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Spatial Development and Local Technology

Klaus Desmet
Esteban Rossi-Hansberg

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Spatial Development†

By Klaus Desmet and Esteban Rossi-Hansberg*

We present a theory of spatial development. Manufacturing and services firms located in a continuous geographic area choose each period how much to innovate. Firms trade subject to transport costs and technology diffuses spatially. We apply the model to study the evolution of the US economy in the last half-century and find that it can generate the reduction in the manufacturing employment share, the increased spatial concentration of services, the growth in service productivity starting in the mid-1990s, the rise in the dispersion of land rents in the same period, as well as several other spatial and temporal patterns. (*JEL* J21, L16, L60, L80, O33, R11, R32)

Economic development varies widely across space. It is a common observation, as stated in the 2009 World Development Report (World Bank 2009), that the location of people is the best predictor of their income. This is clearly true when we move across countries, but there is also significant variation within countries. In the United States, employment concentration and value added vary dramatically across space, and so does the rate of growth (see, e.g., Desmet and Rossi-Hansberg 2009). Even though a casual look at the spatial landscape makes these observations seem almost trivial, there has been little work incorporating space, and the economic structure implied by space, into modern endogenous growth theories. To address this shortcoming, we present a dynamic theory of spatial development and contrast its predictions with evidence on the spatial evolution of the United States in the postwar period.

The theory we present has four main components. First, it includes a continuum of locations where firms produce in one of two industries: manufacturing and services. Production requires labor and land, with technologies being constant returns to scale in these two inputs. Since the amount of land at a given location is fixed, the actual technology experienced at a location exhibits decreasing returns to scale. This constitutes a congestion force. Second, firms can trade goods and services by incurring iceberg transport costs. Given these costs, national goods markets in both

* Desmet: Department of Economics, Universidad Carlos III, 28903 Getafe, Madrid, Spain (e-mail: klaus.desmet@uc3m.es); Rossi-Hansberg: Department of Economics, Princeton University, 309 Fisher Hall, Princeton, NJ 08544 (e-mail: erossi@princeton.edu). We thank Satyajit Chatterjee, Elhanan Helpman, Robert Helsley, David Lagakos, Gianmarco Ottaviano, Diego Puga, Steve Redding, and various seminar participants for useful comments. Financial support from the Sloan Foundation, the Fundación Ramón Areces, the European Commission (EFIGE 225551), the Bank of Spain Excellence Program, and the Spanish Ministry of Science (ECO2008-01300 and ECO2011-27014) is acknowledged. Both authors were consultants for the World Bank, and Rossi-Hansberg was a visiting scholar at the Federal Reserve Bank of Philadelphia and the Federal Reserve Bank of Richmond. None of these relationships affected the research or conclusions described in this paper.
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sectors clear in equilibrium. Labor is freely mobile and workers can relocate every period, so that all workers obtain a common utility in equilibrium.

Third, firms can invest to improve their technology. They can buy a probability of drawing a proportional shift in their technology from a given distribution. Broadly speaking, local technological innovation by firms could be interpreted not only as improving firm technology, but also as adding to the local infrastructure. Finally, technology diffuses spatially. Locations close to others with a more advanced technology get access to a spatially discounted version of that technology through diffusion. Firms in each location will produce using the best technology they have access to, whether through invention or diffusion.

This setup allows us to derive two main theoretical results. First, in spite of the perfectly competitive environment, firms invest in innovation. Competition for land, which is a fixed factor, implies that firms will bid for land until breaking even. Since by innovating firms can enhance their bid for land, they will invest in innovation until ex ante profits net of the cost of innovation equal zero. Second, the ex post benefits from innovation last for only one period, since the following period any possible benefits are diffused and incorporated into land rents. As a result, in equilibrium the dynamic technological investment decision of firms maximizes only current profits. This result, proven in Proposition 1, allows us to write down a dynamic spatial model that is both simple enough to solve and rich enough to connect to the data.

Incorporating a continuum of locations into a dynamic framework is a challenging task for two reasons: it increases the dimensionality of the problem by requiring agents to understand the distribution of economic activity over time and over space, and clearing goods and factor markets is complex because prices depend on trade and mobility patterns. These two difficulties typically make spatial dynamic models intractable, both analytically and numerically.[1] Thus, the only way forward is to simplify the problem. Doing so is one of the two main goals of this paper.

In recent years some progress has been made toward this goal. A set of papers, such as Quah (2002); Boucekkine, Camacho, and Zou (2009); and Brock and Xepapadeas (2008, 2010), introduce a continuum of locations with geography and simplify the problem by assuming that each point in space is isolated, except for spatial spillovers or diffusion. By abstracting from transport costs, national goods markets, and factor mobility, they save the need to calculate price functions across locations over time. They are able to mathematically characterize some aspects of social optima or equilibrium allocations, though they fall short of proposing a complete solution. However, in order to deal with the complexity of forward-looking agents in a spatial context, these papers have to sacrifice many of the relevant spatial interactions, thus keeping them from generating rich empirical predictions.

We get around this problem by imposing enough structure—through the mobility of factors, the land and firm ownership structure, and the diffusion of technology—so that firms do not care to take the future equilibrium allocation path into account when making decisions, given that they do not affect the returns of their current

[1] Numerical methods like those in Krusell and Smith (1998) are not useful in this case since agents care about the distribution of economic activity in space not only through aggregate prices but also directly. Furthermore, the utility and decisions of agents, or the profits and decisions of firms, depend on the distribution of economic activity differently, relative to where they are located.

choices. As for the problem of clearing factor and goods markets in a framework with a continuum of locations, we follow the method in Rossi-Hansberg (2005) that consists of clearing markets sequentially. Proposing a model that is solvable and computable, while keeping the richness of the spatial interactions to connect the theory to the data in a meaningful way, is the second main goal of this paper.[2] Unavoidably, we continue to abstract from many geographic features, and so our paper should be viewed as a first step in developing a spatial dynamic model that can be taken to the data.

To illustrate the potential of the theory, we contrast the predictions of a calibrated version of our model to US macroeconomic and spatial data for the period 1950–2005. Although manufacturing productivity growth has traditionally outpaced that of services, since around 1995 productivity growth in the service industry has accelerated, and on some accounts is now higher than in manufacturing (Triplett and Bosworth 2004). The mid-1990s also represent a breakpoint in many other ways. Real wage growth started to increase, and land prices embarked upon an upward trend. Going beyond these macroeconomic stylized facts and focusing on the spatial dimension, during this period services have become more concentrated, and their geographic distribution is looking increasingly similar to that of manufacturing. Below the veil of increasing aggregate land prices, the mid-1990s also witnessed the start of a rise in the spatial dispersion in those land prices.

Our starting point is the work by Ngai and Pissarides (2007) on the structural transformation. They show that a faster increase in manufacturing productivity, relative to service productivity, together with CES preferences and an elasticity of substitution less than one, can yield some of the main features of the structural transformation, such as the observed decrease in the manufacturing employment share and the drop in the relative price of manufactured goods. We choose initial conditions such that in the beginning firms specializing in manufacturing are more productive, and so have a larger scale and innovate more.

The rest of the mechanisms in this paper are quite different. First, in our model the reallocation of employment toward services at some point endogenously accelerates innovation in some locations specializing in services. From then onward service productivity increases together with manufacturing productivity, ultimately leading to a constant aggregate growth path in both industries and the economy. Since the structural transformation shifts labor from high-productivity growth sectors to low-productivity growth sectors, Baumol (1967) feared that the economy was doomed to long-run stagnation. In our model this dismal prediction fails to materialize because it is exactly the structural transformation that makes the service sector concentrated enough for innovation to endogenously take off. This is consistent with the acceleration of services productivity growth in the mid-1990s, as well as with the increase in land rents and real wages around that period.

Second, the spatial distribution of economic activity interacts with the structural transformation in a non-trivial manner.[3] Once the service sector starts innovating,

[2] The structure of the model allows us to solve a competitive equilibrium, but not the planner's problem. Since the planner would need to take into account all possible distributions of economic activity across time and space, the dimensionality issue would resurface again, making the problem intractable.

[3] See Murata (2008) for an analysis of the structural transformation from agriculture to manufacturing within a New Economic Geography framework. However, in contrast to our work, in that paper there are no dynamics, there

spatial concentration in the service sector increases in terms of both employment and productivity, implying a positive link between employment density, innovation, and productivity growth. Consistent with the data, the service sector becomes more concentrated, in terms of both employment and productivity, making it look increasingly similar to manufacturing along this spatial dimension. The increasing clustering of services makes both sectors compete for the same land in certain locations, leading to a rise in the dispersion of land rents, as observed in the data. The link between innovation and spatial concentration is consistent with the evidence in Desmet and Rossi-Hansberg (2009), who compare spatial growth in two different time periods, 1980–2000 and 1900–1920, and find that service growth at the end of the twentieth century looked very similar to manufacturing growth at the beginning of the twentieth century.[4] Both industries, in very different time periods, exhibited increasing concentration in medium-size locations.[5]

Our calibrated model is successful in quantitatively matching some of the main macroeconomic and spatial stylized facts of the US economy in the last half-century, such as the increasing labor share in services, the timing of the take-off in services productivity growth, and the increase in the level and dispersion of land rents. It is also able to qualitatively account for many of the other key observations, such as the acceleration in wage growth after the mid-1990s and the increasing spatial concentration of services. The good quantitative match of the dispersion in land rents is particularly important, as it lends credibility to our goal of introducing space into endogenous growth models.

In our quantitative exploration we do a number of comparative statics exercises. One parameter of interest that governs the link between time and space are transport costs. We find that even though increases in transport costs lead to the standard static losses familiar from trade models, they also lead to dynamic gains by generating denser areas that, together with the scale effect in innovation, imply faster growth.

The existing literature on spatial dynamic models is fairly small. In addition to the papers mentioned above, there is a successful literature in trade that has focused on dynamic models with two or more countries (see, among others, Grossman and Helpman 1991; Eaton and Kortum 1999; Young 1991; and Ventura 1997).[6] The main difference with our work is that in these models there is no geography in the sense that locations are not ordered in space. In fact, most of these papers do not even introduce transport costs, let alone geography. In contrast, we introduce a continuum of locations on a line. Locations are therefore ordered geographically, and both transport costs and technology diffusion are affected by distance.[7]

In Desmet and Rossi-Hansberg (2009) we use a similar methodology to study the dynamics of manufacturing and service growth across US counties in the twentieth

is no innovation, and space consists of only two regions. Instead, the driving force behind the structural transformation is an exogenous decline in transportation costs.

[4] For further evidence of the increased concentration of services, see Kolko (1999) and Desmet and Fafchamps (2005). For the particular case of the retail industry, see Lagakos (2009).

[5] However, Desmet and Rossi-Hansberg (2009) do not link their findings to the structural transformation and to other macroeconomic variables, which is the main focus of this paper.

[6] See also Baldwin and Martin (2004) for a survey of similar work within the New Economic Geography model.

[7] Another related literature studies the dynamics of the distribution of city sizes. Relevant contributions include Black and Henderson (1999); Gabaix (1999); Eeckhout (2004); Duranton (2007); and Rossi-Hansberg and Wright (2007). Once again, a key limitation of these frameworks is the lack of geography, in the sense that cities are not ordered in space, and the trade links between them are either frictionless or uniform.

century. Although that model also analyzes the link between innovation and spatial growth, our current paper is different in two ways. First, we explicitly model innovation as the outcome of a profit-maximizing problem and, in that sense, provide micro-foundations for why certain locations innovate more than others. Second, in Desmet and Rossi-Hansberg (2009) innovation in a given sector gets jump-started exogenously, thus making its timing ad hoc and independent of what is happening in the other sector. In our current paper innovation starts off endogenously as explained above. Our model can thus be interpreted as an endogenous growth model with spatial heterogeneity.[8]

The rest of the paper is organized as follows. Section I presents the model. Section II presents the data we use to empirically explore the theoretical predictions, carries out numerical simulations of the model, and discusses the link between our results and the data. Section III concludes.

I. The Model

The economy consists of land and agents located in the closed interval $[0, 1]$. Throughout we refer to a location as a point in this interval, and we let the density of land at each location ℓ be equal to one. Hence, the total mass of land in the economy is also equal to one. The total number of agents is given by $\bar{L}$, and each of them is endowed with one unit of time each period. Agents are infinitely lived.

A. *Preferences*

Agents live where they work and they derive utility from the consumption of two goods: manufactures and services. Every period labor is freely mobile across locations and sectors. Agents supply their unit of time inelastically in the labor market. They order consumption bundles according to a homogeneous of degree one instantaneous utility function $U(c_M, c_S)$ with standard properties, where c_i denotes consumption of good $i \in \{M, S\}$. Agents hold a diversified portfolio of land and firms in all locations.[9] Goods are non-storable, and there is no other savings technology apart from land and firm ownership. The problem of an agent at location ℓ is given by[10]

$$(1) \qquad \max_{\{c_i(\ell,t)\}_0^\infty} E\sum_{t=0}^{\infty} \beta^t U(c_M(\ell,t), c_S(\ell,t))$$

$$\text{s.t.} \quad w(\ell,t) + \frac{\bar{R}(t) + \Pi(t)}{\bar{L}} = p_M(\ell,t)\, c_M(\ell,t) + p_S(\ell,t)\, c_S(\ell,t),$$

for all t and ℓ, where $p_i(\ell, t)$ denotes the price of good i, $w(\ell, t)$ denotes the wage at location ℓ and time t, and $\bar{R}(t)$ and $\Pi(t)$ denote total land rents and total firm profits

[8] There is a burgeoning literature that introduces heterogeneity and spillovers into endogenous growth models. In our work the spillovers are between locations that are different, whereas in Lucas and Moll (2011) and Perla and Tonetti (2012) they are between agents or firms that are heterogeneous.

[9] Since $U(\cdot)$ is constant returns to scale, agents are not risk averse. If they were, they would like to hold this diversified portfolio to insure themselves against idiosyncratic local shocks.

[10] Since we assume labor mobility, utility levels will equalize across space each period and so we can study the optimization problem of an agent as if she were to stay in the same location forever.

per unit of land. Given that agents hold a diversified portfolio of land and firms in all locations, $\overline{R}(t)/\overline{L}$ and $\Pi(t)/\overline{L}$ represent the per agent dividend from land and firm ownership. The first-order conditions of this problem yield $U_i(c_M(\ell, t), c_S(\ell, t)) = \lambda(\ell, t)\, p_i(\ell\ t)$, for all $i \in \{M, S\}$, where $U_i(\cdot)$ is the marginal utility of consuming good i and $\lambda(\ell, t)$ is a location- and time-specific Lagrange multiplier. Denote by $\overline{U}(p_M(\ell, t), p_S(\ell, t), w(\ell, t) + (\overline{R}(t) + \Pi(t))/\overline{L})$ the per-period indirect utility function of an agent at location ℓ.

Free labor mobility in each period guarantees that

$$(2)\quad \overline{U}(p_M(\ell,t), p_S(\ell,t), w(\ell,t) + (\overline{R}(t) + \Pi(t))/\overline{L}) = \overline{u}(t), \quad \text{for all } t \text{ and } \ell \in [0,1],$$

where $\overline{u}(t)$ is determined in equilibrium. In the numerical examples in the next section we will use a CES specification, $U(c_M, c_S) = (h_M\, c_M^{\alpha} + h_S\, c_S^{\alpha})^{1/\alpha}$, with elasticity of substitution $1/(1 - \alpha) < 1$.

We assume that each period labor can move, but only *before* innovations are realized and production takes place. As we specify below, firms will invest in innovation, and the realization of these innovations will be random. But because firms are small, and we assume that the law of large numbers holds, there will be no aggregate uncertainty. Rational expectations then imply that workers correctly anticipate prices and aggregate profits. In addition, wages and rents will be determined when workers move. Hence, at the time of their location decisions, workers either observe or correctly anticipate all the variables they need for calculating their utility levels at all locations. Therefore, mobility guarantees that utility levels equalize across locations each period, as stated in (2).

B. *Technology*

Firms specialize in one sector. The inputs of production are land and labor. Each firm requires one unit of land to produce, so in each location there is one firm. Production of a firm in location ℓ at time t, if it produces in the manufacturing sector, is given by $M(L_M(\ell, t)) = Z_M^{+}(\ell, t)^{\gamma}\, L_M(\ell, t)^{\mu_M}$, and, similarly, if it produces services, its production is $S(L_S(\ell, t)) = Z_S^{+}(\ell, t)^{\gamma}\, L_S(\ell, t)^{\mu_S}$, where $Z_i^{+}(\ell, t)$ is the technology level and $L_i(\ell, t)$ is the amount of labor used at location ℓ and time t in sector i. In the following sections we will describe the determination of technology. For now, we just point out that firms will decide whether and how much to invest in innovation, and that the realizations of local innovations are random.

C. *Diffusion*

Technology diffuses between time periods. This diffusion is assumed to be local and to decline exponentially with distance. In particular, if $Z_i^{+}(r, t - 1)$ was the technology used in location r in period $t - 1$, in the next period, t, location ℓ has access to (but does not necessarily need to use) technology $e^{-\delta|\ell - r|}\, Z_i^{+}(r, t - 1)$. Hence, before the innovation decision in period t, location ℓ has access to

$$(3)\qquad Z_i^{-}(\ell, t) = \max_{r \in [0,1]} e^{-\delta|\ell - r|}\, Z_i^{+}(r, t - 1),$$

which of course includes its own technology of the previous period. This type of diffusion is the only *exogenous* source of agglomeration in the model.[11] The "minus" superscript in $Z_i^-(\cdot)$ refers to the technology a location has access to before innovation, whereas the "plus" superscript in $Z_i^+(\cdot)$ refers to the technology a location ends up using after the innovation decision.

D. *Idea Generation*

A firm can decide to buy a probability $\phi \leq 1$ of innovating at cost $\psi(\phi)$ in a particular industry i (this cost will be paid using local production so the real cost in industry i is given by $\psi(\phi)/p_i(\ell, t)$. This implies that with probability ϕ the firm obtains an innovation and with probability $(1 - \phi)$ its technology is not affected by the investment in innovation.[12]

A firm that obtains the chance to innovate draws a technology multiplier z_i from a Pareto distribution (with lower bound 1), leading to an improved technology level, $z_i Z_i^-(\ell, t)$, where $\Pr[z < z_i] = (1/z)^a$. Thus, conditional on innovation and a technology at the beginning of the period Z_i^-, the expected technology is

$$E(Z_i^+(\ell, t) \,|\, Z_i^-, \mathit{Innovation}) = \frac{a}{a-1} Z_i^- \text{ for } a > 1, \tag{4}$$

where, as mentioned before, we add a "plus" superscript to clarify that it refers to the technology after the innovation decision. The expected technology for a given ϕ, not conditional on innovating but conditional on Z_i^-, is

$$E(Z_i^+(\ell, t) \,|\, Z_i^-) = \left(\frac{\phi a}{a-1} + (1-\phi)\right) Z_i^- = \left(\frac{\phi + a - 1}{a-1}\right) Z_i^-.$$

The innovation draws are i.i.d. across time, but not across space. Conditional on an innovation, let $s(\ell, \ell')$ denote the correlation in the realizations of $z_i(\ell)$ and $z_i(\ell')$. We assume that $s(\ell, \ell')$ is non-negative, symmetric, and $\lim_{\ell \downarrow \ell'} s(\ell, \ell') = 1$ and/or $\lim_{\ell \uparrow \ell'} s(\ell, \ell') = 1$.[13] Hence, innovation draws are spatially correlated, and firms obtain exactly the same innovations as other firms located arbitrarily close to them. This is important since, given diffusion, absent any spatial correlation, an infinite number of i.i.d. draws from a distribution with unbounded support would imply infinite productivity in all locations. In what follows, we assume that $s(\ell, \ell')$ declines fast enough with the distance between ℓ and ℓ' such that the law of large numbers still guarantees that there is no aggregate uncertainty.[14]

[11] As we describe below, there is an endogenous source of agglomeration that results from trade. Locations that experience high relative prices of a given good are more likely to form clusters specialized in the production of that good.

[12] Instead we could assume that firms buy a realization of a Poisson distribution for a number of opportunities to innovate. In this case, we need to calculate the expectation of the maximum draw out of N realizations (see, for example, Lucas and Moll 2012, and Alvarez, Buera, and Lucas 2008).

[13] An example of such a process is the one we use in the numerical simulations. There, we let $s(\ell, \ell') = 1$ when ℓ and ℓ' are within a connected interval of locations (a "county") and $s(\ell, \ell') = 0$ otherwise. This implies that for all ℓ, $\lim_{\ell \downarrow \ell'} s(\ell, \ell') = 1$ or $\lim_{\ell \uparrow \ell'} s(\ell, \ell') = 1$ as long as the interval has positive measure.

[14] In the example we use in the numerical simulations this implies using enough locations. We use 500 locations.

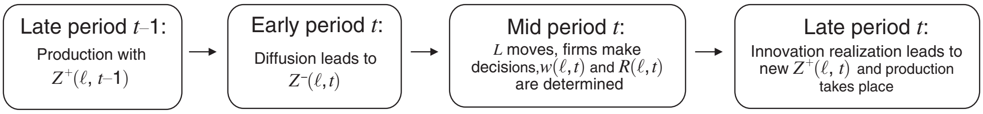

Figure 1. Timing

E. *Timing and Firm Problem*

Figure 1 illustrates the timing in our model. During the night, between periods $t - 1$ and t, technology diffuses locally, as described above. This leads to a level of technology $Z_i^{-}(\ell, t)$, given by (3), in the morning. Each firm then decides on how many workers it wants to hire, how much it wants to bid for land, and its path of innovation investments. Only the firm that offers the highest bid for land in a given location gets to rent the land, hire workers, and invest in innovation. Importantly, there are no sunk costs of innovation. Investment in innovation may then lead to a new technology, $Z_i^{+}(\ell, t)$, depending on whether the firm obtained an idea and on the realization of the draw. Production happens at the end of the period. The level of technology a firm uses in production in period t is then either the one it woke up with or the improved technology, provided it invested in innovation and was successful doing so.[15]

Firms maximize the expected present value of profits with discount factor β. The objective function of a firm in a given location ℓ at time t_0 is therefore[16]

$$\max_{\{\phi_i(\ell, t), L_i(\ell, t)\}_{t_0}^{\infty}} E_{t_0}\left[\sum_{t=t_0}^{\infty} \beta^{t-t_0}\left(p_i(\ell, t)\left(\left(\frac{\phi_i(\ell, t)}{a-1}+1\right) Z_i^{-}(\ell, t)\right)^{\gamma} L_i(\ell, t)^{\mu_i} - w(\ell, t)\, L_i(\ell, t) - R(\ell, t) - \psi(\phi_i(\ell, t))\right)\right],$$

where $R(\ell, t)$ is the firm's bid rent which is chosen to maximize the probability of winning the auction to rent land.

Labor is freely mobile and firms compete for land and labor every period with potential entrants that, because of diffusion, have access to the same technology as they. Hence, the decision of how many workers to hire and how much to bid for land are static problems. The only dynamic problem is the innovation decision, since a firm's decision of how much to innovate in a given period can potentially affect how much it innovates in the future. So, consider first a firm's static problem of choosing labor in sector $i \in \{M, S\}$ at ℓ,

$$(5) \qquad \max_{L_i}\; p_i(\ell, t)\left(\frac{\hat{\phi}_i(\ell, t)}{a-1}+1\right)^{\gamma} Z_i^{-}(\ell, t)^{\gamma} L_i^{\mu_i} - w(\ell, t)\, L_i - \psi\big(\hat{\phi}_i(\ell, t)\big),$$

[15] Firms are price takers even though they are the only producers in a given location. The reason is that prices are determined by no arbitrage with respect to other locations (see equation (10)). This also implies that local innovation realizations have a negligible effect on the local prices of goods and services. The law of large numbers guarantees that general equilibrium effects are deterministic and predictable.

[16] Since the decision of how many workers to hire in a given period is taken before the realization of $z_i(\ell, t)$, it depends on the expected productivity rather than on its actual realization. Formally, the decision depends on $E\big((Z_i^{+}(\ell, t))^{\gamma}\,|\,Z_i^{-}(\ell, t), \phi_i(\ell, t)\big)$. Using a first order approximation to simplify subsequent algebra, for large a we obtain $E\big((Z_i^{+}(\ell, t))^{\gamma}\,|\,Z_i^{-}(\ell, t), \phi_i(\ell, t)\big) \approx \big(E\big(Z_i^{+}(\ell, t)\,|\,Z_i^{-}(\ell, t), \phi_i(\ell, t)\big)\big)^{\gamma} = \big((\phi_i(\ell, t)/(a-1) + 1)\, Z_i^{-}(\ell, t)\big)^{\gamma}$.

where $\hat{\phi}_i(\ell, t)$ denotes the optimal innovation decision. Denote the firm's choice of labor by $\hat{L}_i(\ell, t)$. To solve the above problem, firms must be able to anticipate prices. Since innovations are local, and locations are small (namely, the law of large numbers holds), there is no aggregate uncertainty, so that rational expectations will ensure that this is indeed the case. Firms bid for land and the highest bid gets to produce in that location. The maximum per unit land rent that a firm in sector i is willing to pay at time t, the bid rent, is given by

$$(6) \quad R_i(\ell, t) = p_i(\ell, t)\left(\frac{\hat{\phi}_i(\ell, t)}{a-1} + 1\right)^{\gamma} Z_i^{-}(\ell, t)^{\gamma}\, \hat{L}_i(\ell, t)^{\mu_i} - w(\ell, t)\, \hat{L}_i(\ell, t) - \psi\left(\hat{\phi}_i(\ell, t)\right),$$

which guarantees that firms make zero ex ante profits.

The reason firms make zero ex ante profits every period is because they compete for land with other potential entrants that have access to the same technology. This implies that if a firm bids too low and has positive ex ante profits, it would not be able to win the competition for land, and if a firm bids too high and has negative ex ante profits, this would not give the firm any advantage in bidding for land in the future. Profits are zero ex ante net of the cost of innovation. If a firm were not to invest in innovation but others did, its expected profits would be lower and it would loose the competition for land. Of course, if firms invest in innovation and obtain a good realization, they will make positive ex post profits, whereas if they do not obtain a draw or the realization is low, they will make negative ex post profits. Since there is a continuum of locations, we assume $s(\cdot)$ is such that this logic guarantees that $\Pi(t) = 0$ for all t.

We now turn to the decision of how much to invest in innovation every period. Because of labor mobility and competition for land, expected profits are zero given the optimal innovation decisions every period. Nevertheless, a firm's current innovation decision could in principle affect its future scale, and thus change its future innovation decisions, making the problem dynamic. However, as we prove below, this will not occur because today's innovations diffuse by tomorrow, so that a firm's scale will also be determined by the innovations of neighboring locations: an externality. Then, continuity in the diffusion process and the spatial correlation in innovation realizations guarantee that a firm's own decisions do not affect the expected technology it wakes up with tomorrow, and thus do not change its future innovation decisions. The next proposition formalizes this logic.[17]

PROPOSITION 1: *A firm's optimal dynamic innovation decisions maximize current period profits. That is,* $\phi_i(\ell, t)$ *is chosen so as to maximize the firm's period t profits only.*

[17] The proofs of all propositions are available in the online Appendix.

This proposition is the key result of our theory. It makes our dynamic spatial model solvable and computable, and at the same time keeps it rich enough in its empirical predictions, so that it can be linked to the data in a meaningful way. As argued before, previous attempts to develop dynamic spatial models had to abstract from relevant features, such as transport costs and factor mobility in order to remain tractable (Boucekkine, Camacho, and Zou 2009; Brock and Xepapadeas 2008a, b).

Note that the proposition implies that the innovation problem of a firm, given factor prices and the amount of labor, is given by

$$\text{(7)}\quad \max_{\phi_i} p_i(\ell, t)\left(\frac{\phi_i + a - 1}{a - 1} Z_i^-(\ell, t)\right)^{\gamma} \hat{L}_i(\ell, t)^{\mu_i} - w(\ell, t)\, \hat{L}_i(\ell, t) - R(\ell, t) - \psi(\phi_i).$$

Since firms take the equilibrium wage, $w(\ell, t)$, and the winning bid, $R(\ell, t)$, as given,[18] and the envelope theorem on $\hat{L}_i(\ell, t)$ applies, maximizing profits, or revenue net of the investment costs, is equivalent.

In the numerical exercises we make $\psi(\cdot)$ proportional to wages in each location, so $\psi(\cdot)$ will be a function of time. Hence, if an economy grows (and therefore wages increase), the cost of investment in innovation grows accordingly. Then, the model is such that—with enough locations so that the law of large numbers applies—the economy converges to a balanced growth path. Of course, for a finite number of locations, there will be some fluctuations around this balanced growth path, even in the long run. In contrast, individual locations' employment, specialization, trade, etc. will keep changing over time. The specific functional form for the cost of innovation we will use is

$$\text{(8)}\qquad \psi(\phi; w(\ell, t)) = w(\ell, t)\left(\psi_1 + \psi_2 \frac{1}{1 - \phi}\right) \qquad \text{for } \psi_2 > 0,$$

$\psi'(\phi; \cdot) > 0$ and $\psi''(\phi; \cdot) \geq 0$. The advantage of this cost function is that it has an asymptote at 1. This prevents us from dealing with corner solutions at 1. The first order condition is then given by $(p_i(\ell, t)\gamma/(a - 1))(\phi^*(\ell, t)/(a - 1) + 1)^{\gamma-1} \times Z_i^-(\ell, t)^{\gamma}\, \hat{L}(\ell, t)^{\mu_i} = w(\ell, t)\psi_2/(1 - \phi^*(\ell, t))^2$. By assuming that $\gamma + \mu_i = 1$ and by using the first order condition for labor, $\mu_i\, p_i(\ell, t)(\phi^*(\ell, t)/(a - 1) + 1)^{\gamma} \times Z_i^-(\ell, t)^{\gamma}\, \hat{L}(\ell, t)^{\mu_i - 1} = w(\ell, t)$, we can further simplify this expression to[19]

$$\text{(9)}\qquad \phi_i^*(\ell, t) = 1 - \left(\frac{\psi_2(a - 1)}{\gamma(1 - \gamma)^{\frac{1-\gamma}{\gamma}}} \frac{1}{Z_i^-(\ell, t)} \left(\frac{w(\ell, t)}{p_i(\ell, t)}\right)^{\frac{1}{\gamma}}\right)^{\frac{1}{2}}.$$

[18] Although firms choose their bid for land, the rent that makes firms win the competition for land is determined in the market.

[19] As we will later argue, we can show that the equilibrium of the economy is unique if $\gamma + \mu_i \leq 1$.

Then $\hat{\phi}_i(\ell, t) = 0$ if $\psi(\phi_i^*(\ell, t); w(\ell, t)) \geq p_i(\ell, t)\left((\phi_i^*(\ell, t)/(a-1))Z_i^-(\ell, t)\right)^\gamma \times \hat{L}_i(\ell, t)^{\mu_i}$ and/or $\phi_i^*(\ell, t) \leq 0$ and $\hat{\phi}_i(\ell, t) = \phi_i^*(\ell, t)$ otherwise. Hence, innovation is an increasing function of local productivity, conditional on real wages, and a decreasing function of real wages in terms of locally produced goods, conditional on productivity. Since wages are determined by free mobility and prices by no arbitrage between regions, they do not react directly to local productivity. General equilibrium effects from higher productivity in a single location are negligible. Hence, more productive locations innovate more. This is the main source of growth, through continuous innovation, in the model.

Note also that innovation will be greater in locations with more employment. From the first order condition with respect to L_i in (7), and assuming that $\gamma + \mu_i = 1$, we know that

$$\phi_i^*(\ell, t) = (a-1)\left(\left(\frac{w(\ell, t)}{(1-\gamma)p(\ell, t)}\right)^{\frac{1}{\gamma}} \frac{\hat{L}(\ell, t)}{Z^-(\ell, t)} - 1\right),$$

which is increasing in labor $\hat{L}(\ell, t)$ conditional on productivity $Z^-(\ell, t)$ and real wages $w(\ell, t)/p(\ell, t)$. This generates a scale effect in employment, consistent with Carlino, Chatterjee, and Hunt (2007), who show that in the United States a doubling of employment density leads to a 20 percent increase in patents per capita. This scale effect implies that more dense locations will have higher land rents.

F. *Land, Goods, and Labor Markets*

Goods are costly to transport. For simplicity we assume iceberg transportation costs that are identical in manufacturing and services. This is without loss of generality given that the equilibrium depends only on the sum of transport costs in both industries. If one unit of any of the goods is transported from ℓ to r, only $e^{-\kappa|\ell - r|}$ units of the good arrive in r.[20] Since the technology to transport goods is freely available, the price of good i produced in location ℓ and consumed in location r has to satisfy

$$p_i(r, t) = e^{\kappa|\ell - r|} p_i(\ell, t). \tag{10}$$

Land is assigned to a firm in the industry that values it the most. Hence, land rents are such that $R(\ell, t) = \max\{R_M(\ell, t), R_S(\ell, t)\}$. Denote by $\theta_i(\ell) \in \{0, 1\}$ the fraction of land at location ℓ used in the production of good i. If $R(\ell, t) = R_i(\ell, t)$ then $\theta_i(\ell, t) = 1$. To break ties, when $R_M(\ell, t) = R_S(\ell, t)$, we let $\theta_M(\ell, t) = 1$. Once

[20] We let κ be identical across sectors. Because we have only two industries and trade of a particular good in one direction normally implies trade of the other good in the opposite direction, the sum of transport costs is the key parameter to determine the equilibrium allocation. However, since profits and land rents imply that some locations may have trade surpluses and some others may have deficits, it may be the case that some locations consume their own production of one good and receive the other good as the result of agents' investments in other locations. In those cases having different transport costs in the two industries can have an impact.

again, note that competition for land determines land rents before technological innovations are realized, as discussed above.[21]

In order to guarantee equilibrium in product markets, we need to take into account that some of the goods are lost in transportation. To do this, let $H_i(\ell, t)$ denote the stock of excess supply of product i between locations 0 and ℓ. Define $H_i(\ell, t)$ by $H_i(0, t) = 0$ and by the differential equation

$$(11) \quad \frac{\partial H_i(\ell, t)}{\partial \ell} = \theta_i(\ell, t)\, x_i(\ell, t) - c_i(\ell, t)\left(\sum_i \theta_i(\ell, t)\, \hat{L}_i(\ell, t)\right) - \kappa\,|H_i(\ell, t)|,$$

where the equilibrium production of good i at location ℓ per unit of land net of real technology investment costs is denoted by $x_M(\ell, t) = M\big(\hat{L}_M(\ell, t)\big) - \psi(\phi_M(\ell, t))/p_M(\ell, t)$ and $x_S(\ell, t) = S\big(\hat{L}_S(\ell, t)\big) - \psi(\phi_S(\ell, t))/p_S(\ell, t)$.[22] That is, at each location we add to the stock of excess supply the amount of good i produced and we subtract the consumption of good i by all residents of ℓ. We then need to adjust for the fact that if $H_i(\ell, t)$ is positive and we increase ℓ, we have to ship the stock of excess supply a longer distance. This implies a cost in terms of goods and services given by κ. The equilibrium conditions in the goods markets are then $H_i(1, t) = 0$ for all i. Given the lack of aggregate uncertainty and the fact that there are national goods markets that clear, under rational expectations all agents anticipate the behavior of prices correctly.

In equilibrium, labor markets clear. Given free mobility, we have to guarantee that the total amount of labor demanded in the economy is equal to the total supply $\bar{L}$ before technological innovations are realized. The labor market equilibrium condition is therefore,

$$(12) \quad \int_0^1 \sum_i \theta_i(\ell, t)\, \hat{L}_i(\ell, t)\, d\ell = \bar{L}.$$

G. *Definition and Uniqueness of Equilibrium*

Given initial productivity functions $Z_i^-(\cdot, 1)$, for $i \in \{M, S\}$, an equilibrium is a set of real functions $(c_i, \hat{L}_i, \theta_i, H_i, p_i, R_i, w, Z_i^-, Z_i^+, \phi_i)$ of locations $\ell \in [0, 1]$ and time $t = 1, \ldots,$ for $i \in \{M, S\}$, such that:

- Agents choose consumption, c_i, by solving the problem in (1).

[21] Our model abstracts from demand for land by households. We could easily allow for this possibility without changing the basic setup of the model. Doing so would require introducing the consumption of land in the households' preferences, for example, by assuming the per-period utility $\left((h_M c_M^\alpha + h_S c_S^\alpha)^{1/\alpha}\right)^\beta (c_H(\ell, t))^{1-\beta}$. The firm's problem, expressed in per unit of land terms, would be unchanged. Of course, now that land is shared by households and firms, we would need to move away from the assumption that each firm occupies one unit of land, and write down a land market clearing condition. Denote the mass of firms in each location by $m_i(\ell, t)$. Given that all locations are fully specialized, there is only one type of firms per location, and the market clearing condition would become $m_i(\ell, t)L_i(\ell, t)c_H(\ell, t) + m_i(\ell, t) = 1$, where $m_i(\ell, t)$ can also be interpreted as the share of land occupied by firms. Introducing demand for land by households would somewhat weaken the scale effect in innovation, as it would require firms in more dense locations to pay higher wages.

[22] Recall from Section IB that $M(L_M(\ell, t))$ and $S(L_S(\ell, t))$ refer to, respectively, manufacturing or services output at location ℓ.

- Agents locate optimally, so w, p_i, R_i, and $\hat{L}_i$ satisfy (2).
- Firms maximize profits by choosing the number of workers per unit of land, $\hat{L}_i$, that solves (5), and by choosing the land bid rent, R_i, that solves (6).
- Land is assigned to the industry that values it the most, so if $\max\{R_M(\ell, t), R_S(\ell, t)\} = R_i(\ell, t)$, then $\theta_i(\ell, t) = 1$. To break ties, when $R_M(\ell, t) = R_S(\ell, t)$, we let $\theta_M(\ell, t) = 1$.
- Goods markets clear, so H_i is given by (11) and $H_i(1) = 0$.
- The labor market clears, so θ_i and $\hat{L}_i$ satisfy (12).
- Investment in innovation ϕ_i satisfies (9).
- Technology Z_i^+ satisfies the innovation process that leads to (4) and technology Z_i^- satisfies the diffusion process given by (3).

The following proposition states that the equilibrium is unique if the technology function is sufficiently concave. Namely, if γ is sufficiently small.

PROPOSITION 2: *The equilibrium of this economy exists and is unique if* $\gamma + \mu_i \leq 1$ *for all i.*

II. Evidence and Model Predictions

To illustrate how our theory of spatial development can be taken to the data, we use it to analyze the macroeconomic and spatial evolution of the US economy in the postwar period. Standard macroeconomic models ignore spatial heterogeneity, and standard spatial models ignore macroeconomic dynamics. Our theory aims to account for the main stylized facts along both the macroeconomic and spatial dimensions. We start by discussing the macroeconomic and spatial evidence on the US economy over the period 1950–2005. We then calibrate the model, solve it numerically, and contrast the outcome with the data.

A. *Evidence*

Although many of the stylized facts will appear familiar from the literature on the structural transformation (see, e.g., Ngai and Pissarides 2007; and Buera and Kaboski 2012), we will also emphasize two less well-known aspects. First, in the last 15 years, compared to the earlier period, many of those familiar stylized facts have undergone significant changes. Second, we will present evidence on the spatial dimension, an aspect generally ignored in this literature.

It is well known that employment has been moving out of goods and into services,[23] as can be seen in Figure 2. The solid curves represent the actual employment shares, whereas the dashed and dotted curves represent what the employment shares would be if the United States did not trade with the rest of the world (and factor prices

[23] In the empirical section we distinguish between "goods" and "services" (where "goods" is the aggregation of manufacturing, construction, and mining) because this is the typical distinction in many of the data sources, such as the Industry Economic Accounts of the Bureau of Economic Analysis (BEA). In the rest of the paper, we refer to the two sectors of interest as "manufacturing" and "services."

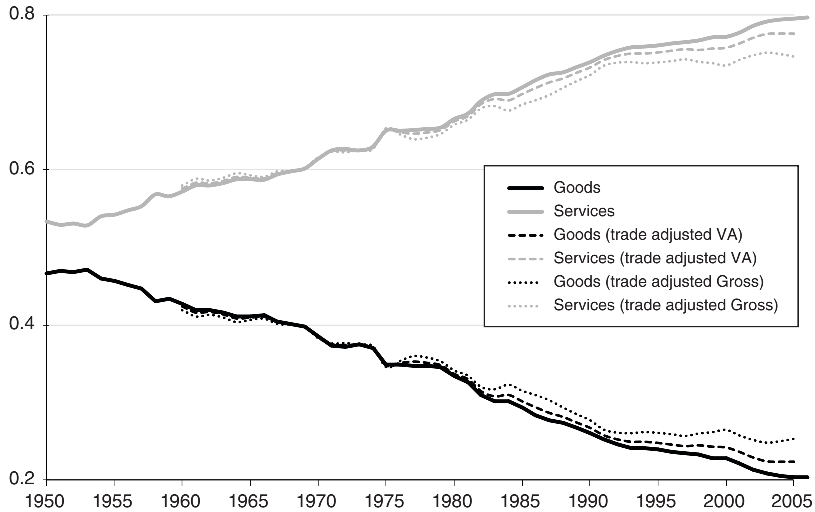

Figure 2. Employment Shares

Sources: Industry Economic Accounts, BEA, US Census Bureau

were not to change).[24] Compared to the actual shares, the trade-adjusted shares can be interpreted as the employment shares based on what consumers buy, rather than on what firms produce. The employment shift out of manufacturing dates back to the 1930s and has continued to the present day. However, since the mid-1990s this shift has been slowing down. When focusing on the trade-adjusted dashed curves, between 1975 and 1990 the service employment share increased by about 8 percentage points, compared to by only 4 percentage points between 1990 and 2005.

This change in employment shares has been accompanied by a decrease in the price of goods, relative to services, as shown in Figure 3. During the 1970s there was a lull in that decline, probably related to the two oil crises. Consistent with this, when looking at the relative price of manufactured goods, which leaves out the energy sector, the decline is more continuous. We would expect the flattening of the employment shares since the mid-1990s to show up as a slowdown in the drop of the relative goods price. The evidence for this is quite weak though, especially when looking at manufacturing rather than goods, possibly because of import competition from less developed countries, such as China or Mexico.

Considering value added per worker as a measure of aggregate labor productivity, Figure 4 shows an important increase starting in the mid-1990s.[25] In the 10 years between 1995 and 2005 the increase in aggregate labor productivity was about as much as in the preceding 25 years. This timing also coincides with the evolution of land and housing prices. Figure 5 shows increases in the real values of land and housing post-1995, following a fairly stable pattern in earlier decades. Of course,

[24] The dashed curves assume the ratio between gross trade and value-added trade is the same as the ratio between gross output and value added in the United States, whereas the dotted curves ignore the existence of intermediate inputs in international trade.

[25] For purposes of comparison with the numerical section, to obtain real wages we deflate by the services price index used in the Industry Economic Accounts of the BEA.

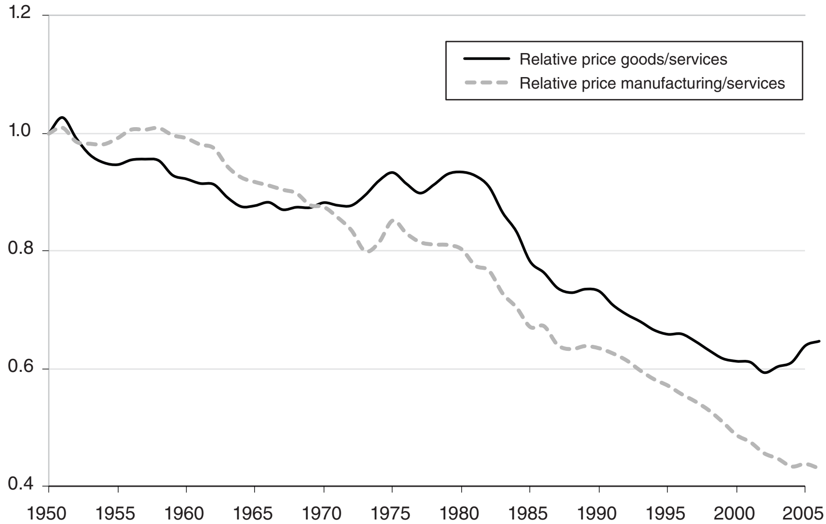

Figure 3. Relative Price (1950 = 1)

Source: Industry Economic Accounts, BEA

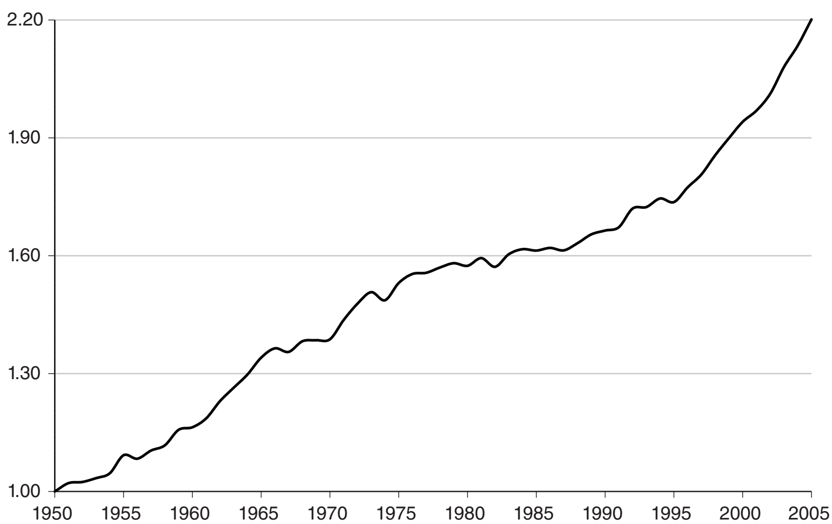

Figure 4. Value Added Per Worker (1950 = 1)

Source: Industry Economic Accounts, BEA

part of this dramatic increase, but not all, is disappearing as a result of the current housing crisis.[26]

The dynamics in our theory are the result of innovations that translate into higher local productivity in the different sectors. Although Figure 4 already reported aggregate productivity, we need to distinguish between goods and services. Figure 6 shows

[26] Once again, we deflate by the services price index used in the Industry Economic Accounts of the BEA. By 2011 the real value of housing had dropped to the level of 2000, and in 2012 had started increasing again.

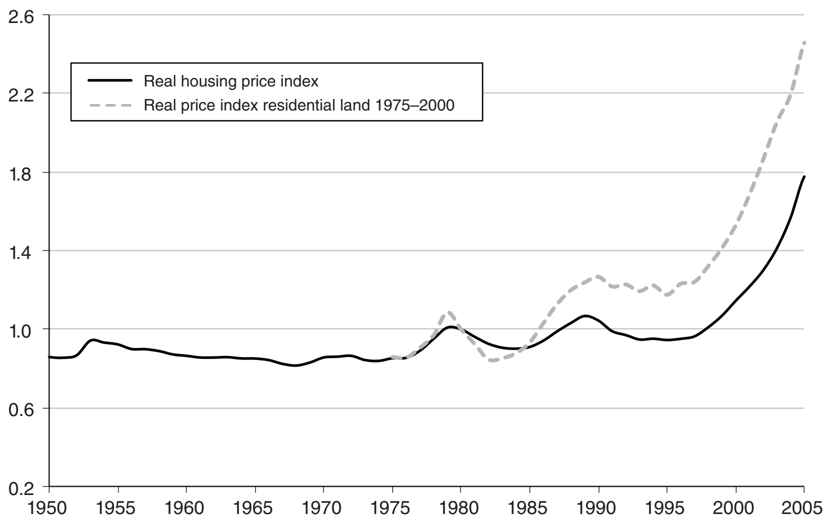

Figure 5. Real Housing and Land Price Index (1980 = 1)

Sources: Shiller (2005) and Davis and Heathcote (2007)

how since the mid-1960s services productivity growth, as measured by value added per worker, was falling increasingly behind that of goods, a phenomenon described by Baumol (1967), who argued that it was inherently more difficult to innovate in services than in goods. However, since the mid-1990s services productivity growth has clearly been catching up and, on some accounts, may even have surpassed productivity growth in the goods-producing sector (Triplett and Bosworth 2004).[27]

As for the spatial dimension, the service sector, that started off being more dispersed than the goods producing sector, has become increasingly concentrated in space.[28] Using US county data, Table 1 confirms this by reporting the evolution of the relative standard deviation of log employment density in both sectors between 1950 and 2005 (as well as the relative log difference between the seventieth and thirtieth percentiles). Sectoral differences in the geographic distribution have thus become mitigated over time.

Another spatial dimension of interest is the dispersion in land prices. Whereas standard macro models can account for the behavior of aggregate land prices, a spatial model is needed if we want to understand the geographic heterogeneity in land prices. Since Figure 5 showed an important increase in land price starting around 1995, we use data from Davis and Palumbo (2008), and plot in Figure 7 the distribution of land values (in logs) across 40 MSAs in 1995 and 2005. As can be seen, the dispersion in land values increased significantly between 1995 and 2005.

[27] As argued by Griliches (1992), an alternative reason for why productivity growth was so low in the postwar period might be poor measurement.

[28] The increased geographic concentration of services has been studied before by, amongst others, Glaeser and Ponzetto (2010), who suggest that this phenomenon may be driven by lower transport and communication costs.

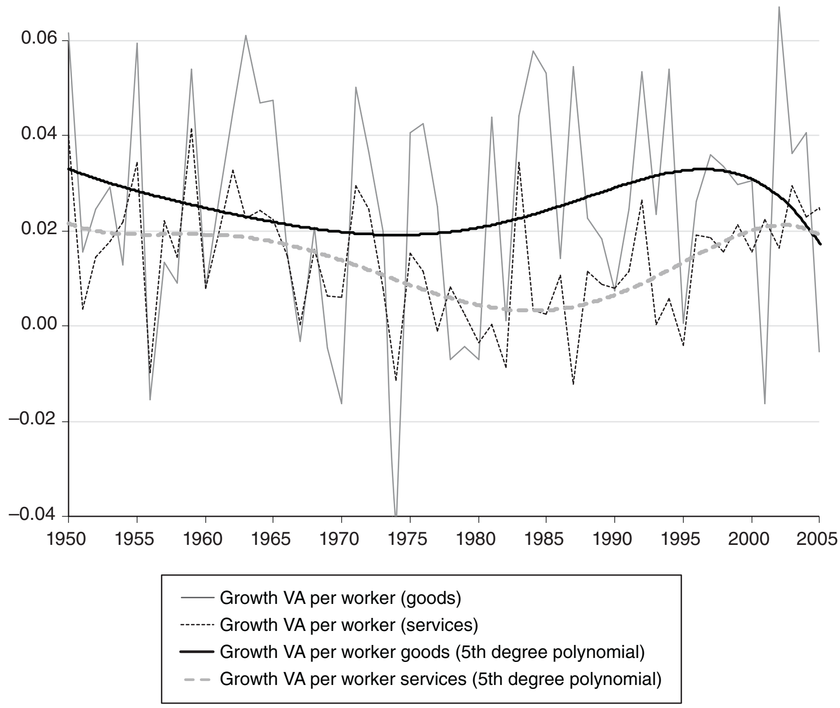

FIGURE 6. GROWTH IN VALUE ADDED PER WORKER

Source: Industry Economic Accounts, BEA

TABLE 1—SPATIAL CONCENTRATION OF EMPLOYMENT

	1950	1970	1980	1990	2000	2005
log employment density						
Difference 70–30						
Goods	1.40	1.71	1.58	1.60	1.57	1.58
Services	1.14	1.24	1.34	1.39	1.44	1.46
Goods/services	1.23	1.37	1.18	1.15	1.09	1.08
Standard deviation						
Goods	1.67	1.80	1.69	1.70	1.64	1.60
Services	1.42	1.51	1.52	1.58	1.59	1.59
Goods/services	1.18	1.20	1.11	1.08	1.03	1.00

Sources: Regional Economic Accounts, BEA; County and City Databooks, US Census Bureau

B. *Comparing Theory and Data*

The basic message we obtain from the evidence presented above is that between the 1950s and the beginning of the 1990s productivity in goods, relative to services, was growing fast, and employment in the goods-producing sectors was steadily falling. During that same period, service productivity growth was low, real land rents did not exhibit significant changes, and manufacturing became increasingly dispersed relative to services. Then, around the mid-1990s, land prices started to increase, value added per worker growth accelerated, and service productivity growth took off. Changes in employment shares slowed down, and the dispersion in land prices

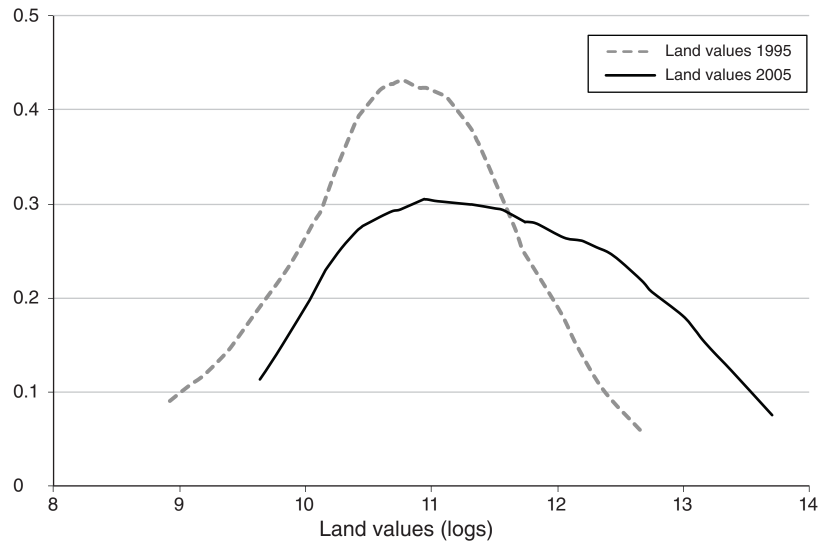

Figure 7. Land Values Distribution across MSAs

increased. At the same time, the tendency toward greater dispersion of manufacturing relative to services slowed down. We now calibrate our theory, and solve it numerically to show that it can account for many of these aggregate and spatial features of the evolution of the US economy since World War II.

Calibration.—Some of the parameter values are taken directly from the literature, while others are chosen to match certain key observations. In what follows we discuss our choices in some more detail and explain the importance of the different parameters for the theory.

The preference parameters, h_M and h_S, were chosen to match the 1950 employment shares in both sectors. A model period equals half a year, and we let the discount factor be equal to $\beta = 0.95$ per year. The elasticity of substitution between manufacturing and services, $1/(1-\alpha)$, is important for our results. A key mechanism in the model is that as productivity in one sector increases, relative to the other sector, the relative price of output in that sector decreases and so does its employment share. For this to happen, the elasticity of substitution between goods and services must be less than 1. This is consistent with empirical estimates. Stockman and Tesar (1995), for example, estimate it to be 0.44 for a set of 30 countries. Given this evidence, we set $\alpha = -1.5$, so the elasticity of substitution is $1/(1-\alpha) = 0.4$. Other papers, such as Mendoza (1992) argue for a slightly higher elasticity of substitution, whereas recent work by Herrendorf, Rogerson, and Valentinyi (2013) argue that an elasticity of substitution of zero cannot be rejected. We will therefore do some robustness analysis on this parameter.

The elasticity of substitution is also important for the incentives to innovate in different sectors. With an elasticity below one, when a sector's relative productivity increases and employment in that sector declines, the increase in employment in the other sector increases the incentives for innovation in certain locations specializing in the slow-growing sector. Eventually, enough people switch to the slow-growing sector for innovation to start there. In that sense, the economy self-regulates.

To compute the model we need to specify initial productivity functions for both manufacturing and services. We let $Z_S(\cdot, 0) = 1$ and $Z_M(\cdot, 0) = 0.8 + 0.4\ell$. The key characteristic of the initial productivity functions we chose is that service productivity is initially larger than that of manufacturing for locations close to the lower border, whereas manufacturing productivity is larger than that of services close to the upper border. Furthermore, the locations with the highest manufacturing productivity have a 20 percent larger productivity than the locations with the highest service productivity. These initial productivity functions imply that if all other parameters are identical between sectors, innovation always happens earlier in manufacturing than in services and always in the locations close to the upper border.[29] These initial productivity functions also imply that services are more dispersed than manufacturing in 1950.

Though we make no attempt at explaining how the economy reached that initial state, by incorporating the earlier structural transformation from agriculture to manufacturing, our theory could easily explain the observed productivity growth and spatial concentration in manufacturing, since the forces at work would be similar to those that account for the more recent productivity take-off and the geographic concentration in the service industry. This also implies that the economy's state in 1950 should not be viewed as a steady state, but rather as a point on the economy's long-term development path. The production functions also require us to choose values for the labor shares. We rely on the work of Valentinyi and Herrendorf (2008) and set the share of labor in both sectors to $\mu_i = 0.6$.

We next turn to discussing how we chose the transport and technology diffusion parameters. For the transport cost parameter, Desmet and Rossi-Hansberg (2012), relying on estimates from Ramondo and Rodríguez-Clare (2013), set $\kappa = 0.00005$, where distance is expressed in kilometers. If our unit interval corresponds to the approximately 5,000 kilometers that separates the East Coast from the West Coast, this corresponds to a value of $\kappa = 0.25$. Given that this estimate is based on inter-country trade, we take a slightly lower value of $\kappa = 0.08$. As we will later show, the transport cost parameter is key in determining the timing of innovation because lower transport costs lead to less concentration of employment, thus delaying the take-off of the service sector. For the technology diffusion parameter, Comin, Dmitriev, and Rossi-Hansberg (2012) estimate a distance decay parameter of 1.5 when analyzing the adoption of 20 major technologies in 161 countries over the last century and a half. Given that their distances are measured in terms of 1,000 kilometers, we multiply this parameter by 5, and set $\delta = 7.5$.

Innovation is key in our model, and there are four parameters that affect it. The cost of innovation has a fixed part and a variable part. The fixed cost parameter ψ_1 is set to ensure there is no productivity growth in services in 1950 but there is some in manufacturing. The variable cost parameter ψ_2 and the shape parameter of the

[29] Since our economy is represented in one-dimensional space, there is obviously no sense in which the two extremes of the line correspond to the two seaboards. However, space is continuous and ordered, and is thus able to capture some spatial patterns, such as the collocation of sectors and the spatial growth of innovation clusters, absent from standard models with two or three locations.

Pareto distribution a are chosen to match the average productivity growth in, respectively, manufacturing and services in the period 1980 to 2005. Lastly, as discussed in the theory, we set $\gamma = 0.4$, so that $\mu_i + \gamma = 1$. This ensures that the equilibrium is unique. Of course, all these parameters determine jointly the moments we match in the data. So this discussion only attempts to describe informally the logic we used in finding a good match.

In order to impose spatial correlation in the innovation draws we assume that space is divided in "counties" of identical size, which are connected intervals in $[0, 1]$. Within a county all firms of a given sector obtain identical innovation draws, while across counties draws are i.i.d. To make the simulations computationally feasible, we divide the unit interval into 500 "counties." Obviously, the more locations, the better the computational exercise approximates the theoretical model. The finiteness of the number of locations implies that local shocks are still noticeable in the aggregate. In our subsequent analysis we eliminate the randomness of particular realizations by focusing on the average outcome of 100 realizations.[30]

Benchmark Analysis.—With these parameters in hand, this section will show that the model can account for the key features of the aggregate and spatial evolution of the US economy in the last half-century. Quantitatively, we are able to match the evolution of employment shares, the productivity growth in manufacturing and services, the take-off of services starting around 1990, as well as the increase in the level and the dispersion of land rents between 1995 and 2005. Qualitatively, we are able to account for the acceleration in wage growth starting in the mid-1990s, the relative decline in goods prices throughout the entire postwar period, and the increased spatial concentration of services.

The subsequent figures show the average of 100 realizations of the model for the period 1950–2050. Averaging over 100 realizations eliminates fluctuations associated with particular realizations of innovation shocks that might match certain futures in the data only by chance. The first part of the period, 1950–2005, aims to match the key data discussed in the empirical section, whereas the second part of the period, 2005–2050, aims to show where the economy is heading if the forces described in the theory continue to apply in the future.

Until the 1990s productivity growth in the goods sector outpaces that in the service sector, both in the model and in the data. Because of the elasticity of substitution being less than one, this leads to employment moving out of the goods sector into the service sector. As more workers find employment in the service industry, the positive scale effect in the theory increases the incentive for service firms to innovate. As shown in Figure 8, this acceleration in the beginning of the 1990s is apparent in both the model and the data.[31,32] Therefore, although we calibrate to the

[30] Because of this, increasing the number of intervals does not change the results qualitatively, as long as it does not increase the number of productivity draws. If it did, productivity growth would obviously be higher, and so the technology parameters would need to be recalibrated.

[31] Figures 8 and 9 show results for different levels of the elasticity of substitution. The benchmark assumes an elasticity of 0.4. We will discuss the other values in the comparative statics section.

[32] For comparison purposes, we normalize to one productivity in goods and services in both the model and the data in 1975 (the mid-point of our sample). In addition, to make the aggregate productivity measure as comparable as possible to the data, we use the Solow residual, $\int_0^1 x_i(\ell, t)\,\theta_i(\ell, t)\,d\ell / \left(\int_0^1 \hat{L}_i(\ell, t)\,\theta_i(\ell, t)\,d\ell\right)^{\mu_i}$. We could also have used

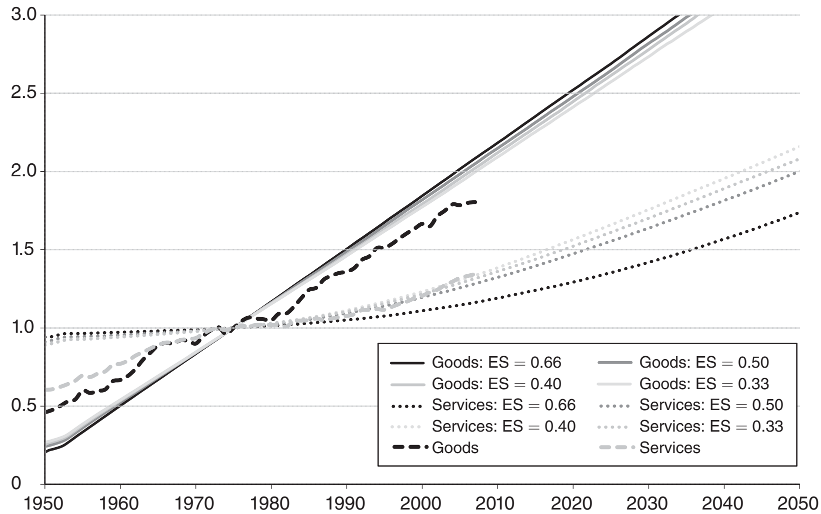

Figure 8. Aggregate Productivity (*Data and Model*)

average growth in both sectors, we show that the model can generate the *acceleration* of growth in services. Given its focus on long-run growth, our theory is not equipped to capture more medium-term phenomena, and thus misses the goods productivity slowdown in the early 1970s and the positive services productivity growth in the 1950s and early 1960s.

As services productivity growth increases, the shift of workers out of manufacturing into services slows down. In Figure 9 this slowdown is more noticeable in the model than in the raw data. However, the model is a closed economy, whereas the United States is an open economy. Since the declining share of workers in the goods sector is related to a declining consumption share, we should adjust the data for the fact that an increasing share of manufactured goods are imported from overseas. Once we adjust for this by computing the employment shares we would need if the United States were a closed economy, the slowdown in the shift out of the goods sector becomes readily apparent and similar to the one in the model. Note furthermore that as time passes, services productivity growth slowly catches up with that of goods. Eventually, if we were to let the model run for long enough, both sectors would grow at a constant common rate. It is the process of shifting employment to the sector that innovates less that equates productivity growth in both sectors asymptotically, thus putting the economy on a balanced growth path. In one of the robustness checks we will show an example where such a balanced growth path is reached early on.

Because of trade costs, as employment moves out of the goods sector, the rising service sector tends to locate in the vicinity of the already existing goods cluster. In line with the actual data in Table 1, this incentive to collocate implies that the service sector becomes increasingly concentrated in space. This is apparent in the top-left

an alternative measure that takes into account the spatial heterogeneity, $\int_0^1 x_i(\ell, t)\,\theta_i(\ell, t)\,d\ell / \int_0^1 (\hat{L}_i(\ell, t)\theta_i(\ell, t))^{\mu_i} d\ell$. The results are very similar.

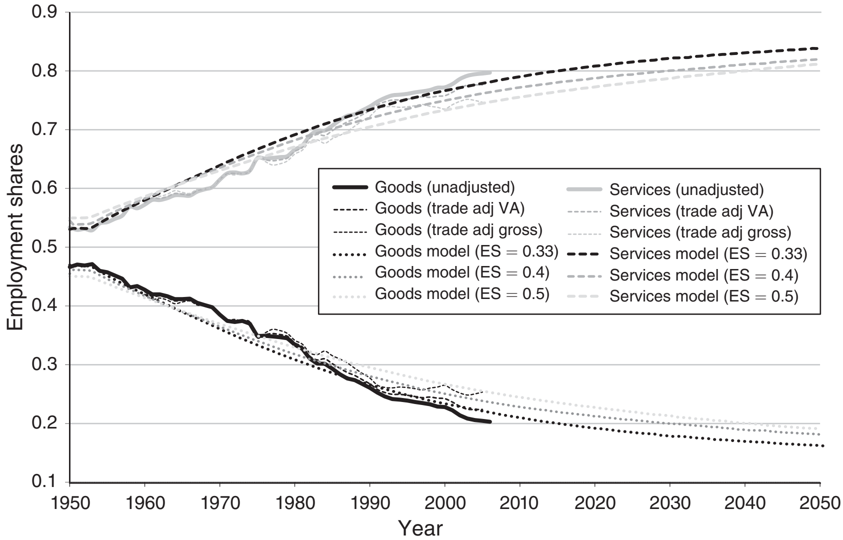

Figure 9. Employment Shares (*Data and Model*)

panel of Figure 10, which shows the standard deviation in the goods sector relative to that in the service sector. Note that a greater standard deviation points to economic activity being spatially more concentrated. A decline in the relative standard deviation therefore implies goods becoming relatively more dispersed, a result of services becoming increasingly concentrated. The model predicts that in the future, as innovation in the sector increases progressively, the relative standard deviation in manufacturing will climb up again.

Once productivity growth accelerates in the service sector, wage growth accelerates (bottom-right panel of Figure 10). This is consistent with the evidence in Figure 4, where wages (as measured by value added per worker) start growing faster around 1995. Utility grows throughout, since productivity growth in any industry always increases welfare independently of the relative price and labor reallocation effects. There is also an acceleration in utility growth, but it is smaller than the one for wages.

The take-off of the service sector increases the demand for land. The collocation of the existing goods cluster and the emerging service cluster further enhances this competition. This explains the acceleration in land rents after 1995 (top-right panel of Figure 10). The land rents distinguish between the value of land specialized in each sector and the value of the diversified portfolio of land held by all agents. Note from the figure how the value of manufacturing land decreases as technology in manufacturing improves and less land is required in the sector. The value of service land, on the other hand, increases throughout. Once innovation in the service sector accelerates, both the value of the portfolio of land and manufacturing land rents start increasing much faster, since both sectors are now competing for the same land close to each other. This is consistent with the US data presented in Figure 5, and the timing coincides with the acceleration in service productivity in Figure 6.

The initial increase in manufacturing productivity, together with an elasticity of substitution of less than one, also implies that the relative price of manufactured

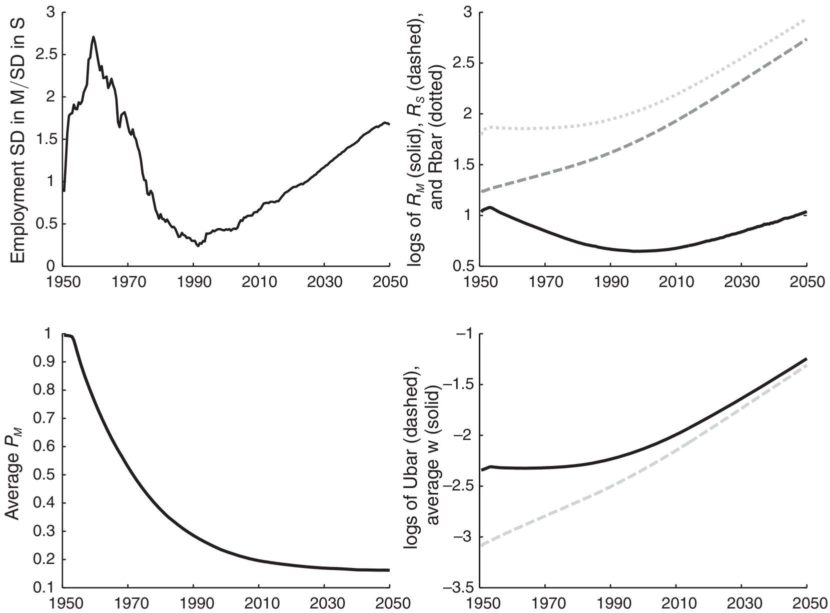

Figure 10. Spatial Concentration, Land Rents, Prices, and Wages (*Model*)

goods declines over time (bottom-left panel in Figure 10). Once service productivity accelerates, the price stabilizes and declines much more slowly. Compared to the data in Figure 3, the magnitude of the drop is too large, and there is too much of a slowdown in the decline in the last decade and a half. The slowdown in the model is a consequence of the increased productivity growth in services. As argued before, the reason for why it is less apparent in the data may be related to increased trade with developing countries, a feature which is absent from the model.

Once the service sector takes off, the increased competition for land should be particularly severe in those areas where the goods cluster and the service cluster collocate. Both sectors do not only want to concentrate in space, but they want to do so next to each other to save on transport costs. As those highly desirable locations become increasingly expensive, more far-off places continue to be cheap. If so, we should witness increased dispersion in land prices. This is indeed the case, as can be seen in Figure 11, which shows the predicted distribution of land rents from the model, and compares it to that in the data.

It is not surprising that the overall increase in land prices between 1995 and 2005 is larger in the data than in the model. Our model proposes a theoretical reason for why land prices started increasing in the mid-1990s, but does not allow for any deviations in land prices from their fundamental values. In that sense our theory is meant to capture only the permanent increase in land prices during the recent boom-bust cycle. Therefore, the smaller increase in land prices in the model than in the data is exactly what we would expect. At the trough of the bust, in 2011, the real value of housing had dropped back to the level of 2000. Thus, the theory suggests that the initial increase in land rents from 1995 to 2000 was related to fundamental forces. More importantly, the core mechanism in our theory emphasizes

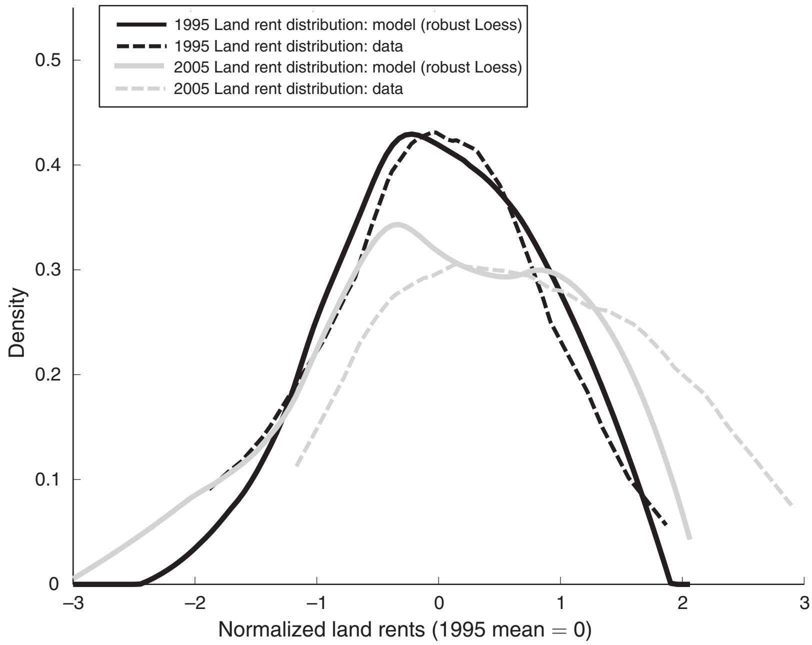

Figure 11. Land Rent Density (*Data and Model*)

the increased competition for land, and thus the increased dispersion in land prices. During the recent bust, this dispersion, if anything, has further increased. Using updated land prices from Davis and Palumbo (2008), the standard deviation of the log of land prices, went from 0.87 in 1995 to 1.07 in 2005 and further increased to 1.24 in 2010. This steady increase gives us confidence that the mechanism in this paper is relevant.[33]

As the service sector takes off and collocates close to the existing goods cluster, the rising land price makes it more expensive for existing goods firms to produce and innovate. This gives them an incentive to relocate to less dense locations. This evolution is shown in Figure 12, which shows the degree of specialization across time and across space. Initially, locations close to the upper border are fully specialized in manufacturing, whereas locations close to the lower border only produce services. Starting around 1990, the goods sector slowly starts moving out, and by 2050 the situation is reversed, with services having replaced goods at the upper border. While our model is too stylized to capture the true geography of the United States, this evolution resembles how in recent decades services have increasingly displaced manufacturing in the Northeast and the Midwest, with manufacturing moving South.

[33] The two-sector nature of our model generates a bi-modal distribution, with the more rightward mode mostly representing locations specialized in services and the more leftward mode corresponding to locations mostly specialized in manufacturing. The intuition for this result is as follows. Initially, when innovation in the service sector is nascent, service producers already have an incentive to concentrate in locations close to the manufacturing clusters, because of the proximity to consumers. This bi-modal distribution is not noticeable in the data, probably because the model distinguishes between land used for services and land used for goods, whereas the data are based on residential land use, thus ignoring differences in the evolution of the value of land in function of its use.

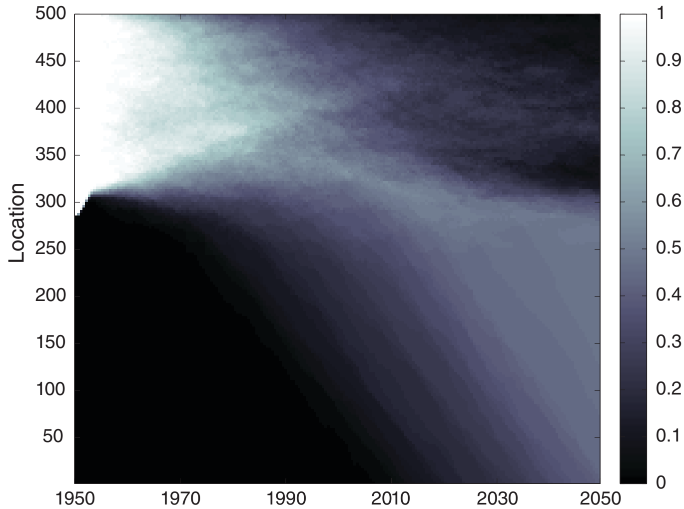

Figure 12. Average Sectoral Specialization ($\theta = 1$ *implies a location is specialized in goods*)

Overall, the model is able to quantitatively match some of the main macro stylized facts, such as the increasing labor share in services and the take-off in services productivity growth, and some of the main spatial stylized facts, such as the increase in the level and dispersion of land rents. It is also able to qualitatively account for many of the other key observations highlighted in the empirical section. The good match between the dispersion of land rents in the model and in the data lends credibility to the view that some of the forces described in the theory have important spatial effects. These findings underscore the need of having a model with many locations that is able to capture both the main macro stylized facts and some of the more salient spatial stylized facts.

C. *Comparative Statics*

In this section we study the impact of some of the key parameters of the model. First, we are interested in understanding how some of the spatial parameters, such as those related to transport costs and technology diffusion, affect spatial dynamics. Second, we also explore the effect of increasing the share of land in production. Third, we analyze how different elasticities of substitution modify the behavior of the economy.

Diffusion of Technology.—Figure 13 shows the impact of stronger technology diffusion. The different pictures present the evolution of productivity over time and space in both sectors. Since these are three-dimensional objects, we present shaded contour plots. Darker areas represent lower productivity, and lighter areas represent higher productivity levels. These pictures are helpful in identifying the areas in which innovation is happening and how clusters of innovation evolve over time.

The top panels show the evolution of productivity over time and space in the benchmark case for the goods sector (top-left) and the services sector (top-right). The

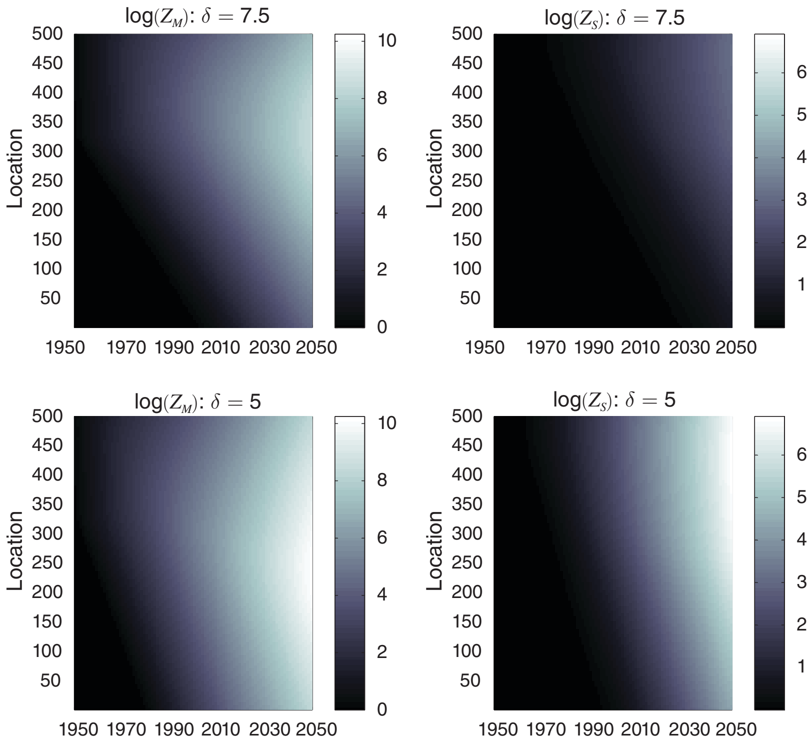

Figure 13. Comparative Statics on Technology Diffusion

picture that emerges is consistent with our previous discussion. The high-productivity goods locations are initially located relatively close to the upper border. When the service sector starts innovating, it has an incentive to collocate. The service cluster therefore emerges close to the goods cluster. This finding is consistent with the evidence on co-agglomeration: Kolko (1999) and Ellison, Glaeser, and Kerr (2010) show that industries that trade with each other tend to locate close to one another. More generally, firms locate close to large markets for their products. This type of clustering has been particularly important in the retail industry. Lagakos (2009) discusses the emergence of Walmart superstores in this context.

As collocation increases the competition for land, the goods cluster starts to gradually move down. This geographic move down is easier to see for specialization (Figure 12) than for productivity (Figure 13) because there is inertia in a location's productivity. That is, a highly productive goods-producing location that loses employment does not become less productive, but starts innovating less. It will therefore only lose productivity in relative terms, not in absolute terms. Consistent with this, we can see that the most productive good-producing locations are slowly moving down as time goes by.

The bottom panels give the same information as the top panels, but for a lower value of the diffusion parameter, $\delta = 5$ (instead of $\delta = 7.5$). This slower spatial decay implies that diffusion is stronger. Not surprisingly, this leads to productivity growth in the service industry accelerating earlier. As as result of the earlier take-off of services, the goods cluster moves down faster. In addition, productivity differences across locations are mitigated, as greater diffusion reduces the productivity advantage of any particular location.

Transport Costs.—In our theory transport costs have the standard negative effect on static welfare that is familiar from trade models. Higher transport costs imply that more goods are lost in transportation and agents obtain fewer gains from specialization. But here higher transport costs also imply that it is more important to produce in areas close to locations where the other sector is producing. So if transport costs are relatively high and one sector is already somewhat clustered, economic activity in the other sector will cluster around it. In our benchmark case, the reason is that relative prices of manufactured goods will rise as we move away from manufacturing clusters (goods have to be transported and are therefore more expensive). Hence, the service-producing locations close to manufacturing areas have a larger scale, which results in more incentives to innovate. Note also that once innovation starts in one location, it increases productivity in other close-by regions and therefore leads to even more innovation in the cluster. So diffusion, although not necessary to obtain this effect, reinforces it.

The next proposition proves this positive effect of higher transport costs on innovation for an initial condition in which the industry is not innovating and therefore not growing. We refer to this industry as stagnant.

PROPOSITION 3: *Consider any level of transport costs κ such that aggregate productivity in industry i is stagnant in some period t. Then, an increase in κ weakly increases aggregate productivity, and it strictly increases aggregate productivity for some level of κ, in industry i at time t.*

An immediate corollary of this proposition is that, if one of the industries is growing, productivity growth in the stagnant industry jump-starts earlier the higher are transport costs. Recall that innovation takes off when aggregate productivity growth in the other industry shifts enough labor to the stagnant sector. With higher transport costs, the increasing labor share of the stagnant sector will be more densely clustered, leading it to jump-start earlier.

To illustrate the logic above, we analyze the effect of making transport costs lower. This should delay the take-off of the service industry. Figure 14 shows the results. Once again, the top panel shows the benchmark for $\kappa = 0.08$, whereas the bottom panel shows the case for a lower transport cost $\kappa = 0.07$.[34] As expected, lower transport costs imply services start innovating later. In terms of welfare, the present discounted value of utility drops when transport costs are lower, from 2.64 when $\kappa = 0.08$ (benchmark) to 2.36 when $\kappa = 0.07$. Lowering transport costs further to $\kappa = 0.06$ reduces welfare further, but by a smaller amount, to 2.32. Of course, if a reduction in transport costs eliminates innovation in services completely, the welfare effect would become negative. Similarly, if transport costs were high but both

[34] The top panels in Figures 13 and 14 are the same, but the shading is different in order to make them comparable with their respective comparative statics exercise.

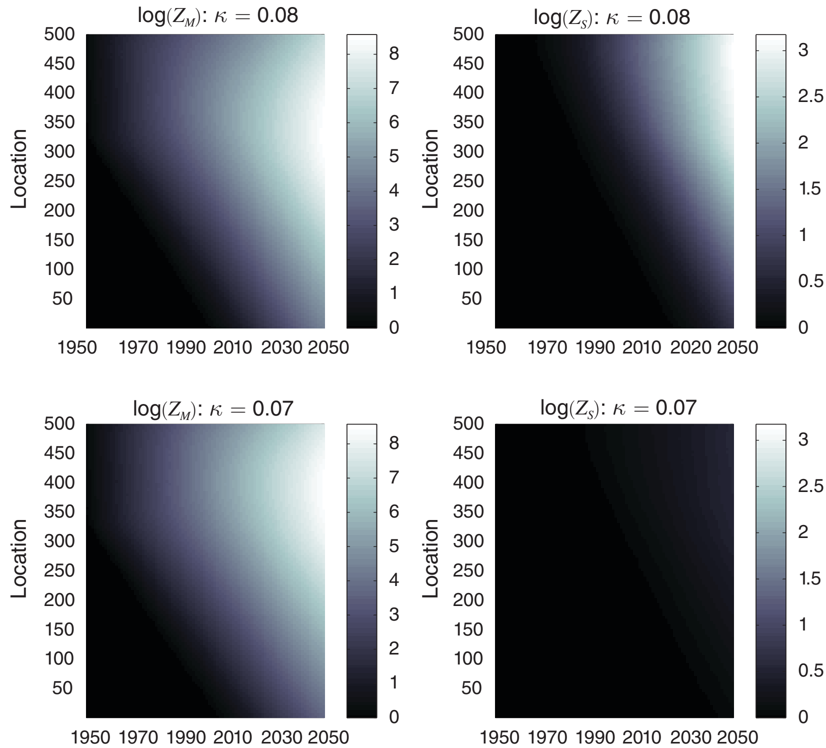

Figure 14. Comparative Statics on Transport Costs

sectors were to innovate from the start, then further increasing transport costs would have the usual negative effect.

Our result shows that, in contrast to standard economic geography models, the static losses from higher transport costs may be outweighed by the higher incentives to innovate in certain areas. The result is that growth and overall welfare may increase when transport costs are higher. Recall that the textbook two-region two-sector economic geography model with labor mobility concludes that higher transport costs lead to more dispersion (Krugman 1991; Puga 1999). The argument runs as follows: if transport costs are high enough and some factors are immobile, the cost of having to trade between the two regions ceases to compensate for the gains from agglomeration, so that it becomes beneficial for both regions to produce both goods. In as far as concentration of economic activity is related to economic growth, this implies a negative relation between transport costs and economic growth (Baldwin and Martin 2004).

Whereas in those models higher transport costs lead to more dispersion, in our model they lead to more concentration. The key difference is that in our model, as in Helpman (1997), both goods face transport costs. This implies that larger transport costs induce services to locate closer to manufacturing. This leads to services becoming less dense in areas far away from manufacturing and more dense in areas closer to manufacturing. The increase in the scale of production then leads to more innovation in service regions that locate close to manufacturing. In contrast to standard economic geography models, the collocation of both sectors thus generates the emergence of a service cluster close to the manufacturing cluster.[35] This collocation is facilitated in a world with many regions. The finding that higher transportation costs may lead to more innovation, growth and welfare underscores how having a rich spatial dimension leads to some novel economic effects.

The possibility of higher transport costs improving welfare can best be understood through a "second best" argument. In our model, the profits from innovation only last for one period. After that, profits get arbitraged away because workers can relocate and technology diffuses. This implies an externality, since firms do not get the full benefits from innovating. Higher transport costs bring the economy closer to its social optimum by increasing clustering and innovation, but come at the cost of losing resources. The optimal policy would be to introduce patents. However, because of the local scale effect in innovation, optimal patents would have to depend on time and location. Given its high information content, such a "first best" policy is probably infeasible.

Elasticity of Substitution.—As mentioned in the section on calibration, certain authors have argued that the elasticity of substitution may be higher than 0.5, whereas others find evidence that it is lower. In Figures 8 and 9 we show how productivity growth, and the corresponding change in the sectoral labor shares, depends on the elasticity. From standard aggregate logic we would expect a lower elasticity of substitution to lead to faster innovation in services. The reason is simple: as the elasticity of substitution drops, the initially higher productivity growth in manufacturing moves a larger share of the labor force into services, implying higher service density and faster growth.

However, the effect of changes in the elasticity of substitution also has a spatial component. Changes in the elasticity of substitution affect the willingness of agents to substitute services for manufactured goods and, therefore, their decision to locate in space. If the elasticity of substitution is low, agents are not willing to substitute consumption across sectors and so, given positive transport costs, care more about locating near areas that specialize in a different sector. This prevents the emergence of large service clusters, since those would increase the average distance to neighboring manufacturing areas. This lowers the scale of service-producing regions, implying less innovation in services.

The result of these different effects leads to a non-monotonic relation between the elasticity of substitution and innovation. Starting from our benchmark value of 0.4, Figure 8 shows that when we increase the elasticity of substitution to 0.5 or to 0.6, the service industry takes off later. However, when we lower the elasticity of substitution to 0.33, the argument is reversed: although the standard macro argument would suggest that take-off happens earlier, it does not. As for the employment shares, Figure 9 shows no such non-monotonicity. A lower elasticity of substitution always implies a greater shift out of goods into services. This implies that the nonmonotonicity in the relation between the elasticity of substitution and productivity

[35] Of course, in principle another possibility would be for manufacturing to disperse and locate closer to services, thus implying less concentration. This does not happen because the initial cluster of manufacturing gets reinforced over time through innovation and diffusion, a force absent in Helpman (1997). In other words, innovation and diffusion imply that there are more incentives for services to concentrate and form a cluster close to manufacturing than for manufacturing to disperse and locate close to services.

growth is driven by where sectors locate, rather than by their aggregate size. That is, the non-monotonicity is the result of spatial interactions.

Land Congestion.—We now discuss how our results change when we increase the share of land in production. Figure 15 reports the impact of reductions in the exponent on labor in the production function from $\mu_i = 0.6$ to $\mu_i = 0.5$. This is equivalent to increasing the share of land from 0.4 to 0.5. Because of the higher congestion for land, the top panel shows that the two clusters no longer collocate, and we get a clean geographic separation, with the goods cluster locating in the upper area and the services cluster locating in the lower area.

Because our model restricts $\gamma + \mu_i$ to be equal to 1, the reduction in μ_i implies an increase in γ. As this makes the technology function less concave, growth is slightly higher, and more importantly, services grow from the very beginning. Furthermore, as can be seen in the bottom panel of Figure 15, both sectors now grow at the same constant rate. In other words, the economy is on a balanced growth path. When presenting our benchmark exercise, we argued that the economy would eventually converge to a steady state if we let it run for enough periods. Figure 15 illustrates what such a steady state looks like.

III. Conclusion

In this paper we have presented a spatial dynamic growth theory. To deal with the intractability of dynamic spatial frameworks, we have assumed that labor is mobile, ownership of land and firms is diversified, and innovation shocks are spatially correlated and diffuse over time. These features imply a perfectly competitive environment in which we prove that firms' decisions to innovate are static. This is the key to having a computable dynamic spatial theory which is rich enough to be contrasted with the data.

To illustrate the potential of our theory, we have applied it to the macroeconomic and spatial evolution of the US economy in the last half-century. We find that employment relocation is crucial in balancing innovation across sectors. As innovation in one sector increases relative to the other sector, employment shifts from the more innovative to the less innovative sector. Relative prices imply that this labor locates close to clusters of the leading sector, thereby increasing the incentives for innovation in the lagging sector. These effects lead to a balanced growth path in which aggregate growth in the economy eventually stabilizes.

The model is able to quantitatively match some of the main macroeconomic and spatial features of the US economy since World War II. In particular, it accounts well for the employment shift out of manufacturing into services, the timing and magnitude of the productivity take-off in services, and the increased dispersion in land rents since 1995. Qualitatively, the model also captures other key observations, such as the increase in wage growth starting in the mid-1990s and the growing spatial concentration of the service industry.

Of course, this model should be viewed as a first step in developing a spatial growth theory. It is unable to quantitatively match some features in the data. For example, the change in employment shares leads to a somewhat too large reduction in the relative price of goods. Exploring other specifications of preferences (such as

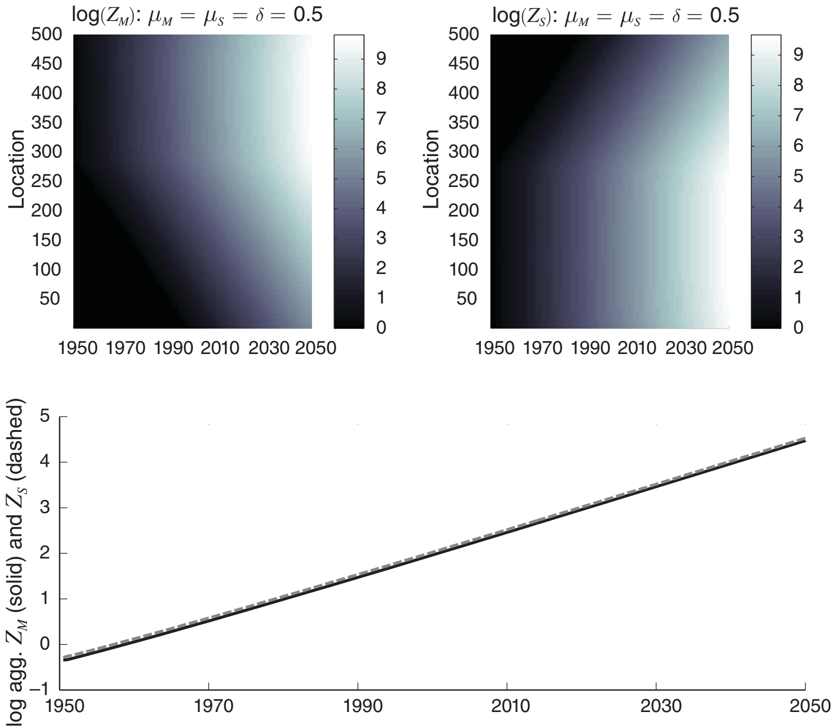

Figure 15. Increasing Land Congestion

non-homotheticities as in Buera and Kaboski 2012) or innovation costs may yield a somewhat better fit. The model also abstracts from many geographic features.

Still, by introducing a link between geography and innovation in a model with many locations, our theory is not only able to account for certain spatial stylized facts, such as the increased dispersion of land rents, it also makes the point that introducing space is potentially important to understand the aggregate economy. For example, the productivity take-off in the service industry is related to its spatial concentration, so that any forces that affect the incentive to concentrate in space, such as transportation costs, are likely to affect the economy's overall growth rate.

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