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Agglomeration and Productivity: New Estimates and Macroeconomic Implications

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Agglomeration and Productivity: New Estimates and Macroeconomic Implications*

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Abstract

We construct a dynamic general equilibrium model of cities and aggregate growth and use it to estimate the effects of local agglomeration on aggregate consumption growth. Agglomeration affects growth through the impact of the amount of economic activity per unit of land on local productivity. Our model predicts a relationship between wages, prices, and labor inputs which we use to estimate the net effect of agglomeration on local productivity with panel data on US cities. We estimate that doubling output in a location raises productivity of firms in that location by 6.1%. According to our model, this seemingly small estimate translates to a large effect of agglomeration on aggregate economic growth: along a balanced growth path, agglomeration accounts for 10% of growth in per-capita consumption.

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1 Introduction

There is widespread agreement that cities emerge because of *agglomeration* effects. For example, workers are more productive when they are near other workers and production is more efficient when transportation costs are reduced. Cities emerge because of agglomeration effects, and most aggregate growth actually occurs in cities. So, how important is local agglomeration for aggregate growth? To answer this question, we build and estimate a dynamic general equilibrium model of cities and aggregate growth in which city-based agglomeration affects per capita consumption growth. We estimate the structural parameters of our model using panel data and use these estimates to quantify the impact of local agglomeration on aggregate per capita consumption growth.

Our model embeds into the neoclassical growth model a version of Roback (1982)'s model of cities, augmented with agglomeration effects in the way proposed by Ciccone and Hall (1996). Production is a function of capital, labor and land. Productivity of each firm in a city is increasing in the total quantity of city output per unit of land used in production, but firms do not take this into account when making their decisions. We study the model's stationary competitive equilibrium and show that along the balanced growth path per capita consumption growth depends on exogenous neutral technical change, the rate of increase in the cost of developing new land for production, a parameter governing the net effect of agglomeration on productivity, and labor's share of income. Using our model and panel data for a sample of US cities we estimate the net impact of the density of economic activity on local productivity, thereby yielding the contribution of agglomeration to aggregate per capita consumption growth.

Our model predicts a specific relationship within each city between wages, output prices, land prices, labor inputs, and the level of the neutral technology. We exploit this relationship to estimate the key parameter underlying the impact of agglomeration on local productivity and aggregate growth. Our data-set merges wage and labor input data from the Current Population Survey, output price data from the Bureau of Economic Analysis (BEA), and data on land prices from a study by Davis and Palumbo (2008). This annual panel data-set covers 42 metropolitan statistical areas (MSAs) over the 1985-2004 period. The twenty year panel sample is particularly amenable to applying modern dynamic panel data methods and we use the Arellano and Bover (1995) estimation strategy. We find that that local agglomeration effects are small but statistically significant: a doubling of output per unit of productive land in a city increases productivity of each firm in the city by 1.2 percent. While seemingly small at the the local level, agglomeration has a substantial effect on aggregate consumption. Combined with evidence on trends in the cost of new productive land, the agglomeration estimate and our model of balanced growth imply that local agglomeration accounts for 11% of per capita consumption growth.

Our work is most closely related to that of Ciccone and Hall (1996). Using a similar model of agglomeration they estimate a much larger net effect of agglomeration on local productivity. Based on our model of growth, their estimate translates to close to 20% of aggregate consumption growth being due to local agglomeration. Our analysis goes beyond their's in several ways. First, we show how to translate estimates of the net impact of agglomeration on local productivity into the impact of agglomeration on aggregate growth. Second, we use 20 years of panel data instead of a single cross-section. Third, we allow for alternative uses of land at a location compared to assuming that all land at a location is used in production. Fourth, we allow for the composition of output across locations to differ instead of assuming output is homogeneous. In our empirical analysis we show how these differences affect our results.

Our work is also related to the literature on endogenous growth. In that literature the most common source of endogenous growth is a human capital externality. The agglomeration effect we discuss is closely related to that kind of externality. Much empirical work has been dev work is related to [Glaeser and Mare (1996), Henderson (2005), Rosenthal and Strange (2003), **TBD** .... old literature, ciccone-hall, ciccone-peri and related cites, island models of cities/other island models, production function, sources of growth - neutral, investment-specific, agglomeration...., Lucas - only externality can imagine is the one that creates cities].

The rest of the paper is organized as follows. The next section describes our model economy and its balanced growth path. Section three describes some implications of the model, including the equation underlying our estimation. Section four describes our econometric strategy and section five the data. Section six discusses our empirical results and quantifies the impact of agglomeration on per capita consumption growth. Section seven concludes.

2 Model Economy

Our model embeds a version of Roback (1982)'s model of cities, modified to include agglomeration effects in the way proposed by Ciccone and Hall (1996), into the neoclassical growth model.

2.1 Economic Environment

We consider a discrete time infinite horizon model with complete markets and no aggregate uncertainty. The economy consists of a unit measure of locations, called cities. Competitive firms in each city produce an intermediate good unique to the city. Each city is surrounded by a limitless supply of undeveloped land which can be developed into a form suitable for habitation or production at a cost. Competitive firms, which can be located anywhere, combine the intermediate goods into a final good. There is also a representative household composed of a unit measure of members. The large household structure allows for full risk sharing within each household, a standard device for studying complete markets allocations.

The representative intermediate goods producer in each city uses a Cobb-Douglas technology with inputs of land, l labor, n and capital, k. Total factor productivity (TFP) in each city, x is taken by households and firms to be given and is specified as

$$x = z^{(1-\alpha)\phi} \left[\frac{y}{l} \right]^{\frac{\lambda-1}{\lambda}}$$

where z is an exogenous city-specific stationary stochastic term and y is total city output.[1] The ratio of output to land is called the *density of economic activity*. If $\lambda = 1$ density has no impact on productivity and if $\lambda > 1$ firms' productivity is increasing in

[1] We could incorporate non-stationary technology along the lines pursued by Alvarez and Shimer (2008) In their model idiosyncratic technology follows a random walk. They achieve a stationary aggregate distribution by assuming that locations are destroyed with constant probability replaced instantaneously by the same number of new locations drawn from the stationary distribution of technology.

density. Ciccone and Hall (1996) show how this production technology can be derived as the reduced form of a micro founded model. Final goods are produced by combining the output of each city using a constant-elasticity-of-substitution production function in which, for simplicity, the goods produced by each city enter symmetrically. These goods are converted one-for-one into consumption and investment goods, and into newly developed land at the rate v, which is stochastic and idiosyncratic to each city.[2] The differences in land development costs across locations could emerge due to differences in the quality of land or legal restrictions on developing new land.

Each household member supplies one unit of labor inelastically and enjoys utility from consumption, c and housing, h. For simplicity housing is just land; there are no structures in the model. The household derives income from labor and capital by allocating its members and its stock of capital, K across the cities, and by collecting rent on its land, d. Each period the household's members are randomly allocated across cities at zero cost, after observing the current level of TFP and land development costs in each city. Household members must consume and enjoy housing in the same city that they work. Capital is perfectly mobile and along with land is also allocated after the household observes TFP and land development costs.

Land and labor are traded in local markets while the intermediate goods, the final good, and capital services are traded in economy-wide markets. For simplicity, we initially assume the aggregate level of technology and the number of households are constant and focus on a stationary equilibrium.

2.2 Stationary Competitive Equilibrium

The stationary competitive equilibrium for the case without density effects, $\lambda = 1$, consists of the following. In each period, the household chooses how much to consume of the final good and housing, and how to allocate its members and stock of capital to each city, in order to maximize the equally weighted utility of all the household's members subject to the technological constraints on allocating members across cities, taking as given the stochastic processes for TFP and land development costs in each city and all prices. Each intermediate and final goods producer maximizes profits by

[2] The underlying technology for land development is Leontief in undeveloped land and the final good.

choosing inputs taking their prices as given. The aggregate intermediate and final good and capital service markets and the local labor and land markets all clear.

In cases with a positive effect of density on productivity, $\lambda > 1$, an additional *productivity consistency* condition must be satisfied. Recall that we assume that the distribution of TFP is taken as given by households and firms. When $\lambda > 1$ the decisions of households and firms affect the TFP distribution, through the resulting distribution of density. In a competitive equilibrium, the solutions of the household and firm problems must generate the underlying distribution of productivity that is taken as given when calculating those solutions.

2.3 Planning Problem

We initially focus on the case without any impact of density on productivity, $\lambda = 1$. The competitive equilibrium for this case solves a planning problem and the two welfare theorems apply. Without aggregate uncertainty decision rules are stationary and so we drop the time subscript where appropriate. Let s denote the vector of exogenous state variables for a city, $s = (x, v)$. Instead of indexing cities on the unit interval, it is convenient to index them according to their history of realizations of the state vector, s^t. Let $\pi(s^t)$ be the probability density of cities across histories.

Since the household perfectly insures itself against consumption risk, the planning problem can be written as

$$\max \sum_{t=0}^{\infty} \beta^t \int n(s^t) \left[\ln c_t + \psi \ln h(s^t)\right] \pi(s^t) ds^t$$

subject to

$$
\begin{aligned}
c_t \int n(s^t)\pi(s^t)ds^t + K_{t+1} - (1-\kappa)K_t &+ \int v(s^t)\left[d_{t+1}(s^t) - d_t(s^{t-1})\right]\pi(s^t)ds^t \\
&\leq \left[\int y(s^t)^\eta \pi(s^t)ds^t\right]^{\frac{1}{\eta}}; \qquad (1) \\
y(s^t) &\leq x_t l(s^t)^{1-\phi} k(s^t)^{\alpha\phi} n(s^t)^{(1-\alpha)\phi}, \ \forall s^t; \\
\int k(s^t)\pi(s^t)ds^t &\leq K_t; \\
n(s^t)h(s^t) + l(s^t) &\leq d_t(s^{t-1}), \ \forall s^t; \qquad (2) \\
\int n(s^t)\pi(s^t)ds^t &\leq 1; \\
& K_0 \text{ and } d_0 \text{ for each city given.}
\end{aligned}
$$

The term on the right-hand side of (1) is the function mapping intermediate into final goods. In this mapping $\eta \leq 1$ and in addition we assume $\eta \neq 0$. Intermediate goods are perfect substitutes if $\eta = 1$ and as $\eta \to -\infty$ the final good is a Leontief function of intermediate goods. In writing the final good aggregator we have made use of the fact that intermediate good production is identical in cities with the same TFP history. This follows from the symmetric way in which intermediate goods enter into the final good aggregator. The variables c_t and $h(s^t)$ are in per capita terms. Finally $\psi > 0$ and $0 \leq \kappa \leq 1$ is capital's rate of depreciation.

Let the Lagrange multipliers for the above restrictions be $\beta^t\vartheta_t$, $\beta^t\vartheta_t\pi(s^t)q(s^t)$, $\beta^t\vartheta_t r_t$, $\beta^t\vartheta_t\pi(s^t)p(s^t)$ and $\beta^t\vartheta_t\theta_t$. Then the first order conditions for c_t, $y(s^t)$, K_{t+1}, $d_{t+1}(s^t)$, $k(s^t)$, $l(s^t)$, $h(s^t)$ and $n(s^t)$ are

$$
\begin{aligned}
\frac{1}{c_t} &= \vartheta_t; \qquad (3) \\
q(s^t) &= Y_t^{1-\eta} y(s^t)^{\eta-1}; \qquad (4) \\
\vartheta_t &= \beta\vartheta_{t+1}\left[r_{t+1} + 1 - \kappa\right]; \\
v(s^t) &= \beta\frac{\vartheta_{t+1}}{\vartheta_t}\int\left[v(s^t, s_{t+1}) + p(s^t, s_{t+1})\right]\frac{\pi(s^t, s_{t+1})}{\pi(s^t)}ds_{t+1}; \qquad (5) \\
r_t &= \alpha\phi q(s^t) x_t l(s^t)^{1-\phi} k(s^t)^{\alpha\phi-1} n(s^t)^{(1-\alpha)\phi}; \qquad (6) \\
p(s^t) &= (1-\phi)\, q(s^t) x_t l(s^t)^{-\phi} k(s^t)^{\alpha\phi} n(s^t)^{(1-\alpha)\phi}; \qquad (7) \\
\frac{\psi}{h(s^t)} &= \vartheta_t p(s^t); \qquad (8) \\
\ln c_t + \psi \ln h(s^t) &= \vartheta_t\theta_t + \vartheta_t\left[c_t + p(s^t)h(s^t) - w(s^t)\right]; \qquad (9)
\end{aligned}
$$

where

$$w(s^t) = (1-\alpha)\phi q(s^t) x_t l(s^t)^{1-\phi} k(s^t)^{\alpha\phi} n(s^t)^{(1-\alpha)\phi-1} \tag{10}$$

is the marginal product of labor in cities with history s^t, and

$$Y_t = \left[\int y(s^t)^\eta \pi(s^t) ds^t \right]^{\frac{1}{\eta}}$$

denotes aggregate final good production.

In the competitive equilibrium corresponding to the solution to this planning problem we use the final good as the numeraire. Then, $v(s^t), w(s^t)$, $p(s^t)$ and $q(s^t)$ are the price of new land, wages, rent on existing land and intermediate good prices at cities with history s^t, and r_t is the economy's rental rate on capital.

Most of the first order conditions are familiar and need no discussion. There are some differences with the traditional growth model and these are worth discussing briefly. First, as indicated by (5), (7) and (10), the price of new land, rent on existing land and wages are idiosyncratic to location. That wages depend on the local conditions follows directly from the inclusion of housing in preferences. Without a preference for housing, wages would be equalized across cities. This can be seen by inspecting (9). The only way for this condition to hold without housing is for wages to be equalized across cities.

Second, equation (5) describes optimal land development in each city. The price of new land depends on the realization of the cost in terms of final goods of land development, v in each city. The equation states that the price of new land in each city at any date equals the discounted expected value in the following period of rent on that land plus the price of new land. Equivalently, the price of new land equals the discounted expected value of future rents on that land.

Third, the *location indifference* condition (9) does not appear in the growth model. This condition contrasts with the static Roback (1982) model where utility is equated across cities. In our dynamic model with complete markets, utility net of the consumption price of the transfer is equated. Since transfers sum to zero, *ex ante expected* utility is equalized.

Equations (3), (8) and (9) combined imply that utility is not identical for each household member but rather household members assigned to relatively high wage cities enjoy a relatively low quantity of housing and thus relatively low utility. As mentioned, this is at odds with a standard assumption in models of Urban economics such as Roback (1982) that the level of utility is equated across all agents in an economy. The result that the planner assignes lower utility to residents in more productive locations is not a result of our production framework, our specification of log-separable preferences, or to any model dynamics, but is a rather general result. It is easiest to understand the intuition in an environment with only two cities; where labor is the only factor of production such that production in city i is $z_i n_i$; and where household members have log-separable preferences for consumption and land for housing. Suppose that the cities are otherwise identical except for the fact that $z_2 > z_1$. It is not optimal for the planner to allocate half the agents to city 1 and half to city 2 (which, when consumption is equalized across agents as implied by log-separable preferences, ensures utility is equalized across agents as well). The planner could move a tiny fraction of agents from city 1 to city 2. Total output and thus consumption for everyone would increase. Although residents of city 2 would have less land for housing, residents of city 1 would have *more* land for housing and therefore (absent concavity effects) there would be no net impact on the average utility from housing from this movement of agents.

Without density effects the competitive equilibrium exists and is unique, by standard arguments. With density effects, the competitive equilibrium is found by finding the planning problem's solution that satisfies the productivity consistency condition. We have not found conditions under which a solution to this fixed point problem exists or is unique. However, using the argument in Kehoe, Levine and Romer (1992) we know that for λ sufficiently close to unity, there exists a unique competitive equilibrium, because the model without density effects has a unique equilibrium. Equilibrium existence and uniqueness under the size of density effects we estimate remain open questions since we do not need to find a solution of the model to identify the impact of density on local productivity or quantify the density effect on aggregate growth, and so do not do so in this paper.

Note that in our framework it is critical that the planner does not internalize the density externality in production for the planner to allocate a non-degerate quantity of land to be used in the production of city output.[3] If the net impact of density

[3]This is in contrast to the model of cities and growth of Rossi-Hansberg and Wright (2005), in

on production is positive, such that $\delta = \phi\lambda > 1$, then city output is increasing as land used in prodution falls. This implies that if the planner were to internalize the density externality the planner would assign as little land as possible to production in each MSA.

2.4 Balanced Growth

Our choices of preferences and technology guarantee that the model has a balanced growth path. We now derive the balanced growth path and show how to use this to quantify the impact of local agglomeration effects on aggregate consumption growth. For this we assume the neutral technology and development costs in each city evolve as

$$z_t = \gamma^t \tilde{z}_t \text{ and } v_t = \tau^t \tilde{v}_t \tag{11}$$

where $\tilde{z}_t$ and $\tilde{v}_t$ are stationary random variables, $\gamma \geq 1$, and $\tau \geq 1$. The number of households grows at the rate $\mu \geq 1$. While we continue to assume that workers are homogeneous, the derivation here also holds under the model of worker heterogeneity considererd below.

The aggregate resource constraint (1) implies per capita consumption, capital and land, all in units of the final good, each grow at the same rate, denoted γ_c. The land constraints (2) imply that in each city per capita land used for production grows at the same rate as per capita developed land, which grows as the rate γ_c/τ. Output in a city is

$$y = z^{(1-\alpha)\phi} \left[\frac{y}{l}\right]^{\frac{\lambda-1}{\lambda}} l^{1-\phi} k^{\alpha\phi} n^{(1-\alpha)\phi.} \tag{12}$$

Let $\delta = \lambda\phi$. This parameter measures the net effect on productivity of diminishing returns to land, otherwise known as congestion, and density. Dividing equation (12) through by n yields an expression involving per capita variables:

$$y/n = z^{(1-\alpha)\phi} \left[\frac{y/n}{l/n}\right]^{\frac{\lambda-1}{\lambda}} [l/n]^{1-\phi} [k/n]^{\alpha\phi}.$$

Dividing this equation by the equivalent one for the previous period and making appropriate substitutions for the growth rates of the variables in the resulting expression,

which the planner internalizes human capital and employment externalities.

yields

$$\gamma_c = \gamma \tau^{\frac{\delta-1}{(1-\alpha)\delta}}. \tag{13}$$

Below we use this equation, in combination with estimates of δ, to quantify the contribution of agglomeration to aggregate consumption growth.

Equation (13) shows that per capita consumption growth depends on the rate of neutral technology growth and, if $\delta \neq 1$, the rate of growth in development costs as well. If the relative price of new land is growing, $\tau > 1$, then land growth will not keep up with output growth so that the density of economic activity must grow. If agglomeration effects outweigh congestion effects, $\delta > 1$, then this provides an endogenous source of consumption growth in addition to exogenous neutral technical change. Without any productivity effect of density, $\lambda = 1$ and $\delta = \phi$, and (13) implies

$$\gamma_c = \gamma \tau^{\frac{\phi-1}{(1-\alpha)\phi}}.$$

Since $0 < \phi < 1$, in this case per capita consumption growth is lower than the rate of growth of the neutral technology because of decreasing returns to land. Finally, if agglomeration and congestion effects cancel out, that is $\delta = 1$, then consumption growth equals the rate of neutral technology growth, as in the standard neoclassical growth model.

3 Implications of the Model

In this section we examine some implications of our model. To begin, we derive the key equation underlying our estimates of agglomeration's effect on local productivity. We then characterize the model's implications for the cross-sectional pattern of output, employment and prices. After this we consider three extensions to the model involving city-specific amenities,worker heterogeneity, and housing as a combination of land and structures.

3.1 Equation Underlying Our Estimation

Consider any two cities with different histories, indexed i and j, in some arbitrary period. Solving for output in (12) and dividing output in city i by that in city j yields

$$\frac{y_i}{y_j} = \left[\frac{z_i}{z_j}\right]^{\delta(1-\alpha)} \left[\frac{l_i}{l_j}\right]^{1-\delta} \left[\frac{k_i}{k_j}\right]^{\delta\alpha} \left[\frac{n_i}{n_j}\right]^{\delta(1-\alpha)}.$$

Using (6) to eliminate the capital terms in this last equation we have

$$\frac{y_i/l_i}{y_j/l_j} = \left[\frac{z_i}{z_j}\right]^{\frac{\delta(1-\alpha)}{1-\delta\alpha}} \left[\frac{n_i/l_i}{n_j/l_j}\right]^{\frac{\delta(1-\alpha)}{1-\delta\alpha}} \left[\frac{q_i}{q_j}\right]^{\frac{\delta\alpha}{1-\delta\alpha}} \tag{14}$$

Equation (14) is closely related to equation 19 in Ciccone and Hall (1996), which is the basis for their estimation equation. It differs in two key respects. First, because Ciccone and Hall (1996) assume intermediate goods are perfect substitutes in producing final goods, $\eta = 1$, their equation does not contain any output prices. In this case their equation is subject to an omitted variable bias. Second, they assume all land in a given location is used in production while we have competing uses for land. Since the allocation of land between residential and non-residential uses in U.S. cities is unavailable to us, we cannot use (14) as a basis for estimation. Further complicating our analysis, annual data on real city output that is produced by the BEA is available for too short a time period (2001-2006) to be useful.

We eliminate land and output from (14) using (7) and (10) to arrive at the key equation underlying our estimation:

$$\frac{w_i}{w_j} = \frac{z_i}{z_j} \left[\frac{p_i}{p_j}\right]^{\frac{\delta-1}{\delta(1-\alpha)}} \left[\frac{q_i}{q_j}\right]^{\frac{1}{\delta(1-\alpha)}}. \tag{15}$$

It is important to note that (15) follows directly from profit maximization by firms and the functional form of the production function. In particular, it does not depend on the assumption of perfect risk sharing or any assumptions about preferences. If we were to add other local factor inputs to the model with competing uses, such as energy, their prices would also appear in (15) in the same way that land prices do.

3.2 Characterization of the Cross-Section of Cities

It is useful to characterize the cross-sectional relationships among the model's endogenous variables. The implications of idiosyncratic development costs for the cross-section are ambiguous. Consequently, we proceed under the assumption that idiosyncratic variation in development costs is sufficiently small such that it does not impact the qualitative pattern of variation among the model's endogenous variables determined by idiosyncratic productivity alone. Our characterization strategy considers small perturbations to the exogenous component of technology of a given city, holding fixed all aggregate variables and local variables in other cities.

Combining (3), (8) and (9) and differentiating it is straightforward to show that

$$\frac{d\ln p}{d\ln z} = \frac{w\,n}{p\,nh}\frac{d\ln w}{d\ln z}. \tag{16}$$

It follows immediately that the model predicts land prices and wages are positively correlated in a cross-section of cities.

The cross-sectional relationship between employment and wages is derived as follows. From (2), (3) and (8)

$$\frac{d\ln l}{d\ln z} = \frac{p\,nh}{p\,l}\left[\frac{d\ln p}{d\ln z} - \frac{d\ln n}{d\ln z}\right]. \tag{17}$$

This derivation uses the fact that developed land in a city is fixed in a given period. Taking logs of (7) and (10) and subtracting one resulting expression from the other leaves an equation in employment, wages, land and its price. Substituting for land in this last equation using (17) and the price of land using (16) and solving for the employment elasticity yields

$$\frac{d\ln n}{d\ln z} = \frac{\frac{p\,l}{p\,nh}wn + wn - p\,l}{p\,nh + p\,l}\frac{d\ln w}{d\ln z} \tag{18}$$

Any empirically plausible calibration of the model will have labor's share exceeding land's share in production, *i.e.* $wn > p\,l$. From now on we assume that this condition is satisfied. It follows that employment is positively correlated with wages.

The relationships of output and its price with wages depend on the degree of substitutability of intermediate goods in the production of final goods. To see this, eliminate the local output price from (10) using (4),

$$\frac{d\ln y}{d\ln z} = \frac{1}{\eta}\left[\frac{d\ln n}{d\ln z} + \frac{d\ln w}{d\ln z}\right].$$

Use this last expression to substitute for output in (4),

$$\frac{d\ln q}{d\ln z} = \frac{\eta - 1}{\eta}\left[\frac{d\ln n}{d\ln z} + \frac{d\ln w}{d\ln z}\right]$$

Given our previous result for the employment elasticity, it is clear that if $\eta > 0$, that is if intermediate goods are substitutes, then output is positively correlated with wages and the local output price is negatively correlated with wages. The opposite relationships hold if $\eta < 0$, that is if intermediate goods are compliments.

Land use in production is positively related to wages. This follows from substituting for prices and employment in (17) using (16) and (18):

$$\frac{d\ln l}{d\ln z} = \frac{nh}{nh + l}\frac{d\ln w}{d\ln z}.$$

This last equation is interesting in light of our result for output. The two results imply that the density of employment activity can be positively or negatively related to wages in the cross section, depending on the degree of substitutability of intermediate goods in the production of final goods, η. In particular, even without any effects of density on total factor productivity, we could observe a positive relationship between wages, or labor productivity since this is proportional to wages in our model, and density in a cross-section of cities.

3.3 Amenities

Cities clearly vary by amenities in addition to productivity and the ease with which land can be developed. Therefore it is natural to ask whether our results in the previous two subsections are affected by including amenities in the model. The short answer to this question is that if amenities appear in individuals' preferences in a logarithmically separable way, then none of our results thus far are affected. We now elaborate on this answer briefly.

Suppose the new planning objective is given by

$$\sum_{t=0}^{\infty}\beta^t \int n(s^t)\left[\ln c_t + \psi \ln h(s^t) + \varsigma \ln a(s^t)\right]\pi(s^t)ds^t$$

where we redefine $\pi(s^t)$ to be the distribution of cities across productivity, land development cost *and* amenity histories, $a(s^t)$ denotes the quantity of amenities at a city with history s^t, and $\varsigma > 0$. The only first order condition affected from the problem without amenities is the location indifference condition. This becomes

$$\ln c_t + \psi \ln h(s^t) + \varsigma \ln a(s^t) = \pi_t \theta_t + \pi_t \left[(1+\psi)c - w(s^t)\right].$$

Amenities matter because they effect the allocation of labor, which then effects relative prices across cities. We pointed out earlier that introducing housing was important for generating a non-trivial wage distribution in the model. This is only true if we exclude amenities. Inspection of the new indifference condition shows that wages can differ by city if amenities do, even without housing.

Since the other first order conditions are unaffected by introducing amenities, the equation underlying our estimation, (15), is also unchanged. It also follows that the relationship between the endogenous variables due to idiosyncratic variation in technology is qualitatively unchanged. Moreover, idiosyncratic variation in amenities induces the same qualitative pattern of variability as with idiosyncratic variation in technology. This latter result can be verified by following the same proof strategy as before. Assuming that amenities are orthogonal to productivity, it follows that the general model including both sources of cross-sectional variability will share the same relationship between endogenous variables as with cross-sectional variation in technology only.

3.4 Heterogeneous Workers

So far we have assumed that workers are homogeneous. This is a questionable assumption from an empirical perspective. Locations with a high density of economic activity may have high wages because of a concentration of high human capital workers, not because of a density effect on productivity. Without accounting for cross-sectional variation in the distribution of human capital we could overstate density effects. Ciccone and Hall (1996) address this concern by accounting for the average level of educational attainment in a location. [**TBD** xxx rewrite this next sentence]. Ciccone and Peri (2006) have raised doubts about this approach. Their argument is focused on the issue of identifying human capital externalities, but is relevant in our context as well. They argue that the kind of approach adopted by Ciccone and Hall (1996) confounds positive externalities with wage changes due to a downward sloping demand curve for human capital. Consistent with Ciccone and Peri (2006), we address the issue by allowing high skill and low skill workers to be imperfect substitutes in producing labor services. We now derive a version of the equation underlying our estimation which incorporates heterogeneous workers.

Suppose that effective labor input in (12) is a constant elasticity of substitution aggregate of unskilled and skilled labor:

$$n = \left[\sigma u^{\xi} + (1-\sigma)e^{\xi}\right]^{1/\xi},$$

where $0 < \sigma < 1$ and $\xi \leq 1$. We can exploit previous derivations from above by using the notion of the demand for composite labor n. Composite labor satisfies (10) as before. Efficient use of unskilled and skilled labor implies

$$\begin{aligned} w_{ui} &= \sigma w_i {n_i}^{1-\xi} {u_i}^{\xi-1} \\ w_{ei} &= (1-\sigma) w_i {n_i}^{1-\xi} {e_i}^{\xi-1} \end{aligned}$$

where w_{ei} and w_{ui} are wages paid to skilled and unskilled workers respectively in city i. Notice that

$$\frac{w_{ui}u_i + w_{ei}e_i}{w_{ui}u_i} = 1 + \frac{1-\sigma}{\sigma} m_i^{\xi} \equiv \chi_i,$$

so that

$$w_{ei} = (1-\sigma)\sigma^{1/\xi-1}(1-\alpha)\phi w_i \chi_i^{1/\xi-1} m_i^{\xi-1}$$

where w_i is interpreted as the implicit wage for the composite labor input, n_i, and $m_i = e_i/u_i$. Substituting for composite wages using (15), we have the version of our key estimation equation incorporating skilled and unskilled labor:

$$\frac{w_{ei}}{w_{ej}} = \frac{z_i}{z_j}\left[\frac{p_i}{p_j}\right]^{\frac{\delta-1}{\delta(1-\alpha)}}\left[\frac{q_i}{q_j}\right]^{\frac{1}{\delta(1-\alpha)}}\left[\frac{\chi_i}{\chi_j}\right]^{1/\xi-1}\left[\frac{m_i}{m_j}\right]^{\xi-1}. \qquad (19)$$

Equation (19) reduces to equation (15) if $\xi = 1$, that is if unskilled and skilled labor are perfect substitutes.

3.5 Housing as a Combination of Land and Structures

So far we have assumed that households derive utility directly from land rather than from housing. A very simple extension specifies that housing services are produced as a Cobb-Douglas aggregate of land and capital, with the additional restriction that capital used by households in production of housing services can not be used by firms to make the intermediate output. Suppose housing services $h(s_t)$ are produced as

$$h\left(s^t\right) = k_h\left(s^t\right)^{\omega} l_h\left(s^t\right)^{1-\omega} \ , \tag{20}$$

where k_h and l_h are capital and used in the production of per-capita housing services in a city with productivity history s^t. Then, constraint (2) is replaced with the following two constraints

$$\begin{aligned} n\left(s^t\right) k_h\left(s^t\right) + k_b\left(s^t\right) &= k\left(s^t\right) \quad \forall s^t; & (21) \\ n\left(s^t\right) l_h\left(s^t\right) + l_b\left(s^t\right) &= d_t\left(s^{t-1}\right) \quad \forall s^t & (22) \end{aligned}$$

where k_b and l_b are capital and land used by firms.

These additional constraints do not change our analysis of the accounting for the impact of the density externality on the growth rate of per-capita output. Along a balanced growth path, in every city k_b increases at the same rate as k and l_b increases at the same rate as d.

For convenience, drop the productivity history notation. Denote the price of one unit of rented housing services in city i as p_i^h and denote the price of one unit of rented land services in city i as p_i (as before). Given the production function in equation (20), it is possible to show that

$$p_i = \omega^{\frac{\omega}{1-\omega}} (1-\omega) (p_i^h)^{\frac{1}{1-\omega}} r^{\frac{-\omega}{1-\omega}} \ , \tag{23}$$

where r is the rental price of capital (the same in all cities). The ratio of the price of land in any two cities i and j will be the following straightforward function of the ratio of the price of housing:

$$\frac{p_i}{p_j} = \left(\frac{p_i^h}{p_j^h}\right)^{\frac{1}{1-\omega}} \ . \tag{24}$$

This relationship is convenient for estimation, since data on housing rents are available, but data on rents accruing to developed land are not.

4 Econometric Strategy

This section describes how we estimate the parameters of our model, in particular the net agglomeration effect coefficient, δ. To begin, take logs of equation (19) and rearrange terms:

$$\begin{aligned}\ln(w_{ei}) - \ln(w_{ej}) &= \frac{\delta-1}{\delta(1-\alpha)}\left[\ln(p_i) - \ln(p_j)\right] + \frac{1}{\delta(1-\alpha)}\left[\ln(q_i) - \ln(q_j)\right] \\ &+ \frac{1-\xi}{\xi}\left[\ln(\chi_i) - \ln(\chi_j)\right] + (\xi-1)\left[\ln(m_i) - \ln(m_j)\right] \\ &+ \ln(z_i) - \ln(z_j)\end{aligned}$$

At all points in time, this equation holds for any two cities i and j. Therefore, it must also hold for city i and the average of the $j = 1, \ldots, N$ cities. Define a "hat" over a variable for city i to mean the difference of the log of that variable and the average of the same logged variable for all N cities in the sample, for example

$$\hat{w}_{ei} \equiv \ln(w_{ei}) - \frac{1}{N}\sum_{j=1}^{N} \ln(w_{ej}).$$

Re-introducing the time subscript, it follows that

$$\hat{w}_{ei,t} = \frac{\delta-1}{\delta(1-\alpha)}\hat{p}_{i,t} + \frac{1}{\delta(1-\alpha)}\hat{q}_{i,t} + \frac{1-\xi}{\xi}\hat{\chi}_{i,t} + (\xi-1)\,\hat{m}_{i,t-1} + \hat{z}_{i,t}. \tag{25}$$

Equation (25) holds at all dates.

We have data available on all variables in this equation except for $\hat{z}_{i,t}$. The model tells us that $\hat{z}_{i,t}$ and the other right hand side variables are correlated. So, to estimate the structural parameters we must use an instrumental variables approach. If we had only one wave of data, we would need to argue for an instrument that is correlated with the observable variables and uncorrelated with the $\hat{z}_{i,t}$ term. This is the econometric approach adopted by Ciccone and Hall (1996). Since we have access to a long panel, we use a different estimation strategy.

We exploit the panel nature of our data by making an explicit assumption about the stochastic process driving exogenous neutral technology in the model. In particular, we assume the stationary component in (11) is the sum of two random variables, one which is a city-specific first-order auto-regressive process, and one which is common to all cities, but we do not specify explicitly. This second term is included to make it clear that our analysis is consistent with there being aggregate uncertainty in the model. For every city i, $\ln(z_{i,t})$ evolves according to:

$$\begin{aligned}\ln(z_{i,t}) &= \ln(z_{i,0}) + \gamma t + \ln(\tilde{z}_{i,t}) + u_t;\\ \ln(\tilde{z}_{i,t}) &= \rho \ln(\tilde{z}_{i,t-1}) + e_{i,t},\end{aligned}$$

where γ is the deterministic rate of growth from (11), u_t is the economy-wide stationary part of technology, $-1 < \rho < 1$ is the autocorrelation coefficient for the city-specific technology, and $e_{i,t}$ is the city-specific i.i.d. shock that is orthogonal to all variables dated $t-1$ and earlier. Both γ and ρ are assumed to be common to all cities. The variable $z_{i,0}$ is the initial level of neutral technology specific to city i.

We now use our assumptions on the evolution of $\tilde{z}_{i,t}$ to manipulate (25) into an equation with an error term that is uncorrelated with all variables from previous years. This forms the basis of our instrumental variables estimation. Notice that our assumptions on the evolution of $z_{i,t}$ imply that the growth term and the economy-wide stochastic term drop out of the deviation of $\ln(z_{i,t})$ from its cross-section average, $\hat{z}_{i,t}$, and

$$\hat{z}_{i,t} - \rho \hat{z}_{i,t-1} = (1-\rho)\,\hat{z}_{i,0} + \epsilon_{i,t}, \tag{26}$$

where $\epsilon_{i,t} = [e_{i,t} - \bar{e}_t]$ with $\bar{e}_t$ equal to the average value of $e_{j,t}$ for all N cities in the sample in period t. Now, from each variable in equation (25) subtract ρ times its once-lagged value. This is a valid operation since equation (25) holds at all dates. Then, using equation (26), we have

$$\begin{aligned}\hat{w}_{ei,t} &= (1-\rho)\hat{z}_{i,0} + \rho \hat{w}_{ei,t-1} + \frac{\delta-1}{\delta(1-\alpha)}\left[\hat{p}_{i,t} - \rho \hat{p}_{i,t-1}\right] + \frac{1}{\delta(1-\alpha)}\left[\hat{q}_{i,t} - \rho \hat{q}_{i,t-1}\right]\\ &\quad + \frac{1-\xi}{\xi}\left[\hat{\chi}_{i,t} - \rho \hat{\chi}_{i,t-1}\right] + (\xi-1)\left[\hat{m}_{i,t} - \rho \hat{m}_{i,t-1}\right] + \epsilon_{i,t}.\end{aligned} \tag{27}$$

To make further progress on estimating the structural parameters of our model we need to find a set of instruments that are correlated with the wage, price, and skill variables and are uncorrelated with $\epsilon_{i,t}$. Finding valid instruments for equation (27) is straightforward because $\epsilon_{i,t}$ is an i.i.d. shock; any variable dated $t-1$ or earlier is potentially a valid instrument. In addition, we need to address the unobserved variable $\hat{z}_{i,0}$. This variable is a "fixed effect" in the sense that it varies across cities, but is fixed over time in each city.

Several strategies have been proposed to handle the city-level fixed effect. The most common one involves eliminating the fixed effect by taking first differences. A second strategy that has been proposed is to assume that the level of the fixed effect, $\hat{z}_{i,0}$, is uncorrelated with the first-differences of all model variables. The application of this method to our case would involve using equation (27) with lagged growth rates of model variables as instruments. A third strategy, which is more powerful and consequently has been widely used, combines the first two strategies. This approach was originally proposed by Blundell and Bond (2000). We are uncomfortable assuming that the fixed effect is uncorrelated with lagged changes of model variables, since we have no theory suggesting this to be the case. Therefore we not use the Blundell and Bond (2000) estimation procedure.

Instead we use a procedure, which, like the first strategy, directly removes the city-level fixed effects. When more waves of data are available than are the minimum necessary to implement the first strategy, taking first-differences does not use all the available information on the fixed effect and so is inefficient. Consequently we use the estimation procedure proposed by Arellano and Bover (1995) which takes advantage of the additional information on the fixed effects which comes with long panel data.

In this approach, each time-t variable in equation (27) is expressed as a deviation from the average of all future observations for city i in the sample. For any variable x_t with observations $t = 1, \ldots, T$, define the Arellano-Bover difference operator as of date t, Δ_t, as follows:

$$\Delta_t x_t \;=\; \omega_t \left[x_t - \frac{1}{T-t} \sum_{s>t} x_s \right].$$

where

$$\omega_t \;=\; \left(\frac{T-t}{T-t+1} \right)^{1/2}.$$

Applying the Arellano-Bover difference operator to (27) yields

$$\begin{aligned}\Delta_t \hat{w}_{ei,t} \;=\; & \rho \Delta_t \hat{w}_{ei,t-1} + \frac{\delta - 1}{\delta(1-\alpha)} \left[\Delta_t \hat{p}_{i,t} - \rho \Delta_t \hat{p}_{i,t-1} \right] + \frac{1}{\delta(1-\alpha)} \left[\Delta_t \hat{q}_{i,t} - \rho \Delta_t \hat{q}_{i,t-1} \right] \\ & + \frac{1-\xi}{\xi} \left[\Delta_t \hat{\chi}_{i,t} - \rho \Delta_t \hat{\chi}_{i,t-1} \right] + (\xi - 1) \left[\Delta_t m_{i,t} - \rho \Delta_t \hat{m}_{i,t-1} \right] + \Delta_t \epsilon_{i,t}. \quad (28)\end{aligned}$$

Including the weight term ω_t in Δ_t guarantees that the error term $\Delta_t \epsilon_{i,t}$ in (28) has a constant variance. We use equation (28) to estimate the structural parameters of our model using the levels of $\hat{w}_{ei,t-s}$, $\hat{p}_{i,t-s}$, $\hat{q}_{i,t-s}$, $\hat{\chi}_{i,t-s}$, and $\hat{m}_{i,t-s}$ for $s = \{3, 4\}$ as instruments. We do not use $s \geq 5$ as instruments because typically they do not add much information. We do not use earlier lags to accommodate classical measurement error in all the variables.

5 Data

We estimate the parameters of the model twice using two complementary sources for data on the price of land. The exact procedures we use to construct and merge the data are detailed in the data appendix. A brief summary follows here.

In both sets of estimates, we construct our wage and employment variables from the March Current Population Survey (CPS). We label any worker with at least four years of college as high skill, and workers with less than four years of college are labeled as low skill workers. We also use data from the Bureau of Economic Analysis (BEA) to construct MSA-specific price indexes for output. We create these indexes by merging annual data on income earned by industry by MSA with price indexes for industry output. Because the mix of industries varies by MSA, and price indexes vary by industry, our price index for output also varies by MSAs. We normalize the price index for MSA-level output to 1.0 in 1969 in every MSA. This arbitrary normalization introduces another MSA-level fixed effect that is differenced-out by the Arellano and Bover (1995) procedure.

To generate our first set of parameter estimates, we merge the annual CPS and BEA data with data on the purchase price of land in residential use as estimated by Davis and Palumbo (2008) to construct $\hat{p}_{i,t}$. This merge yields a balanced annual panel data set covering 42 MSAs over the 1985-2004 period.[4] The first year of data for both the CPS and the Davis and Palumbo (2008) data is 1985.[5] The CPS data

[4] Davis and Palumbo (2008) construct time-series estimates of the price of land for 46 MSAs, but we discard four of the MSAs from their study due to lack of CPS and BEA data. We convert the quarterly Davis and Palumbo (2008) data to the annual frequency by setting the annual estimates equal to the average of the reported quarterly values.

[5] The CPS identifies only 15 metropolitan areas in prior years.

are available through 2006, but the last year of Davis and Palumbo (2008) data is 2004, explaining the range of the sample.

To generate our second set of parameter estimates, we merge the annual CPS wage and employment data and the BEA data on output prices with annual data on housing rents by MSA, yielding an annual panel covering 22 MSAs over the 1985-2006 period. We construct the annual data on housing rents by combining micro-level data from the 1990 Decennial Census of Housing (DCH) with housing rental price indexes from the Bureau of Labor Statistics (BLS). Specifically, we use the data from the 1990 DCH to estimate the level of housing rents by MSA in 1990, and then use the MSA-specific BLS rental price indexes to extrapolate the rental price level backwards to 1985 and forwards to 2006. After dropping MSAs with incomplete or missing wage, employment, output price or house price data, we are left with 22 MSAs, 21 of which are in the first data set.

Denoting $\hat{p}^h_{i,t}$ as housing rents in period t, our estimating equation with data on the level of housing rents is nearly identical to equation (28), except we have an extra parameter ω representing structures share of housing services that we need to account for in estimation:

$$\begin{aligned}\Delta_t \hat{w}_{ei,t} \quad = \quad & \rho \Delta_t \hat{w}_{ei,t-1} + \frac{1}{1-\omega} \frac{\delta - 1}{\delta(1-\alpha)} \left[\Delta_t \hat{p}^h_{i,t} - \rho \Delta_t \hat{p}^h_{i,t-1}\right] + \frac{1}{\delta(1-\alpha)} \left[\Delta_t \hat{q}_{i,t} - \rho \Delta_t \hat{q}_{i,t-1}\right] \\ & + \frac{1-\xi}{\xi} \left[\Delta_t \hat{\chi}_{i,t} - \rho \Delta_t \hat{\chi}_{i,t-1}\right] + (\xi - 1) \left[\Delta_t m_{i,t} - \rho \Delta_t \hat{m}_{i,t-1}\right] + \Delta_t \epsilon_{i,t}. \qquad (29)\end{aligned}$$

Neither of these data sets is exactly what the model calls for, which is why we explore the implications of both. The model calls for data on the rental price of developed land by MSA, but these data are unavailable. In the first set of estimates, we have direct observation on the purchase price of residential land. The assumption we make is that over the 1985-2004 period, the log rental and log purchase price of land in a given MSA move together over time except for a serially uncorrelated error. The second set of estimates is based on observations on housing rents. The assumption we make with these data is that land rents are linearly proportional to housing rents: As shown earlier, this assumption is consistent with Cobb-Douglas production of housing services of structures and land.

6 Results and Analysis

6.1 Baseline Estimates

Table 1 reports our parameter estimates, standard errors, and test statistics. Column (1) reports the results when we use data on land prices, equation (28), and columns (2) and (3) report results using using data on housing rents, equation (29). Standard errors are computed using the "delta" method. In all three cases, capital's share of output α has been fixed to 0.3. We have experimented with different values for α, and we discuss the results in our sensitivity section.

Focusing first on the bottom set of rows of table 1, we employ three different specification tests of the model. The first is the standard J-test of the overidentifying restrictions of the model from Hansen (1982) and Sargan (1958). The p-values of the standard J-test indicate that the model is not rejected in all three specifications we estimate. The second two tests of the model are from Arellano and Bond (1991), who report that the power of the J-test to detect misspecification can be quite low. As a more powerful alternative they suggest a test of the serial correlation of the residuals. Under correct model specification, the residuals of our estimating equation should only exhibit autocorrelation up to order one. For each model we report the $m2$ test of second order serial correlation from Arellano and Bond (1991), as well as an analogous test for third-order serial correlation, which we dub $m3$. Shown by the p-value estimates, in all three specifications we fail to reject that the residuals do not display second or third-order serial correlation.

Focusing on the results using the land price data, column 1, we estimate the annual auto-regressive coefficient of the city-specific component of multi-factor TFP, ρ, to be 0.57 with a standard error of 0.02. This value is lower than the typical value of 0.96 used by macroeconomists when specifying the persistence of aggregate fluctuations in TFP around its trend. The interpretation of this estimate is that *city-specific* shocks to TFP are persistent but relatively short-lived, at least compared to the persistence of shocks to aggregate TFP. Our estimate of $\xi = 0.55$ implies an elasticity of substitution of 2.22 between low- and high- skilled labor types. This is above the typical range of recent estimates of the elasticity of substitution between college and non-college educated workers of 1.3 to 1.7 as reported by Autor et al. (1998) (see also Katz and

Murphy (1992), Heckman et al. (1998) and Krusell et al. (2000)). However, Autor et al. (1998) note that "substantial uncertainty exists concerning the magnitude" of the elasticity of substitution; for example, roughly speaking the results of Katz and Murphy (1992) suggest that a two standard error bracket around the elasticity of substitution is $[1.01, 2.44]$.

For this data set, we estimate δ, the parameter of the main interest to the study, to be equal to 1.012, with a standard error of 0.004. Thus, we find a statistically significant positive net-impact of agglomeration externalities on production at the MSA level. Recall that δ is the product of ϕ, land's share of production, and λ. δ is thus the impact of the density externality (output per unit land) on production, net of the fact that land is also input in production. Since $\delta > 1$, a reduction in the amount of land used in production, on-net, increases output: The positive impact from the change in output density more than compensates for the reduction of one of the inputs in production. If we assume that $\phi = 0.95$ (**TBD** Basu and Fernald (1995)), then this implies $\lambda = 1.065$. Our estimates suggest that a firm located in an area with twice the output density will produce 6.1 percent more output than an otherwise identical firm, holding all other inputs to production constant.

The second and third columns of this table show parameter estimates when we use our data on housing rents. In column (2), the percentage of housing rents accounted for by services from structures has been set to $\omega = 0.89$ and in column (3) ω is set to 0.60. It is our view that the true value of ω lies somewhere inbetween these two values. The value of $\omega = 0.89$ comes from a Census Bureau estimate of new house value that is accounted for by land, as reported by Davis and Heathcote (2005). Based on the national and cross-sectional estimates from Davis and Heathcote (2007) and Davis and Palumbo (2008) of the value of owned housing attributable to the value of land, we believe $\omega = 0.60$ to be a plausible lower bound.

A quick comparison of the estimates of ρ and ξ in columns (2) and (3) show that the choice of ω does not affect either estimate: Under both values of ω, we estimate ρ to be about 0.57 and χ to be about 0.56 – almost identical to the estimates from the first data set. In contrast, our estimates of δ does importantly depend on our choice of ω. In the case of $\omega = 0.89$, we estimate $\delta = 1.015$, almost identical to our estimate of δ from the first data set. For $\omega = 0.60$, we estimate $\delta = 1.064$. Both estimates of δ are statistically significantly different from 1.0. Assuming $\phi = 0.95$, an estimate of $\delta = 1.064$ corresponds to $\lambda = 1.12$, implying a firm located in an area with twice the output density will produce 10.7 percent more output than an otherwise identical firm, holding all other inputs to production constant.

6.2 Robustness

TBD

6.3 Implications for Balanced Growth

In this section, we determine the rate of consumption growth along a balanced growth path under the assumption that there are no gross benefits to agglomeration, i.e. under the assumption that $\lambda = 1$. For convenience, we copy equation (13) below, which describes the relationship of per-capita consumption growth γ_c, growth in neutral technical change γ and the inverse of growth in the relative productivity of new land development τ:

$$\gamma_c = \gamma \tau^{\frac{\delta-1}{(1-\alpha)\delta}}.$$

Over the 1982-2003 period, the National Income and Product Accounts estimates aggregate real consumption to have increased from \$3,470.3 to \$7,295.3 billion and data from the Bureau of Labor Statistics shows that total nonfarm payrolls increased from 89.677 to 129.999 million workers. This suggests that per-worker consumption increased by 1.8 percent per year over this period: $\gamma_c = 1.018$. Over the same time period, the 2003 National Resources Inventory, published by the United States Department of Agriculture (USDA), estimates total developed land in the US, defined as "large urban and built-up areas, small built-up areas, and rural transportation land" to have increased by 1.88 percent per year. Developed land per worker increased by 0.1 percent per year. Along a balanced growth path, τ times growth in developed land per worker is equal to growth in growth in per-capita consumption, implying τ is equal to $1.017 = 1.018/1.001$.

Broadly speaking, this estimate of τ is consistent with data from two other sources. First, data from the USDA suggests that the real price per acre of farm land has increased by 2 percent per year over the 1950-2005 period, implying an estimate of $\tau = 1.02$.[6] Second, according to Consumer Price Index data from the Bureau of Labor Statistics, real tenant rent has increased by 0.6 percent per year over the 1982-2003 period. Equation (23) suggests that the growth rate of the real rental price of land is somewhere 1.5 percent per year assuming $\omega = 0.60$ and 5.5 percent per year if $\omega = 0.89$, implying τ is somewhere beteen 1.015 and 1.055.

With $\gamma_c = 1.018$, and assuming $\tau = 1.017$, $\alpha = 0.3$, and $\delta = 1.012$, equation (13) suggests that the rate of growth of neutral technical change is 1.77 percent: $\gamma = 1.0177$. Under the counterfactual assumption that there are no agglomeration effects ($\lambda = 1.0$ and thus $\delta = \phi = 0.95$) and given $\gamma = 1.0177$, the growth rate of per-capita assumption would have been 1.64 percent per year, $\hat{\gamma}_c = 1.0164$. From these calculations, we estimate the contribution of agglomeration to per-capita consumption growth to be 9.6 percent, computed as $(\gamma_c - \hat{\gamma}_c) / (\hat{\gamma}_c - 1)$.

We test the sensitivity of our estimate of the contribution of agglomeration to per-capita consumption growth in two ways. First, we repeat the exercise holding all parameters fixed from before, with the exception that we assume that $\tau = 1.055$, the estimate implied by the data on real housing rents when $\omega = 0.89$. In this case, absent agglomeration effects, real per-capita consumption growth would have been 1.3 percent per year, implying agglomeration effects account for about 40 percent of consumption growth. Second, we repeat the exercise with $\tau = 1.017$, but $\delta = 1.056$, the estimate reported by Ciccone and Hall (1996) (and roughly consistent with our estimate from the housing rents data with $\omega = 0.6$). In this case, the rate of growth of per-capita consumption in the absence of a density externality would be 1.54 percent per year. This estimate suggests agglomeration boosts per-capita consumption growth by 16.8 percent. Based on these two sensitivity analyses, our estimate that agglomeration boosts consumption growth by 9.6 percent can be viewed as a lower bound.

[6] We include the entire 1950-2005 period so our estimate is not contaminated by the outsized run-up and subsequent decline of farm prices in the mid 1970s and early 1980s.

7 Conclusions

TBD

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A Data Appendix

In this appendix, we document how we construct key variables from our various data sources (section A.1) and then document how we merge our different data sources together to create our two data sets for estimation (section A.2).

A.1 Data Sources

A.1.1 CPS Data (Wages and Hours Worked by Skill)

The March CPS data are available for download at *http://cps.ipums.org/cps/* as part of the Integrated Public Use Microdata Series (IPUMS-CPS) project at the University of Minnesota Population Center.

We download the March CPS data from 1986 through 2007. We chose 1986 as our starting year because the CPS identifies only 15 metropolitan areas in prior years. The CPS wage and employment questions refer to the "previous calendar year." Therefore, data for any given year's CPS is treated as data appropriate for the previous calendar year. For example, variables generated from the March 2005 CPS would be treated as data for the year 2004.

In each year of our data, we use the following criteria to restrict the sample (with IPUMS-CPS variables in italics)

- Respondent lives in a household, not in group quarters or vacant units ($gq = 1$)
- Is aged 20 to 65 ($age \geq 20$ and $age \leq 65$)
- Wage and salary income in the previous calendar year is identified and is nonzero ($incwage > 0$ and $incwage < 999998$)
- Educational attainment is recorded ($educrec \geq 1$ and $educrec \leq 9$)
- Has an identified metro area of residence (*metarea* non missing)[7]

For each MSA, we create the following three variables:

1. Ratio of labor input of high skill to labor input of low skill, e_i/u_i
2. Ratio of total wages paid to total wages paid to low skill workers, χ_i
3. Average weekly wage of high skill workers, $w_{e,i}$.

We use the *educrec* categorical variable to label respondents as either "low" or "high" skill workers. High skill workers are assumed to have completed 1+ years of college. Everyone else in the sample is assumed to be a low skill worker.

e_i is created as the total of weeks worked the previous calendar year ($wkswork1$) multiplied by the number of hours per week the respondent usually worked ($uhrswork$) for high skill workers. u_i is created as the same product, but for low skill workers. For each respondent, we weigh the product of $wkswork1$ and $uhrswork$ using the IPUMS-CPS sampling person weights, *perwt*.

[7] According to notes from the IPUMS-CPS, the metro area of residence was not collected from respondents, but added by the Census Bureau. The metro areas of residence is based on FIPS codes used in the 1990 census.

χ_i is computed as

$$\frac{w_{e,i}e_i + w_{u,i}u_i}{w_{u,i}u_i} = \frac{\sum_{j\epsilon MSA_i} perwt_j \cdot wages_j}{\sum_{j\epsilon MSA_i} perwt_j \cdot wages_j \cdot 1\{unskilled_j\}}$$

for respondent j in MSA i, i.e. as the sum of all workers' pre-tax wage and salary income for the previous calendar year (*incwage*) divided by the sum of all low skill workers' pre-tax wage and salary income for the previous calendar year. We weigh pre-tax wage and salary income for all persons using the IPUMS-CPS sampling person weights.

$w_{e,i}$ is created as the sum of all high skill workers' pre-tax wage and salary income for the previous calendar year (created as an input into χ_i) divided e_i.

A.1.2 BEA Data (Output Prices)

We use two data sources from within the BEA web site: The Annual Industry Accounts,
http://www.bea.gov/industry/index.htm#annual, and the Regional Economic Accounts data on Local Area Personal Income, *http://www.bea.gov/regional/reis/*.

Chain-type price indexes for industry output are available over the 1947-2007 period in the Annual Industry Accounts. Many industry price indexes are missing in 2007, so we do not use data from that year. To construct a price index for output produced by MSA, we merge this information with MSA-level data on earnings by industry that is available in Tables CA05 and CA05N of the Regional Economic Accounts. Earnings is inclusive of wage and salary disbursements, supplements to wages and salaries, and proprietors' income.

Thus, we assume that the price of output varies across MSAs because that industry composition varies across MSAs, and the price index for industry output varies across industries.

Denote $g_{t,j}$ as the growth rate of the price of industry output j from periods t to $t+1$ and g_t^i as the growth rate of the price of all output produced in MSA i between years t and $t+1$. Assuming output from $j = 1, \ldots, N$ industries is produced in MSA i in year t, we set the growth rate of the price of output produced in MSA i between years t and $t+1$ as

$$g_t^i \;=\; \sum_{j=1}^{N} \omega_{t,j}^i \; g_{t,j} \; . \tag{30}$$

The weight on each industry, $\omega_{t,j}^i$, is the share of total MSA earnings attributable to earnings of industry j in MSA i in year t:

$$\omega_{t,j}^i \;=\; \frac{\epsilon_{t,j}^i}{\sum_{k=1}^{N} \epsilon_{t,k}^i} \; , \tag{31}$$

where $\epsilon_{t,j}^i$ stands for total earnings of employees in industry j in MSA i during year t. In these computations, we only consider earnings from non-farm private industries. For each MSA, we construct a price index for output, normalized to 1.0 in the year 1969, that is consistent with the sequence of time-series estimates of g_t^i.

Ideally, we would compute the growth rate of the price of output produced in city i between years t and $t+1$ as

$$\sum_{j=1}^{N} \phi_{t,j}^i \; g_{t,j} \; , \tag{32}$$

with $\phi_{t,j}^i$ equal to the fraction of the nominal value of output in year t in MSA i that is accounted for by industry j. In an environment in which (a) output in each industry is produced by a set of identical firms all using a Cobb-Douglas combination of capital, labor, and land and (b) the labor-share of output is identical in each industry, assumptions that hold in our model, then industry j's share of nominal GDP in MSA i in year t, $\phi_{t,j}^i$, is equal to its earnings share $\omega_{t,j}^i$, and equations (30) and (32) are equivalent. In these calculations, we assume that proprietors' income are payments to labor.[8]

A few details complicate these calculations.

First, on a somewhat infrequent basis, Tables CA05 and CA05N do not report estimates of earnings for a given industry in an MSA in a given year. In these cases,

[8]In the event that proprietors' income includes some payments to capital, equations (30) and (32) are equivalent as long as capital's share of proprietors' income and the fraction of earnings attributable to proprietors' income are both constant across industries.

we set earnings for this industry-MSA-year cell to zero.[9] Also, some of the industry-MSA-year employment estimates are marked with code E. According to the BEA web site, these estimates "constitute the major portion of the true estimate." In these cases, we assume that the reported estimate is equal to the actual estimate.

Second, the definition of industries in the Regional Accounts is not consistent across years. Table CA05 reports employment based on SIC-industry classifications over the 1969-2000 period and CA05N reports employment based on NAICS industry classifications spanning the years 2001-2006.

We map SIC and NAICS industry employment from Tables CA05 and CA05N to prices from the Annual Industry Accounts according to the tables below. The tables below list all the categories of nonfarm private employment. The sum of the earnings estimates in each of these categories is considered as total nonfarm private earnings, and is used to compute the denominator of equation (31).

Data for Earnings Weights, $w^i_{t,j}$ Regional Accounts Table CA05, 1969-2000		Data for Growth in Prices, $g^p_{t,j}$ Industry Accounts, 1969-2001	
Line	Label	Line	Label
100	Agricultural services, forestry fishing and other	3	Agriculture, forestry, fishing and hunting
200	Mining	6	Mining
300	Construction	11	Construction
400	Manufacturing	12	Manufacturing
500*	Transportation and public utilities less electric, gas, and sanitary services	36	Transportation and warehousing
570	Electric, gas, and sanitary services	10	Utilities
610	Wholesale trade	34	Wholesale trade
620	Retail trade	35	Retail trade
700	Finance, insurance and real estate	50	Finance, insurance, real estate, rental and leasing
800	Services	59	Professional and business services

* See text for details.

[9] The three reasons that are listed for omission are (a) avoid disclosure of confidential information (code D), (b) earnings are less than $50,000 (code L), or (c) data not available for this year (code N). These omissions occur in approximately six percent of industry-MSA-year cells from 1969 to the mid-1990s and about thirteen percent of cells from the mid-1990s through 2006.

Data for Earnings Weights, $w^i_{t,j}$ Regional Accounts Table CA05N, 2001-2005		Data for Growth in Prices, $g^p_{t,j}$ Industry Accounts, 2001-2006	
Line	Label	Line	Label
100	Forestry, fishing, related activities and other	5	Forestry, fishing and related activities
200	Mining	6	Mining
300	Utilities	10	Utilities
400	Construction	11	Construction
500	Manufacturing	12	Manufacturing
600	Wholesale trade	34	Wholesale trade
700	Retail trade	35	Retail trade
800	Transportation and warehousing	36	Transportation and warehousing
900	Information	45	Information
1000	Finance and insurance	51	Finance and insurance
1100	Real estate and rental and leasing	56	Real estate and rental and leasing
1200	Professional, scientific and technical services	60	Professional, scientific and technical services
1300	Management of companies and enterprises	64	Management of companies and enterprises
1400	Administrative and waste services	65	Administrative and waste management services
1500	Educational services	69	Educational services
1600	Health care and social assistance	70	Health care and social assistance
1700	Arts, entertainment and recreation	75	Arts, entertainment and recreation
1800	Accommodation and food services	78	Accommodation and food services
1900	Other services except public administration	81	Other services except government

In all cases except one, there is an exact correspondence of earnings estimates from Tables CA05 and CA05N to prices from the Annual Industry Accounts. For the SIC category of "Transportation and public utilities," line 500 of Table CA05, there is no clean analogous price index in the Annual Industry Accounts. Instead, the Annual Industry Accounts includes separate price indexes for "Transportation and warehousing" and "Utilities." In Table CA05, we therefore separate earnings of the single Transportation and public utilities into earnings in two categories: Earnings from utilities ("electric, gas, and sanitary services", line 570) and earnings from transportation and public utilities less earnings from utilities (i.e. line 500 less line

570).

A.1.3 Davis and Palumbo Data (Land Prices)

Davis and Palumbo (2008) report the quarterly value of land on a typical owner-occupied single-family lot for 46 MSAs over the 1984:4 - 2004:4 period. We directly use their data, but set the annual estimate to equal the average of the quarterly readings. Davis and Palumbo estimate the value of land as the market value of housing units less an estimate of the replacement cost of the structure (after accounting for depreciation) – see their paper for details.

A.1.4 BLS Data and 1990 Decennial Census of Housing (Housing Rents)

We create annual estimates over the 1985-2006 period of the average rents paid for certain types of rental units, by MSA, using a two-step procedure.

In the first step, we estimate the average rents paid for certain types of rental housing units in 1990 using household-level data from the 1990 Decennial Census of Housing (DCH). These data are available for download at *http://usa.ipums.org/usa/* as part of the Integrated Public Use Microdata Series (IPUMS-USA) project at the University of Minnesota Population Center. We use data from the 1990 DCH reports data by metropolitan area for more metropolitan areas than the 2000 DCH.

With IPUMS-USA variables in italics, we restrict the 1990 DCH sample to renter non-farm households in 2-19 unit residences in a building built between 1940 and 1986 and living in an identifiable MSA ($ownershg = 2$, $farm \neq 1$, $unitsstr \in \{5, 8\}$, $builtyr \in \{3, 7\}$, and $metarea > 0$) who live in households and do not live in group quarters ($gq \in \{3, 4, 6\}$) and where the reported monthly gross rent of the house (rent inclusive of utilities) is nonzero ($rentgrs > 0$). Conditional on these restrictions, we compute the weighted average value of units by MSA using the sampling weight variable $hhwt$. These calculations yield estimates of the average rental price of housing for 272 metro areas as identified in the 1990 DCH. We exclude single-family rented units, rented high-rise units ($>$ 20 units), and units in very old (built before 1940) or very new (built after 1986) apartment buildings to attempt to keep the average characteristics of rental units roughly constant across metropolitan areas without resorting to hedonic regressions.

In the second step, we extrapolate the annual rental price of housing in each metro area forward from 1990 to 2006 and backwards from 1990 to 1985 using annual MSA-specific constant-quality price indexes for rental units. These price indexes for tenant rents are published by the Bureau of Labor Statistics (BLS) as part of computations for the Consumer Price Index, and are available at *http://www.bls.gov*. The BLS reports rental price indexes for 27 MSAs, but the indexes of three of these MSAs (Phoenix, AZ, Washington, DC, and Tampa Bay, FL) do not extend back to 1985 and we exclude these from our sample.

After merging the 1990 DCH with the BLS price indexes, and eliminating the MSAs for which are not available back to 1985, we are left with annual estimates of the rental price of housing units over the 1985-2006 period for 24 MSAs.

A.2 Merging the Data

A.2.1 Annual Data Set with Land Prices, 1985-2004

Our first data set we use in estimation contains annual data with land prices over the 1985-2004 period. To create this data set, we merge the CPS data on wages and employment (section A.1.1) with the BEA data on output prices (A.1.2) and the Davis and Palumbo data on land prices (section A.1.3), which yields annual data on 42 MSAs.[10] In every MSA and date, the minimum number of respondents from the CPS is never less than 100. The median number of respondents is about 420 until about 2000, at which point the median jumps to about 650. The maximum number of respondents is typically over 4,000.

We merge these data by MSA. Note that the MSA definitions may not be completely consistent. In the BEA data, MSAs definitions are given by the list in the November, 2007 report of the Office of Management and Budget.[11] The MSA definitions in the CPS data are consistent with the definitions as of the 1990 Census. The

[10] We discard information on four areas reported by Davis and Palumbo because information on these areas is not available in the CPS.

[11] For a complete list of the counties comprising each MSA, go to *http://www.census.gov/population/www/metroareas/metrodef.html*.

Davis and Palumbo data are created by merging data from various sources, and the MSA definition of one of the key sources (data from the R.S. Means corporation) is not known.

A.2.2 Annual Data Set with Housing Rents, 1985-2006

Our second data set we use in estimation contains annual data with the rental price of housing over the 1985-2006 period. To create this data set, we merge the CPS data on wages and employment (section A.1.1) with the BEA data on output prices (A.1.2) and the annual data we construct on housing rents by merging the BLS rental price indexes with information on housing rents in the 1990 Decennial Census of Housing (section A.1.4). After all data are merged, we are left with a balanced panel of 22 MSAs.

With the exception of Honolulu, HI, all of the MSAs in this data set are also in the first data set. In every MSA and date, the minimum number of respondents from the CPS is never less than 200. The median number of respondents is about 540 until about 2000, at which point the median jumps to about 1,000. The maximum number of respondents is always above 3,500 and is typically about 5,000.

All data files are merged by MSA, and the caveat from the previous section – that the MSA definitions may not be completely consistent across data sets – applies.

Table 1: Parameter Estimates (Standard Errors in Parentheses)

	Land Prices 42 MSAs 1985-2004	Housing Rents 22 MSAs 1985-2006	
		$\omega = 0.89$	$\omega = 0.60$
	(1)	(2)	(3)
ρ	0.568	0.572	0.554
	(0.021)	(0.010)	(0.010)
ξ	0.550	0.563	0.565
	(0.005)	(0.004)	(0.004)
δ	1.012	1.015	1.064
	(0.004)	(0.002)	(0.006)
J-test	58.190	35.972	36.012
p-value	1.000	1.000	1.000
d.o.f.	147	167	167
m2 test	0.043	-0.135	-0.092
p-value	0.483	0.446	0.463
m3 test	0.129	0.453	0.476
p-value	0.449	0.325	0.317