{c,t+1}}{\tilde{\Lambda}_{ct} \lambda_{z,t+1}} Q_{kt+1} \varphi_{I,t+1} \Omega (\gamma_{I,t+1} - \gamma_I) \gamma_{I,t+1}^2. \end{aligned} \quad (\text{A13})$$

(7) Capacity utilization decision:

$$R_{kt} = \gamma_2 (e_t - 1) + \gamma_1. \quad (\text{A14})$$

(8) Capitalist's marginal utility

$$\tilde{\Lambda}_{ct} = \frac{1}{\tilde{C}_{ct} - \eta_c \tilde{C}_{c,t-1} / \lambda_{zt}} - E_t \frac{\beta_c \eta_c}{\tilde{C}_{c,t+1} \lambda_{z,t+1} - \eta_c \tilde{C}_{ct}}. \quad (\text{A15})$$

(9) Household's flow-of-funds constraint:

$$\tilde{C}_{ht} + \frac{\tilde{B}_t}{R_t} + \tilde{Q}_{lt} (L_{ht} - L_{h,t-1}) = \frac{\tilde{B}_{t-1}}{\lambda_{zt}} + \tilde{W}_t h_t N_t, \quad (\text{A16})$$

where we have substituted out the lump-sum taxes using the government budget constraint.

(10) Household's bond Euler equation:

$$\frac{1}{R_t} = E_t \beta_h \frac{\tilde{\Lambda}_{h,t+1}}{\tilde{\Lambda}_{ht} \lambda_{z,t+1}}. \quad (\text{A17})$$

(11) Household's land Euler equation:

$$\tilde{Q}_{lt} = MRS_{lt} + E_t \beta_h \frac{\tilde{\Lambda}_{h,t+1}}{\tilde{\Lambda}_{ht}} \tilde{Q}_{l,t+1}, \quad (\text{A18})$$

where the marginal rate of substitution between housing and consumption is given by

$$MRS_{lt} = \frac{\widetilde{MUL}_t}{\tilde{\Lambda}_{ht}}.$$

(12) Household's marginal utility of consumption

$$\begin{aligned} \tilde{\Lambda}_{ht} &= L_{ht}^{\varphi_{Lt}(1-\gamma)} \left(\tilde{C}_{ht} - \frac{\eta_h \tilde{C}_{h,t-1}}{\lambda_{zt}} \right)^{-\gamma} \\ &- \beta_h \eta_h E_t \left[L_{h,t+1}^{(1-\gamma)\varphi_{L,t+1}} \left(\tilde{C}_{h,t+1} - \frac{\eta_h \tilde{C}_{h,t}}{\lambda_{z,t+1}} \right)^{-\gamma} \frac{1}{\lambda_{z,t+1}} \right]. \end{aligned} \quad (\text{A19})$$

(13) Household's marginal utility of housing

$$\widetilde{MUL}_t = \varphi_{Lt} L_{ht}^{\varphi_{Lt}(1-\gamma)-1} \left(\tilde{C}_{ht} - \eta_h \frac{\tilde{C}_{ht-1}}{\lambda_{zt}} \right)^{1-\gamma}. \quad (\text{A20})$$

(14) Matching function

$$m_t = \varphi_{mt} u_t^a v_t^{1-a}. \quad (\text{A21})$$

(15) Job finding rate

$$q_t^u = \frac{m_t}{u_t}. \quad (\text{A22})$$

(16) Vacancy filling rate

$$q_t^v = \frac{m_t}{v_t}. \quad (\text{A23})$$

(17) Employment dynamics:

$$N_t = (1 - \rho) N_{t-1} + m_t. \quad (\text{A24})$$

(18) Number of searching workers:

$$u_t = 1 - (1 - \rho) N_{t-1}. \quad (\text{A25})$$

(19) Aggregate production function:

$$\tilde{Y}_t = \left[(Z_t^m L_{c,t-1})^\phi \left(\frac{e_t \tilde{K}_{t-1}}{\lambda_{zt}} \right)^{1-\phi} \right]^\alpha (Z_t^m h_t N_t)^{1-\alpha}. \quad (\text{A26})$$

(20) Capital rental rate:

$$R_{kt} = \alpha(1 - \phi) \frac{\tilde{Y}_t \lambda_{zt}}{e_t \tilde{K}_{t-1}}. \quad (\text{A27})$$

(21) Land rental rate:

$$\tilde{R}_{lt} = \alpha \phi \frac{\tilde{Y}_t}{L_{c,t-1}}. \quad (\text{A28})$$

(22) Capital law of motion:

$$\tilde{K}_t = (1 - \delta) \frac{\tilde{K}_{t-1}}{\lambda_{zt}} + \varphi_{It} \left[1 - \frac{\Omega}{2} (\gamma_{It} - \gamma_I)^2 \right] \tilde{I}_t. \quad (\text{A29})$$

(23) Aggregate Resource constraint:

$$\tilde{C}_t + \tilde{I}_t + \tilde{G}_t + \Phi(e_t) \frac{\tilde{K}_{t-1}}{\lambda_{zt}} + \kappa v_t = \tilde{Y}_t. \quad (\text{A30})$$

(24) Land market clears (normalize aggregate supply of land to $L = 1$):

$$L_{ct} + L_{ht} = 1. \quad (\text{A31})$$

(25) Optimal vacancy posting:

$$\frac{\kappa}{q_t^v} = (1 - \alpha) \frac{\tilde{Y}_t}{N_t} - \tilde{W}_t h_t + E_t \frac{\beta_c \tilde{\Lambda}_{c,t+1}}{\tilde{\Lambda}_{ct}} (1 - \rho) \frac{\kappa}{q_{t+1}^v}. \quad (\text{A32})$$

(26) Nash bargaining wage:

$$\tilde{W}_t h_t = \frac{\chi_t g(h_t)}{\tilde{\Lambda}_{ht}} + b + \vartheta_t \frac{\kappa}{q_t^v} - E_t \frac{\beta_h \tilde{\Lambda}_{h,t+1}}{\tilde{\Lambda}_{ht}} \left[(1 - \rho) (1 - q_{t+1}^u) \vartheta_{t+1} \frac{\kappa}{q_{t+1}^v} \right], \quad (\text{A33})$$

where

$$g(h_t) = \frac{h_t^{1+\nu}}{1+\nu}, \quad \nu \geq 0.$$

(27) Aggregate consumption

$$\tilde{C}_t = \tilde{C}_{ht} + \tilde{C}_{ct}. \quad (\text{A34})$$

(28) Unemployment rate:

$$U_t = 1 - N_t. \quad (\text{A35})$$

(29) The value of the firm:

$$\tilde{J}_t^F = \frac{\kappa}{q_t^v}. \quad (\text{A36})$$

(30) The value of employment:

$$\tilde{J}_t^W = \tilde{W}_t h_t - \frac{\chi_t g(h_t)}{\tilde{\Lambda}_{ht}} + E_t \frac{\beta_h \tilde{\Lambda}_{h,t+1}}{\tilde{\Lambda}_{ht}} \left[(1 - \rho) (1 - q_{t+1}^u) \left(\tilde{J}_{t+1}^W - \tilde{J}_{t+1}^U \right) + \tilde{J}_{t+1}^U \right]. \quad (\text{A37})$$

(31) The value of unemployment:

$$\tilde{J}_t^U = b + E_t \frac{\beta_h \tilde{\Lambda}_{ht+1}}{\tilde{\Lambda}_{ht}} \left[q_{t+1}^u \tilde{J}_{t+1}^W + (1 - q_{t+1}^u) \tilde{J}_{t+1}^U \right]. \quad (\text{A38})$$

(32) Bargaining solution for hours:

$$\frac{\chi_t g'(h_t)}{\Lambda_{ht}} = (1 - \alpha) \frac{Y_t}{N_t h_t}. \quad (\text{A39})$$

APPENDIX C. DATA AND SHOCKS

C.1. Data description. All data are constructed by Patrick Higgins at the Federal Reserve Bank of Atlanta. Some of the data are taken directly from the Haver Analytics Database (Haver for short). This section describes, in detail, how the data are constructed.

The model estimation is based on six U.S. aggregate time series: the real price of land (Q_{lt}^{Data}), real per capita consumption (C_t^{Data}), real per capita investment (I_t^{Data}), vacancies (v_t^{Data}), the unemployment rate (U_t^{Data}), and per capita total hours (H_t^{Data}). All these series are constructed to be consistent with the corresponding series in Greenwood, Hercowitz, and Krusell (1997), Cummins and Violante (2002), and Davis and Heathcote (2007). Since the

earliest date for the land price data to be available is the first quarter of 1975, the sample period used for this paper range from the first quarter of 1975 to the fourth quarter of 2012.

These series are defined as follows:

- $Q_{tt}^{\text{Data}} = \frac{\text{LiqLandPricesSAFHFACoreLogicSplice87}}{\text{DGDP@USNA}};$
- $C_t^{\text{Data}} = \frac{(\text{NomConsNHSplusND})/\text{DGDP@USNA}}{\text{POPSMOOTH@USECON}};$
- $I_t^{\text{Data}} = \frac{(\text{CD@USECON} + \text{FNE@USECON})/\text{DGDP@USNA}}{\text{POPSMOOTH@USECON}};$
- $v_t^{\text{Data}} = \frac{\text{JOLTS Higgins}}{\text{JOLTS Higgins} + \text{LANAGRA@USECON}};$
- $U_t^{\text{Data}} = \text{UnempRate};$
- $H_t^{\text{Data}} = \frac{\text{TotalHours}}{\text{POPSMOOTH@USECON}}.$

The original data, the constructed data, and their sources are described below.

LiqLandPricesSAFHFACoreLogicSplice87: Liquidity-adjusted price index for residential land. The series is constructed as follows. We seasonally adjust the FHFA home price index (USHPI@USECON) for 1975Q1-1991Q1, spliced together with Haver’s seasonally adjusted CoreLogic home price index (USLPHPIS@USECON) for the third month of the first quarter of 1987 to present. We then use this home price index to construct the land price series with the Davis and Heathcote (2007) method.⁷ The adjustment methods of Quart and Quigley (1989, 1991) are used to take account of time-on-market uncertainty. The CoreLogic home price index series provided by Core Logic Databases is similar to the Case-Shiller home price index but covers far more counties than the Case-Shiller series.

The CoreLogic land price, as well as the Cash-Shiller land price, shows much larger fluctuations than the FHFA land price. The large difference comes mainly from home price indices. The FHFA home price series includes only conforming/conventional mortgages insured by Fannie Mae and Freddie Mac and excludes subprime or expensive homes with mortgages above the conforming loan limit (\$417,000 in 2008 for example). The FHFA series is an equally weighted home price index so that expensive homes receive the same weight as inexpensive homes. The CoreLogic and Case-Shiller series are both value-weighted so that a home’s weight in the index is (roughly) proportional to its price. The FHFA series is perhaps representative of the home price before 1987. But in the 1990s and 2000s, subprime or un-conforming mortgages were so popular that an exclusion of the prices of such homes would bias against the actual volatility of home/land prices. The volatility of our CoreLogic land price series is similar to the land price series constructed in other studies (Sirmans and Slade, 2012; Nichols, Oliner, and Mulhall, 2013).

⁷For details of this methods, see http://www.marginalq.com/morris/landdata_files/2006-11-Davis-Heathcote-Land.appendix.pdf.

Nonetheless, our results obtain when we use the FHFA land price constructed in the same way except that the CoreLogic home price index is replaced by the FHFA home price index.

Source for USHPI@USECON and USLPHPIS@USECON: BEA and Haver.

DGDP@USNA: Implicit gross domestic product deflator (2005=100). The results in the paper obtain when we use other overall price indices, such as consumer price index and personal consumption expenditure index.

NomConsNHSplusND: Nominal personal consumption expenditures: non-housing services and nondurable goods (seasonally adjusted). Source: BEA and Haver.

POPSMOOTH@USECON: Smoothed civilian noninstitutional population with ages 16 years and over (thousands). This series is smoothed by eliminating breaks in population from 10-year censuses and post 2000 American Community Surveys using the “error of closure” method. This fairly simple method is used by the Census Bureau to get a smooth monthly population series to reduce the unusual influence of drastic demographic changes.⁸ Source: BLS and Haver.

CD@USECON: Nominal personal consumption expenditures: durable goods (seasonally adjusted). Source: BEA and Haver.

FNE@USECON: Nominal private nonresidential investment: equipment & software (seasonally adjusted). Source: BEA and Haver.

JOLTSHiggins: Job openings. From January 1975 to December 2000, we use the composite Help-Wanted-Index built by Barnichon (2010),⁹ expressed in number of vacancies and rescaled to match its value in December 2000 to LJJTLA@USECON (LJJTLA@USECON is a series of total seasonally adjusted job openings expressed in thousands from the BLS-JOLTS survey that started in December 2000). From January 2001 to present, our series is the same as LJJTLA@USECON. We then take the quarterly average of the monthly series. Source for LJJTLA@USECON: BLS and Haver.

LANAGRA@USECON: BLS nonfarm payroll employment series. The series contains total nonfarm seasonally adjusted employees expressed in thousands. Source: BLS and Haver.

UnempRate: Unemployment rate. Source: BLS and Haver.

TotalHours: Total hours in the nonfarm business sector. Source: BLS and Haver.

⁸The detailed explanation can be found in http://www.census.gov/popest/archives/methodology/intercensal_nat_meth.html.

⁹The series can be downloaded from Regis Barnichon’s website at http://sites.google.com/site/regisbarnichon/cv/HWI_index.txt?attredirects=0.

C.2. **Shocks.** We include six shocks in the model: a housing demand shock (φ_{Lt}), a credit shock (ξ_t), two technology shocks (the permanent shock λ_{zt} and the stationary shock Z_t^m), and two labor market shocks (the matching efficiency shock φ_{mt} and the bargaining shock ϑ_t). Housing demand shocks are shown to be an important driving force of house-price (land-price) fluctuations in DSGE models without labor search frictions (Iacoviello and Neri, 2010; Liu, Wang, and Zha, 2013). Credit shocks are important for macroeconomic fluctuations in a DSGE model with financial frictions (Jermann and Quadrini, 2012). Technology shocks are typically considered as important sources of business cycles in an RBC model.

The matching efficiency shock and the bargaining shock are useful to fit our model to the labor-market data. The matching function describes a reduced-form aggregate relation between the number of hires on one hand and the number of searching workers and job vacancies on the other. There is no presumption that this reduced-form relation holds exactly in the data. In fact, frequent deviations to this relation have been observed. For examples, in our sample, there have been important shifts in the Beveridge curve relation (a relation between the unemployment rate and the job vacancy rate derived from the matching function). Shifts in the Beveridge curve can be captured by variations in the matching efficiency (i.e., the residuals in the matching function).

Recent studies find that incorporating matching efficiency shocks is important for fitting a DSGE model to the labor market data (Lubik, 2009; Justiniano and Michelacci, 2011; Sala, Söderström, and Trigari, 2012). Other studies find that introducing shocks to the relative bargaining power in a DSGE model with search frictions helps fit the data for labor market variables (Gertler, Sala, and Trigari, 2008; Christoffel, Kuester, and Linzert, 2009; Christiano, Trabandt, and Walentin, 2011). We are aware of the legitimate criticism that these shocks do not offer a deeper understanding of the labor market. Since our focus is on the dynamic links between the land price and the unemployment rate, we use these shocks to be consistent with the existing literature as well as for the purpose of fitting the model to the data without insisting on interpretation of these shocks' effect on the labor market.

APPENDIX D. PRIOR DISTRIBUTIONS FOR STRUCTURAL PARAMETERS

We categorize the structural parameters in three groups. The first group of parameters are calibrated because they are difficult to identify by the model. These parameters are a , the elasticity parameter in the matching function; b , the flow benefit of unemployment; ϑ , the Nash bargaining weight; α , the income share of capital input; γ , the relative risk aversion; ξ , the average loan-to-value ratio; ρ , the job separation rate; ω_1 , the fraction of land value that can be used as collateral; and Z^m , the mean of the stationary technology shock.

We set the match elasticity parameter to $a = 0.5$ as suggested by Hall and Milgrom (2008) and Gertler and Trigari (2009), which is in the range estimated by Petrongolo and Pissarides

(2001). Following Christiano, Eichenbaum, and Trabandt (2013), we set the replacement ratio to $\frac{b}{W} = 0.75$, where W is the steady-state real wage.¹⁰ We set the value of ϑ such that the worker's bargaining weight is $\frac{\vartheta}{1+\vartheta} = 0.3$ as estimated by Christiano, Trabandt, and Walentin (2011). We set $\alpha = 0.33$, consistent with the average labor income share of about two-thirds. We set the risk aversion parameter to $\gamma = 2$, in line with in the macroeconomics and finance literature (Kocherlakota, 1996; Lucas Jr., 2003). Following Liu, Wang, and Zha (2013), we set the mean value of the loan-to-value ratio to $\xi = 0.75$. We set the job separation rate to $\rho = 0.12$ as suggested by Blanchard and Galí (2010), which is broadly consistent with the average monthly job separation rate of 0.034 reported in the Job Openings and Labor Turnover Survey (JOLTS). We normalize the values of ω_1 and Z^m to unity.

The second group of structural parameters are estimated. They are η_h and η_c , the habit persistence parameters for households and capitalists; ν , the curvature parameter of the dis-utility function of labor hours; γ_2 , the curvature parameter of the capacity utilization cost function; Ω , the investment adjustment cost parameter; λ_z , the mean growth rate of technology; ω_2 , the fraction of capital value in the collateral constraint; λ_z , the mean growth rate; and all the parameters for shock processes. The complete prior specifications are reported in Tables 3 and 4. Tables 1 and 2 reproduce some of the prior information for comparison with the estimated posterior distributions.

We first discuss Table 3. The prior for the technology growth rate λ_z is such that the 90-percent probability interval for the annualized growth rate lies between 0.4% and 6%.

We assume that the priors for η_h and η_c follow the beta distribution with the hyperparameters taking the values of 1 and 2. This particular specification allows the possibility of no persistence at all for the habit parameters. Clearly, the 90% probability interval covers most of the calibrated values of habit persistence parameters in the literature (Boldrin, Christiano, and Fisher, 2001).

The priors for the remaining parameters to be estimated follow gamma distributions, all of which allow the possibility of zero value. The 90% probability interval for Ω and γ_2 ranges from 0.17 to 10, covering most of the values considered in the DSGE literature (Christiano, Eichenbaum, and Evans, 2005; Smets and Wouters, 2007; Liu, Waggoner, and Zha, 2011). The hyperparameter values for the prior distributions of ν and ω_2 are selected so that the 90% probability intervals for these parameters cover a wide range of values.

We now discuss Table 4. The selected hyperparameters for the prior distributions of all the persistence parameters allow the possibility of zero persistence and at the same time give a wide range of values as shown by the 90% probability intervals. The priors for the standard deviations follow the inverse gamma distribution with the 90% probability interval

¹⁰Our estimated results are insensitive to the value of the replacement ratio. For example, the results hold if we lower the ratio to $\frac{b}{W} = 0.4$ as suggested by Ravenna and Walsh (2008) and Hall (2005).

given by $[0.0001, 2]$. The priors for all these shock process parameters are very agnostic and in fact much looser than those used in the DSGE literature.

The third group of structural parameters are determined by the deterministic steady state, conditional on calibrated and estimated values of the first two groups of parameters. These parameters include δ , the capital depreciation rate; β_h and β_c , the subjective discount factors for households and capitalists; ϕ , the land income share; γ_1 , the slope parameter in the capacity utilization function; φ_L , the steady-state level of the housing demand shock; χ , the scale parameter for the disutility of working; and κ , the vacancy cost parameter.

The values of these parameters are obtained so that the model's steady-state equilibrium matches the following first-moment conditions in the data: (1) the investment-output ratio is 0.26; (2) the average loan interest rate is 4% per year; (3) the average ratio of commercial land value to annual output is about 0.625 (Liu, Wang, and Zha, 2013); (4) the average ratio of capital stock to annual output is 1.25;¹¹ (5) the average ratio of the vacancy cost to output is 0.005 (Christiano, Eichenbaum, and Trabandt, 2013); (6) the steady-state unemployment rate is 0.055; (7) the average quarterly job filling rate is about 0.7 (den Haan, Ramey, and Watson, 2000).

Given the calibrated parameter values, the prior distributions of the first two groups of parameters, and the steady state equilibrium, we simulate the prior distributions for the third group of parameters. The 90% probability intervals for these parameters are reported in the bottom panel of Table 3.

APPENDIX E. ESTIMATION ISSUES

We use our own algorithm to estimate the structural model. One natural question is why we do not avail ourselves of Dynare. There are two layers of problems. First, as one can see from Appendix B, the steady state is too complicated for Dynare to solve it efficiently. Second, the posterior distribution is full of thin winding ridges as well as local peaks, finding its mode has proven to be a difficult task. More than often Dynare either terminates prematurely in finding the peak or stops because of the failure of solving the steady state. At the premature solution, one would conclude with a misleading result that land-price dynamics have very small effects on unemployment.

Our own optimization routine, based on Sims, Waggoner, and Zha (2008) and coded in C/C++, has proven to be both efficient and able to find the posterior mode. The routine relies in part on the Broyden–Fletcher–Goldfarb–Shanno (BFGS) updates of the inverse of the Hessian matrix. When the inverse Hessian matrix is close to be numerically ill-conditioned, our program resets it to a diagonal matrix. Given an initial guess of the values of the parameters, our program uses a combination of a constrained optimization algorithm and

¹¹The capital stock in our model is the value of equipment, software, and consumer durable goods.

TABLE 3. Prior distributions of structural parameters

Description	Parameter	Distribution	a	b	Low	High
Habit (capitalist)	η_c	Beta(a,b)	1.00	2.00	0.025	0.776
Habit (worker)	η_h	Beta(a,b)	1.00	2.00	0.025	0.776
Investment adjustment costs	Ω	Gamma(a,b)	1.00	0.30	0.171	10.00
Capacity utilization (curvature)	γ_2	Gamma(a,b)	1.00	0.30	0.171	10.00
Inverse Frisch elasticity (hours)	ν_h	Gamma(a,b)	1.00	0.60	0.086	5.000
Weight of capital value	ω_2	Gamma(a,b)	1.00	1.00	0.048	2.821
Output growth	$100(\lambda_z - 1)$	Gamma(a,b)	1.86	3.01	0.100	1.500
Depreciation rate	δ	Simulated			0.043	0.051
Worker's discount	β_h	Simulated			0.991	0.999
Capitalist's discount	β_c	Simulated			0.968	0.997
Land share	ϕ	Simulated			0.032	0.085
Capacity utilization (slope)	γ_1	Simulated			0.060	0.064
Housing demand	φ_L	Simulated			0.003	0.031
Disutility of labor hours	χ	Simulated			0.014	0.527

Notes: “Low” and “high” denotes the bounds of the 90% probability interval for each parameter.

an unconstrained BFGS optimization routine, to find a local peak. We then use the local peak to generate a long sequence of Monte Carlo Markov Chain posterior draws. These simulated draws are randomly selected as different starting points for our optimization routine to find a potentially higher peak. We iterate this process until the highest peak is found. The computation typically takes four and a half days on a cluster of five dual-core processors. We are in the process of collaborating with the Dynare team to incorporate our estimation software into the Dynare package.

TABLE 4. Prior distributions of shock parameters

Description	Parameter	Distribution	a	b	Low	High
Persist: Housing demand	ρ_L	Gamma(a,b)	1.0	2.0	0.025	0.776
Persist: Wage bargaining	ρ_ϑ	Gamma(a,b)	1.0	2.0	0.025	0.776
Persist: Matching efficiency	ρ_m	Gamma(a,b)	1.0	2.0	0.025	0.776
Persist: Permanent technology	ρ_{zp}	Gamma(a,b)	1.0	2.0	0.025	0.776
Persist: Stationary technology	ρ_{zm}	Gamma(a,b)	1.0	2.0	0.025	0.776
Persist: Credit constraint	ρ_ξ	Gamma(a,b)	1.0	2.0	0.025	0.776
Std Dev: Housing demand	σ_L	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000
Std Dev: Wage bargaining	σ_ϑ	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000
Std Dev: Matching efficiency	σ_m	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000
Std Dev: Permanent technology	σ_{zp}	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000
Std Dev: Stationary technology	σ_{zm}	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000
Std Dev: Credit constraint	σ_ξ	Inv-Gam(a,b)	0.326	1.45e04	1.00e-04	2.000

Notes: “Low” and “high” denotes the bounds of the 90% probability interval for each parameter.

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