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## Time-varying agglomeration economies and aggregate wage growth

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**Abstract**

We examine how agglomeration economies have influenced labour earnings in France over forty years. First, we define cities dynamically to account for their changing footprints. Our findings show that aggregate wage growth is mainly driven by growth in larger cities, rather than smaller ones or by population shifts across cities. We estimate individual wages incorporating time-varying city and individual fixed effects, and analyse how city characteristics (employment density, area, and market access) and their returns impact wage evolution. Changes in the values of these characteristics have minimal effect, but changes in their returns significantly influence wages, with notable variation across cities. Overall, aggregate wage growth in France reflects larger returns to larger city size. Our model, that incorporate the impact of agglomeration economies on city size and population, suggests that changes in returns do not drive population or area changes sufficiently to impact aggregate labour earnings, supporting our empirical findings.

**JEL Codes:** R23, J31, J61

**Keywords:** Agglomeration economies, endogenous city size, growth, wages

# Executive summary

Over the last fifty years, cities around the world have grown at different rates, with some countries seeing the emergence of urban giants, concentrating population and employment. These large cities drive economic growth through productivity gains, innovation, and economies of scale. As cities expand and adapt to structural changes—like the rise of service industries and improved transportation—returns to agglomeration economies have evolved, impacting labour earnings and aggregate productivity. This study examines the dual role of changes in city characteristics and their returns in explaining aggregate labour earnings in France from 1976 to 2015.

Our contribution is threefold. First, we delineate cities every year, enabling us to capture changes in land area and not solely in population or employment. This approach allows for a more dynamic view of how cities grow, absorb surrounding areas, and sometimes merge. Second, we estimate the magnitude of agglomeration economies for three city variables: employment density, land area, and market access. This helps us identify whether shifts in aggregate labour earnings are driven by changes in these city characteristics or by changes in their returns over time. Finally, we model a system of cities with endogenous employment and land area to analyse the equilibrium effects of agglomeration economies on labour earnings. This model captures both the direct impact of changes in agglomeration returns on earnings and indirect impacts from shifts in city characteristics. We also investigate how changes in returns to agglomeration can influence migration patterns and firm relocations between cities, which, in turn, affect spatial wage disparities and urban development. We consider equilibrium effects, which shed light on how urban policies aimed at fostering agglomeration economies in specific cities might lead to the redistribution of economic activity across the broader urban landscape.

In order to measure the time-varying cities' footprint, we delineate cities each year from 1976 onwards using the dartboard approach proposed by de Bellefon *et al.* (2021). This involves dividing mainland France into 200 m x 200 m squares and calculating their built-up volume density each year on the basis of CEREMA and BDTOPO data, which includes the footprint, height and year of construction of buildings. This approach enables us to capture city expansions, mergers, and absorptions, in contrast to studies that view cities as fixed entities.

Using these annual city delineations, we estimate time-varying agglomeration economies based on administrative panel data for 1976-2015. In a first step, we regress individual daily wages on city-year fixed effects, controlling for individual observed and unobserved heterogenity, and industry. In a second step, we regress the estimated city-year fixed effects on our three agglomeration variables—employment density, land area, and market access—allowing coefficients to vary over time. Our findings show that the elasticity of wages with respect to city density, land area, and market access has grown over time, which suggest that larger cities have become more advantageous for driving wage growth. These estimates are barely affected when instrumenting agglomeration variables with historical city characteristics and geological features.

Our results show that changes in the returns to agglomeration variables have a much larger impact on wage growth than changes in the values of city characteristics themselves. While cities have evolved, the shifting returns to agglomeration played a more substantial role in explaining wage disparities. In particular, we observe that large cities display increasing returns to scale, which in turn contributes to their higher aggregate wage growth compared to smaller cities. A log-wage growth decomposition confirms that changes in returns to agglomeration are the main driver of wage growth, while shifts in city characteristics contribute less significantly.

To explore the indirect effects of agglomeration economies, we propose a theoretical model that incorporates them within a system of monocentric cities. Agglomeration economies are specified as a Cobb-Douglas function of city characteristics, in line with our empirical findings. Although the model cannot be solved analytically, we perform comparative statics to evaluate the direct and indirect effects of changes in agglomeration returns on wages. Our results suggest that while the direct effects are substantial, the indirect effects—such as migration-induced changes in city density and land area—are relatively small. This aligns with our empirical observation. From a policy perspective, these findings imply that urban policies aimed at boosting agglomeration economies in specific cities may yield local gains but are unlikely to substantially affect national wage growth unless they significantly alter returns to city characteristics.

To sum up, we highlight the importance of agglomeration returns in driving labour earnings in urban settings. By considering both the direct and indirect effects of agglomeration economies, we offer a more comprehensive view of how city characteristics and their returns shape wage distributions in France. This understanding has implications for urban policy, suggesting that efforts to improve city productivity should focus on factors that increase the returns to city size rather than merely expanding city boundaries. Larger cities benefit disproportionately from increasing returns to scale, contributing to their dominance in driving aggregate wage growth. A nuanced approach that considers the evolving returns to agglomeration will likely be more effective in shaping a productive and equitable urban landscape.

# 1 Introduction

Over the last fifty years, cities have grown steadily worldwide, though at different rates. Many countries have seen the rise of urban giants that generate agglomeration economies and benefit from them (Duranton and Puga, 2014). Returns to city size may also have evolved due to structural changes such as the rise of service industries and improved transport. Their evolution affects aggregate productivity and labour earnings even for a given distribution of city sizes. This study aims to quantify the simultaneous role of changes in city characteristics and their returns on labour earnings in France over the 1976-2015 period using individual wage panel data.

Our contribution is fourfold. First, we delineate cities annually to properly consider the evolutions of city land area, rather than only city population or employment changes, as is standard in the literature. We then estimate each year separately the magnitude of agglomeration economies embodied in three variables: city employment density, land area, and market access. This allows us to subsequently assess whether changes in aggregate labour earnings are rather driven by changes in the values of city characteristics or by changes in their returns. Finally, we model a system of cities with endogenous employment and land area to study the equilibrium effects on labour earnings of changes in agglomeration economies. We show that labour earnings are affected by both direct effects due to changes in returns to city characteristics and indirect effects coming from their endogenous impact on the values of city characteristics.

The influence of agglomeration economies on spatial wage disparities has been studied recently from a macroeconomic perspective in a descriptive way. Bauluz *et al.* (2023) quantify the evolution of wage disparities across local labour markets within and between countries in North America and Western Europe over the past fourty years. Butts *et al.* (2023) focus on changes in the urban wage premium in the US since 1940, and find that it decreased until the 1980s before stabilizing. Giannone (2022) and Eckert *et al.* (2022*a*) reconcile this empirical evidence with the spatial diffusion of technology and skill-biased technological change that have mostly affected large cities. We depart from this literature by considering a system of cities with varying footprint and employment density, consistently with urban economics theory. Our interest lies in the simultaneous impact of changes in city characteristics and their returns on aggregate wage growth.

Our study complements a large body of literature that examines time-constant effects of agglomeration economies on productivity and wages. (see Combes and Gobillon, 2015; Ahlfeldt and Pietrostefani, 2019; Duranton and Puga, 2020). In particular, Combes *et al.* (2008) estimate static agglomeration economies by regressing individual wages on city employment density and area, while taking into account the spatial sorting of individuals on observables and unobservables.[1] Their work has been extended to consider learning effects in cities that may be transferable when moving to another city (de la Roca and Puga, 2017; Koster and Ozgen, 2021; Eckert *et al.*, 2022*b*). Contributions in a historical perspective are scarce because data on firms and wages are often missing over the long run. An exception is Combes *et al.* (2011) who estimate the effects of agglomeration economies on value added over 140 years. Whereas returns to agglomeration economies are usually considered to be constant over time, we evaluate how they evolve over a forty-year period.[2]

Some recent contributions from the labour literature explore the influence of agglomeration variables on local productivity residuals constructed as local averages of firm fixed effects derived from a wage specification that also includes individual fixed effects (Dauth *et al.*, 2022; Card *et al.*, 2024). This indirect approach mitigates biases from the sorting of individuals into non-representative firms when moving across cities. Given our interest in the evolution of agglomeration economies over time, we extend this approach by considering firm-year fixed effects instead of time-constant firm fixed effects. This allows us to derive city-year effects and evaluate how they are influenced by the evolution of agglomeration economies. Our conclusions remain when considering this extension.

Changes in returns to agglomeration economies can generate migration flows of people and firms between cities, affecting spatial wage disparities similarly to how urban policies influence city development. Urban policies can foster agglomeration economies in certain cities by attracting people and firms from other cities, which then benefit less from agglomeration economies. The overall impact of urban policies depends on the relative magnitude of the local gains and losses (Glaeser and Gottlieb, 2008; Kline and Moretti, 2014; Gaubert, 2018). We account for such equilibrium effects when studying the evolution of aggregate labour market earnings by summing the effects of changes in agglomeration economies across all cities.

There is an extensive literature on systems of cities that studies their evolution over time

[1] See Moretti (2013) and Diamond (2016) for frameworks involving spatial sorting depending on education, and Diamond and Gaubert (2022) for a survey and discussion of spatial sorting and its evolution over time.

[2] Our work somehow complements Steijn *et al.* (2022) who study how spatial determinants of industry co-agglomeration patterns have seen their effects vary over the 1970-2014 period in the US.

in the presence of static and dynamic agglomeration economies (Duranton and Puga, 2014; Behrens and Robert-Nicoud, 2015). City growth can be generated by human capital externalities (Black and Henderson, 1999; Duranton and Puga, 2023) or size externalities (Combes *et al.*, 2024). We model a system of cities that incorporates only static agglomeration economies but allows city size to evolve over time as a result of changes in returns to agglomeration variables affecting the productivity of cities differently depending on their size. An advantage of this approach is that time-varying agglomeration parameters directly correspond to those in our wage specification. Using comparative statics, we can then compute separately the direct effect of changes in agglomeration parameters on productivity and the indirect effects mediated through changes in the values of agglomeration variables.

To our knowledge, our study is the first to introduce time-varying delineations of cities to accommodate variations in their footprint due to changes in agglomeration economies, and local productivity and amenity shocks. We delineate cities annually from 1976 onwards using the dartboard approach proposed by de Bellefon *et al.* (2021). We use a 200m $\times$ 200m grid over metropolitan France for which we compute built-up volume density for each year from information on building footprint, height and construction year from CEREMA and BDTOPO data. Pixels are classified as "urban" if their built-up density exceeds most values obtained when reallocating randomly built-up several times over the whole territory. Urban areas are defined as sets of contiguous urban pixels, with "urban cores" being pixels significantly denser than random within urban areas. Cities are finally defined as urban areas with at least one core. Overall, this approach allows us to consider expansions, absorptions and fusions of cities unlike other studies that usually consider a constant set of cities with fixed boundaries over time. Interestingly, we observe that large cities can have different trajectories. In particular, Lille was historically specialised in mining, textile and heavy industries, and has not evolved much, whereas Marseilles on the French Riviera has expanded a lot, absorbing many urban areas during our study period. This is consistent with an increasing role for consumption amenities, especially nice weather and coastal locations (Rappaport and Sachs, 2003; Rappaport, 2007, 2009).

Equipped with our yearly delineations of cities, we estimate time-varying agglomeration economies using administrative panel data (*Déclarations Anuelles des Données Sociales*-DADS) over the 1976-2015 period. In a first step, we regress individual daily wages on city-year fixed effects, controlling for individual observed and unobserved heterogenity, and industry. In a second step, we regress the estimated city-year fixed effects on city characteristics (employment density, land area, and market access). Importantly, the coefficients of these variables may vary over time. The elasticity of wages with respect to city density (land area and market access, respectively) increases over time from 0.011 to 0.042 (0.007 to 0.022 and 0.039 and 0.082, respectively). These estimates are barely affected when instrumenting agglomeration variables with historical city characteristics and geological features. Using a log-wage growth decomposition, we show that changes in returns to agglomeration variables have a large effect on wage growth, while changes in their values do not. Indeed, even if cities evolved, changes over time are small compared to cross-sectional disparities.

Finally, we propose a theoretical model to evaluate the indirect effects of changes in returns to city density and land area at the equilibrium. Changes in the returns to city characteristics affect agglomeration economies and, consequently, the attractiveness of cities. This triggers migrations that alter city density and land area, which in turn changes agglomeration economies. Specifically, the model incorporates the effects of agglomeration economies on wages within a system of monocentric cities. Agglomeration economies are specified as a Cobb-Douglas function of city characteristics consistent with our empirical specification. Although the model cannot be solved analytically, we are able to conduct comparative statics for wages with respect to returns to agglomeration variables. This allows us to quantify not only the direct effect of changes in these returns, but also the indirect effect stemming from their influence on the values of agglomeration variables. We show with a calibration exercise that the indirect effect is rather small, which aligns with our empirical finding that changes in the values of agglomeration variables have a negligible role.

The rest of the paper is structured as follows. Section 2 explains how we delineate cities each year. Section 3 presents our wage and employment data, and provides stylized facts about the distribution of wages and agglomeration variables. Section 4 details our empirical strategy and Section 5 discusses our results. Section 6 reports robustness checks when using alternative definitions of cities and alternative specifications. Section 7 presents our model of a system of cities involving agglomeration economies and its quantification. Finally, Section 8 concludes.

## 2 Delineating cities over time

The attractiveness of cities for workers changes with variations in the returns to agglomeration economies, as well as local productivity and amenity shocks. Housing and population adjust, which affects both the intensive margin of cities, i.e. population density per squared meter, and their extensive margin, i.e. land area (see model in Section 7). We need delineations of cities that vary over time to study changes at both margins in a meaningful way. In France, an official definition of cities was introduced in 1954, but it changed many times, and it is not consistent during our study period. We thus rather rely on delineations specifically built for the present study using the dartboard approach proposed de Bellefon *et al.* (2021). These delineations are based on precise built-up information continuously varying over space and time.

### 2.1 Built-up data

As described in Appendix A, we match two data sources, the land files from the tax administration (*Fichiers Fonciers*) and a 3D modelling of buildings (*BDTOPO*). The resulting dataset gives the footprint, height and construction year for every building existing in 2020. It is used to produce annual built-up densities over a grid that divides metrotpolitan France into around 13.5 million 200 x 200 meter pixels for the 1976-2015 period. In a given year, the built-up density of a pixel is the sum of volumes (footprint times height) across buildings located there which are built before that year. Our approach therefore accounts for vertical urban development, but it bears the limitation that buildings destroyed after the considered year are not taken into acount. We do not expect this bias to be large over 40 years. Moreover, the delineation procedure described in the next subsection smooths measurement errors.

### 2.2 Algorithm to delineate cities

Our delineation methodology can be decomposed into four steps. The first step consists in slightly smoothing built-up density across pixels to deal with possible measurement errors and fill small holes in built-up due for instance to small parks or roads, as we want to consider them as part of the cities.[3] The second step computes random counterfactual distributions of smoothed built-up densities. Observed pixel built-up densities are redistributed $5,000$ times with

[3]For the smoothing procedure, we use a bi-square kernel with a 2.1-kilometer bandwidth, such that, for each pixel, smoothing takes into account 10 pixels on each of its sides. More details on bandwidth choice are provided in Section 6

replacement across all buildable pixels and the resulting counterfactual densities are smoothed in the same way as the actual data.[4]

In the third step, a pixel is defined as urban if its actual smoothed density is above the $95^{th}$ percentile of its smoothed counterfactual densities. 'Urban areas' are sets of contiguous urban pixels. This approach leads to many urban areas, some of which have a small population or land area (de Bellefon *et al.*, 2021). The fourth step consists in determining the most prominent ones which have a core. For that purpose, we compute counterfactual density distributions by randomly redistributing built-up densities within the set of all urban pixels, and we consider that a given urban pixel belongs to a core if its smoothed density is above the corresponding $95^{th}$ percentile of counterfactuals. We finally name 'city' an urban area that has at least one urban core.

Wage data records location at the municipality level only (there are around 36,000 municipalities in mainland France). We thus need to modify our definition of cities so that they are aggregates of municipalities. We consider a city to include all municipalities with at least 50% of their built-up area in that city, and the area of the city is then the sum of the land areas of these municipalities. Using this modified definition also allows us to compute city populations at census dates from population counts at the municipality level. Cities are named after the most populated municipality in 2015.

### 2.3 Description of delineated cities

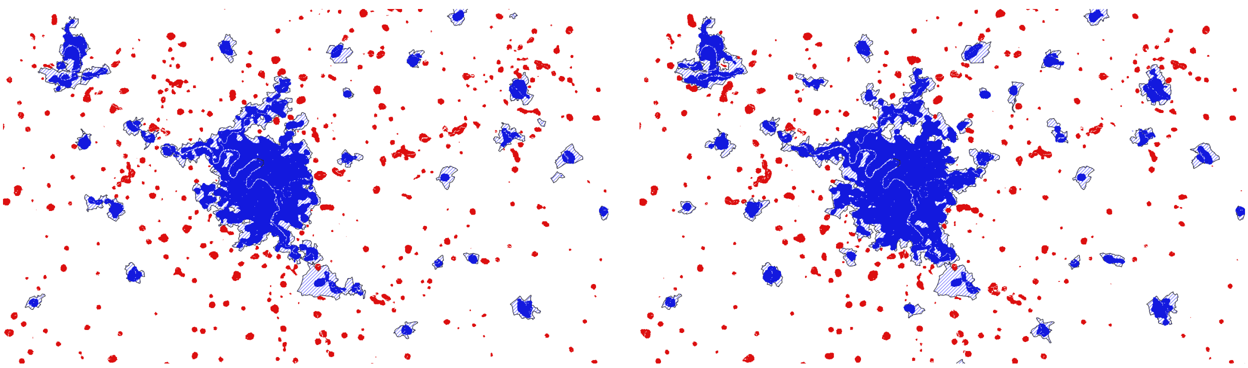
Table B.1 reports descriptive statistics on delineated cities at every census year. The number of cities is fairly stable over time, at around 290-310 cities. The $95^{th}$ percentile of city population size is at around 250,000. Importantly, the median population size is still sizable at around 27,000 every census year.

In Figure 1 and Figure B.1, we represent the four largest cities over our study period to visualise their evolution over the period. Cities are represented in blue stripes (with cores in deep blue), and urban areas without a core are represented in red. Figures 1.a and 1.b show that Paris has grown significantly, and has absorbed several urban areas without a core. This is also the case for Lyon (Figures B.1.a and B.1.b) that has absorbed not only urban areas without a core, but also cities. Marseilles is an interesting case because it has evolved considerably between

[4]Non-buildable pixels are defined as pixels above the $99^{th}$ percentile of elevation, slope, and share of water of the pixels where there is some built-up, consistently with de Bellefon *et al.* (2021).

Figure 1: City delineations for Paris and nearby, 1976 and 2015

1.a: Paris, 1976 | 1.b: Paris, 2015



*Notes*: Urban areas obtained from our delineation algorithm separately run for 1976 (Figure 1.a) and 2015 (Figure 1.b) using a 2.1km bandwidth. Urban areas with cores (cities) are in blue and urban areas without a core are in red. Borders of municipalities including part of a city are in black, and the area of the municipalities not covered by the delineation but then considered as part of the city because corresponding to more than 50% of the municipality are in blue stripes.

1976 and 2015 (Figures B.1.c and B.1.d). Its area has increased a lot with the absorption of cities, urban areas without cores, and rural areas. In particular, Marseilles absorbed the rather large city of Aix-en-Provence in 1989. Finally, the area of Lille has not evolved much (Figures B.1.e and B.1.f). This is not surprising since its growth has been slowed down by the decline of mines, and heavy and textile industries which were located there.

# 3 Wage data and city characteristics

## 3.1 Individual wage panel and local data

In the estimations, we mainly rely on a matched employer-employee dataset, the *Déclarations Annuelles des Données Sociales* (DADS) for the 1976-2015 period. It reports yearly details on every job for all individuals born in October of an even year. We use information giving the daily wage, occupation (1 digits), industry (3 digits) and location at the municipality level. We restrict our attention to observations for individuals aged 18-65 working full time in the private and semi-public sectors. Our final sample includes 18,619,578 observations. More details on data construction are given in Appendix A.2.

From this data, we compute employment density and market access for each city and year.

Employment density is defined as the number of employees divided by the land area. Market access is the sum of employment densities in other cities weighted by the inverse of distance (Harris, 1954), the city itself being excluded from this sum. The distance between two cities is that between the geographic barycentre of their municipalities' city hall weighted by municipal employment. Note that this distance depends on time because the delineation of cities depends on time. We thus have three variables which can be used to identify and study agglomeration economies: density, area, and market access, which are the three most studied variables in the agglomeration economies literature (Combes and Gobillon, 2015).

We introduce them simultaneously in our wage specification. Density measures city agglomeration economies at the intensive margin, i.e. from having more jobs per square kilometre while holding constant city footprint. Land area evaluates city agglomeration economies at the extensive margin, i.e. from being geographically larger at given density, which is equivalent to having more jobs. Finally, market access gives agglomeration economies due to interactions with neighbouring major cities.

### 3.2 Stylized facts

We now provide descriptive statistics on cities over the 1976-2015 period. Figure 2 represents moments of the distributions of city employment density, land area and market access and wages over time. Density exhibits small variations without trend (Figure 2.a). This is not surprising since, for growing cities, even if centres may become denser, new peripheries resulting from the absorption of rural and urban areas are likely to be less dense. Hence, the evolution of density can go both ways for a given city and is in general fairly stable. This is well illustrated by Figure 3.a that represents the evolution of density for the four largest cities, with Marseilles standing as an exception. Density increases and then significantly decreases for this city as it expands quite a lot by absorbing many other less dense urban areas.

As for the growth of land area, the $75^{th}$ and $90^{th}$ centiles increase in a sizable way between 1976 and 2015 (Figure 2.b). Again, there is heterogeneity among large cities (Figure 3.b). Whereas land area grows a lot for Paris, Lyon and especially Marseilles, it does not evolve much for Lille during our study period. Market access exhibits time variations which are consistent with those of density overall (Figure 2.c) and for the four largest cities (Figure 3.c). Finally, wages (in constant euros) increase over time at any point of the city distribution (Figure 2.d) and for the four largest cities (Figure 3.d) without any specific trend in terms of wage disparities.

Figure 2: Moments of city distributions for delineated cities


*Notes*: Employment density is computed as the ratio between employment in our dataset and area (in km$^2$). Since our dataset includes only individuals born in October of even years, densities should be multiplied by 24 to obtain figures that are consistent with employment densities in France. Market access is the sum of employment densities divided by distances, excluding the city itself. Wage is in constant euros.

Figure 3: Evolution of city variables for Paris, Lyon, Lille, and Marseilles


*Notes*: Employment density is computed as the ratio between employment and area (in km$^2$). Market access is the sum of employment densities divided by distances, excluding the city itself. Wage is in constant euros.

# 4 Empirical strategy

Equipped with our time-varying delineations of cities, we quantify how changes of agglomeration economies affected labour earnings over the past forty years in France using the following empirical strategy. First, we estimate a log-wage specification that involves city-year effects, while taking into account the sorting of individuals with respect to observed and unobserved characteristics across cities. City-year effects are then regressed on our agglomeration variables separately for each year of our study period. We finally turn to a decomposition of the evolution of average daily wage into changes of composition effects, agglomeration variables and returns to these variables.

## 4.1 Specification

In our log-wage specification, we distinguish spatial effects for three types of workplace: cities ($\mathcal{C}$), urban areas without a core ($\mathcal{U}$), and rural areas that gather remaining places ($\mathcal{R}$).[5] We introduce city-year fixed effect for each city, but only location-year fixed effects for urban areas without a core (resp. rural areas) considered as a whole. Our specification is the following:

$$\ln w_{i,t} = X_{i,t}\beta + 1_{\{(i,t)\in\mathcal{C}\}}\gamma_{c(i,t),t} + 1_{\{(i,t)\in\mathcal{U}\}}\gamma_t^{\mathcal{U}} + 1_{\{(i,t)\in\mathcal{R}\}}\gamma_t^{\mathcal{R}} + \mu_{s(i,t),t} + u_i + \varepsilon_{i,t}, \qquad (1)$$

where $w_{i,t}$ is the daily wage of an individual $i$ in year $t$, $k \in \{\mathcal{C}, \mathcal{U}, \mathcal{R}\}$ is the workplace type, $c(i,t)$ (resp. $s(i,t)$) is the city (resp. industry) where individual $i$ works in year $t$ (when working in a city), $\gamma_{k,t}$ is a location-year fixed effect (when not working in a city), $X_{i,t}$ are time-varying individual variables (in practice, age squared), $\mu_{s,t}$ is an industry-year fixed effect, $u_i$ is an individual fixed effect and $\varepsilon_{i,t}$ is a random component.[6]

We then estimate the following second-step specification of city-year fixed effects separately for each year:

$$\gamma_{c,t} = Z_{c,t}\theta_t + \delta_t + \eta_{c,t}, \qquad (2)$$

where $Z_{c,t}$ is a vector of time-varying city characteristics, i.e. density, land area and market access, $\theta_t$ are their time-varying effects, $\delta_t$ is a year fixed effect and $\eta_{c,t}$ is a city random compo-

[5] Note that the three sets $\mathcal{C}$, $\mathcal{U}$ and $\mathcal{R}$ change over time during our study period. For the sake of simplicity, we do not index these three sets by $t$.

[6] As the definition of industries changes over time due to classification changes in 1993 and 2009, we use three sets of fixed effects $\{1, ...S\}$, $\{S+1, ..., S+S'\}$ and $\{S+S'+1, ..., S+S'+S''\}$ such that $s(i,t)$ is included in the first set before 1993, in the second set from 1993 to 2008, and in the third set after 2008.

nent capturing city unobserved effects such as the influence of amenities. Our yearly regressions are weighted by city-year numbers of workers.[7]

### 4.2 Instrumentation

As agglomeration variables are endogenous when households and firms rationally choose their location, we instrument these variables in the second stage with historical variables constructed from past censuses in line with Combes *et al.* (2008). We resort to EHESS historical population data that give population counts for all municipalities in France for every censuses over the 1793-2006 period. We reaggregate these data at the city level to construct our instruments. Since we consider time-varying delineations of cities, the reaggregation of municipalities is specific to the year that is considered. More precisely, instruments are the logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years . We expect the explanatory power of these instruments to be large because there is inertia of local housing stocks that induces inertia of local population. At the same time, we expect these instruments to verify the exclusion restrictions because the production processes have changed a lot over 150 years with the rise of services industries and several disruptions due to wars.

An alternative set of instruments consists in the aggregates of small-scale soil information at the city level (Rosenthal and Strange, 2008; Combes *et al.*, 2010). We aggregate data from the European Soil Database (ESDB) compiled by the European Soil Data Centre that originally comes as a raster of 1 km x 1 km cells. These instruments are expected to have some explanatory power because geology is likely to influence the productivity in the agricultural sector and should thus explain the location of first settlements which might have turned into cities. At the same time, the exclusion restrictions are expected to be satisfied because there is no clear link between geology and the production processes of the modern era. In practice, we use as instruments the proportions of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

[7] We use these weights for two reasons. First, we have adopted the perspective of individuals re-aggregated at the city and national levels. We want the estimated effects of agglomeration variables to fit this individual perspective. Note that this is consistent with the estimation at the individual-year level of equation (1) after replacing city-year fixed effects with their expression (2). We did not proceed this way because estimates are then consistent under stronger assumptions. Second, city-year effects used as dependent variable in the second step are estimated with a sampling error since they are recovered from the first-step estimation. Our weights give more importance to city-year effects of large cities that are estimated more accurately, and this makes the second-step estimates more accurate. This also means that we recover effects of agglomeration variables using variations for larger cities rather than for the whole set of cities. From an econometric point of view, this means estimating the effects of agglomeration variables locally, at large city sizes.

### 4.3 Assessing the role of agglomeration economies in wage evolution

Our main goal is to assess how changes in average daily wages between two periods, say $t-1$ and $t$, are related to the location type (city, urban area without a core, rural) and agglomeration economies within cities. For that purpose, we first decompose national log-wage growth into two components:

$$\overline{\log w}_t - \overline{\log w}_{t-1} = \sum_{k\in\{\mathcal{C},\mathcal{U},\mathcal{R}\}} (p_{k,t} - p_{k,t-1})\,\overline{\log w}_{k,t-1} + \sum_{k\in\{\mathcal{C},\mathcal{U},\mathcal{R}\}} p_{k,t}\left(\overline{\log w}_{k,t} - \overline{\log w}_{k,t-1}\right), \quad (3)$$

where $\overline{\log w}_t$, $\overline{\log w}_{k,t}$ and $p_{k,t}$ denote respectively the average log-wage in year $t$, the average log-wage in type-$k$ locations in year $t$, and the related proportion of workers. On the right-hand side, the first sum captures the time variations in the allocation of workers between the three location types, and the second sum captures the evolution of log-wages in every location type.

We are particularly interested in cities and we thus focus on the evolution of average log-wage in cities, $\overline{\log w}_{\mathcal{C},t} - \overline{\log w}_{\mathcal{C},t-1}$. Denote by $p_{c,t}$ the proportion among cities of workers located in city $c$ at date $t$. The evolution of average log-wage in cities can be decomposed in the following way:

$$\overline{\log w}_{\mathcal{C},t} - \overline{\log w}_{\mathcal{C},t-1} = \sum_c (p_{c,t} - p_{c,t-1})\,\overline{\log w}_{c,t-1} + \sum_c p_{c,t}\left(\overline{\log w}_{c,t} - \overline{\log w}_{c,t-1}\right) \quad (4)$$

where $\overline{\ln w}_{c,t}$ is the city-year average of log-wages. The first right-hand side sum captures the change in the distribution of workers across cities, holding constant the average log-wage in cities. The second sum captures the changes in log-wage in every city, holding constant the proportions of workers in cities.

We now detail the causes of log-wage evolution for any given city $c$. We first insert expression (2) into equation (1) and average the resulting expression at the city level for a given year:

$$\overline{\log w}_{c,t} = \bar{X}_{c,t}\beta + Z_{c,t}\theta_t + \bar{\mu}_{c,t} + \bar{u}_{c,t} + \delta_t + \eta_{c,t}, \quad (5)$$

where $\overline{X}_{c,t}$, $\overline{u}_{c,t}$ and $\overline{\mu}_{c,t}$ denote respectively city-year averages of individual variables, individual fixed effects and industry effects. Note that, since city-year fixed effects are introduced in equation (1), the city-year average of first-stage residuals is zero by construction and thus does not intervene in this equation. From expression (5), we get the following decomposition of city log-wage growth into four components:

$$\overline{\log w}_{c,t} - \overline{\log w}_{c,t-1} = (M_{c,t} - M_{c,t-1}) + Z^*_{c,1}(\theta_t - \theta_{t-1}) + \left(Z^*_{c,t} - Z^*_{c,t-1}\right)\theta_{t-1} + (\eta_{c,t} - \eta_{c,t-1}), \quad (6)$$

where $Z^*_{c,t} = Z_{c,t} - Z^*$ with $Z^*$ the values of city variables for a reference city, and $M_{c,t} = \overline{X}_{c,t} + \overline{u}_{c,t} + \overline{\mu}_{c,t} + Z^*\theta_t + \delta_t$ the composition effect for city $c$ in year $t$. The first right-hand side term captures changes in composition effects (related to age, individual unobservables and industry structure) and time effects. It cannot be decomposed further because individual fixed effects, time fixed effects and linear age effects (not introduced here) cannot be identified separately due to collinearity. The second term corresponds to the effect of changes in returns to agglomeration variables. The third one captures the impact of changes in the values of agglomeration variables. Note that terms two and three constitute a Oaxaca-Blinder decomposition of spatial effects. Finally, the fourth term corresponds to the evolution of city unobserved effects.[8]

Decomposition (6) can be quantified for each city and then aggregated over France, weighting by the city share of workers, to obtain a more detailed decomposition of the second component of $\overline{\log w}_{\mathcal{C},t} - \overline{\log w}_{\mathcal{C},t-1}$ in decomposition (4).

# 5 Results

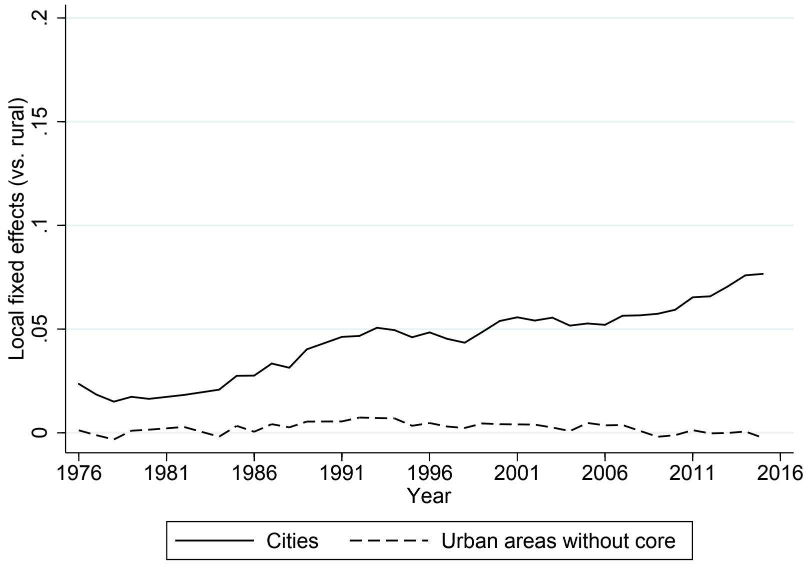
## 5.1 Local effects and spatial sorting

We first estimate the log-wage specification that involves location-year fixed effects and controls for individual observed and unobserved characteristics, as well as industry (equation 1). For now, we focus on the estimates for the effects of being in a rural area, $\gamma_t^{\mathcal{R}}$, in an urban area without a core, $\gamma_t^{\mathcal{U}}$, and in a city, $\gamma_t^{\mathcal{C}} \equiv \sum_{c=1}^{C} p_{c,t}\gamma_{c,t}$. Figure 4 graphs $\gamma_t^{\mathcal{U}} - \gamma_t^{\mathcal{R}}$ and $\gamma_t^{\mathcal{C}} - \gamma_t^{\mathcal{R}}$ as a function of time. Urban areas without a core are characterized by yearly effects that remain close to those of rural areas. This is not really surprising since these urban areas are usually quite small and without a denser core, and agglomerations economies are not really expected to

[8] We introduce a reference city to make a meaningful assessment of the effect of changes in returns to agglomeration variables. As these variables are in logarithmic form, changing their measurement unit changes their values but not their returns. Considering the difference between cities and the reference makes this issue disappears since logarithm differences are immune to changes of measurement unit. For the reference, we consider a fictitious city which values for all the agglomeration variables are the minimum. This way, differences of agglomeration variables with the reference city are all positive, and the effect of changes in returns to agglomeration variables captures effects for cities having agglomeration economies that are larger than for the minimum. For instance, if returns to density are increasing over time, it captures the average effect of an increase in returns when having a density larger than the minimum.

emerge. By contrast, yearly effects for cities are above those for rural areas and the difference is increasing over time, suggesting an increase in agglomeration economies. These results can be contrasted with those obtained when individual unobserved heterogeneity is ignored. In that case, differences in local effects between cities and rural areas are larger and there is no increasing trend (Figure D.1). The contrast between the two figures suggests a strong sorting of workers with higher unobserved skills in cities that largely declines over time.

Figure 4: Yearly effects of working in an urban area without a core or a city relatively to the rural area




*Notes*: Differences between yearly effects of being in an urban area without a core or in a city and yearly effects of being in the rural area. Yearly effects of being in a city are yearly averages of city-year fixed effects weighted by the yearly share of individuals working in the city. There are no yearly effects for 1981, 1983 and 1990 since data are missing for those years, and we therefore consider instead the average value of neighbouring years.

We then turn to the estimation results when regressing estimated city-year fixed effects on agglomeration variables (equation 2), with the constraint that the coefficients of city variables are constant over time. This gives us a benchmark that is comparable to regressions conducted in the literature. Results detailed in Appendix C are in line with previous studies. In particular, OLS estimates for density, land area and market access are respectively 0.025, 0.014 and 0.065. When instrumenting all the agglomeration variables with both historical and soil instruments, estimates are rather stable and take respectively the values 0.031, 0.014 and 0.050.

Finally, we consider the results based on equation (2) when coefficients of density, land area and market access depend on time. Figures 5.a and 5.c show that the estimated effects of density (resp. land area) increase over time from 0.011 to 0.042 (resp. 0.007 to 0.022) whereas, according to Figure 5.e, there is no clear pattern for the estimated effects of market access. Interestingly, when omitting individual fixed effects in the first stage (equation 1), the patterns are quite different (Figures D.2.a, D.2.c and D.2.e). In particular, there is no upward trend for the estimated effects of density and land area after 1995, which suggests some variations in the spatial sorting of individuals across time.

We investigate this sorting further by representing the yearly correlation between city-year fixed effects and individual fixed effects computed at the individual-year level. Interestingly, Figure D.3.a shows that this yearly correlation increases until 1990, then remains stable and finally decreases after 2000. Turning to agglomeration variables, the yearly correlation between market access and individual fixed effects is rather stable until 2002 and then decreases (Figure D.3.d). The yearly correlation between density (resp. land area) and individual fixed effects is positive, decreases slightly after 1992, before decreasing more abruptly after 2002 (Figures D.3.b and D.3.c).

Since the yearly correlations between density (resp. land area) and individual fixed effects are positive, taking into account individual unobserved heterogeneity lowers the estimated coefficients of density and land area. This lowering gets smaller and smaller after 1992, because the yearly correlation between density (resp. land area) and individual fixed effects decreases over time after 1992. The estimated coefficients of density and land area have a humped-shape profile with a small plateau ending up in 2000 in absence of individual fixed effects. Introducing individual fixed effects modifies the trend from the middle of the plateau (around 1992) and makes it increasing instead of decreasing. Because of that, the overall profile for the estimated coefficients of density and land area ends up being increasing. Overall, correlation patterns are consistent with the changes in the estimated coefficients of agglomeration variables obtained when introducing individual fixed effects.

Still, individual fixed effects capture both unobserved skill effects and average age effects,[9] which matters for the interpretation of correlations. In particular, there is a time pattern for the average age since it is computed for years present in the panel and it decreases as one enters the labour market closer to the end of the panel. We try to isolate unobserved skill effects by

[9]Indeed, remember that the linear effect of age cannot be identified separately from individual fixed effects and time effects captured by city-year and industry-year fixed effects.

considering the individual residuals obtained when regressing the sum of the individual fixed effect and the effect of squared age on age, squared age and year fixed effects, which we name "net individual effects". Yearly correlations between city variables and net individual effects have shapes similar to those obtained when considering individual fixed effects, but they are larger. In particular, the correlations involving density and land area are still decreasing after 1992. This suggests a decrease over time in the spatial sorting according to unobserved individual skills.[10]

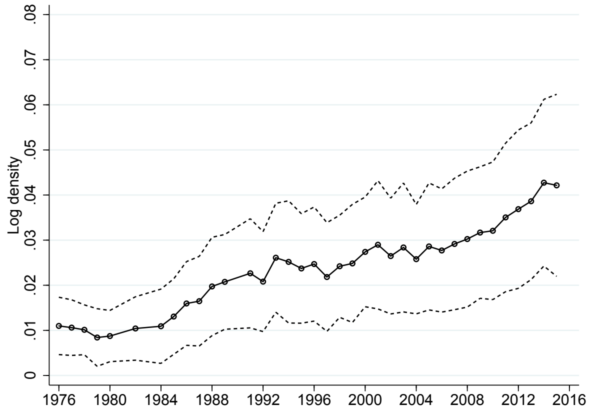
Finally, we assess the importance of endogeneity issues by instrumenting agglomeration variables in the second-stage equation with historical and geological variables. Results represented in Figures 5.b, 5.d and 5.e are very close to those obtained without instrumentation (Figures 5.a, 5.c and 5.e).

[10]One may also wonder whether important changes in the profiles of estimated coefficients when introducing individual fixed effects could be an artefact due to periods involved in their identification. Indeed, in 1976 (resp. 2015), only observations from 1976 onward (resp. 2015 downward) for individuals participate to the identfiication of the density, land area and market access coefficients for year 1976 (resp. 2015). For a given year $\tau$ between 1976 and 2015, coefficients are identified thanks to observations at year $\tau$, as well as years before and after $\tau$. To investigate the existence of a possible bias due to edge effects, we re-estimate our specification when considering only the first four observations for individuals appearing at least four times in the panel. Considering short time spans for individuals should lessen edge effects although restricting the estimations to individuals appearing at least four times in the panel may lead to sample selection. Making such restriction changes profiles of estimated coefficients that are now rather decreasing over time when individual fixed effects are not introduced, especially for density and land area (Figure D.4.b, D.4.d and D.4.f), suggesting sample selection in our robustness check. But profiles are modified in the same direction as with the whole sample when introducing individual fixed effects, as estimated coefficients are then increasing over time for density and market access, and rather stable for land area (Figure D.4.a, D.4.c and D.4.e).

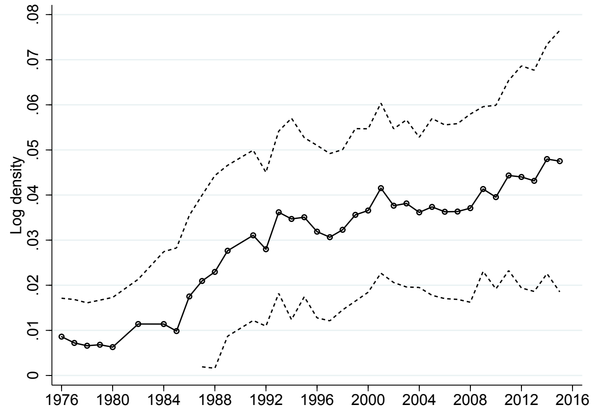
Figure 5: Estimated yearly coefficients of city variables with individual effects in the first-stage specification,

with and without instrumentation with historical and geological variables

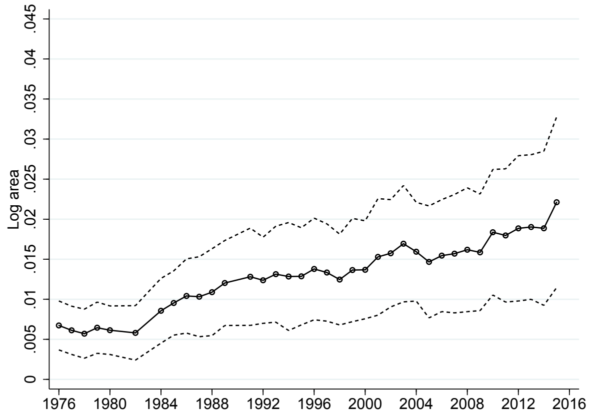
5.a: Density, no instrumentation



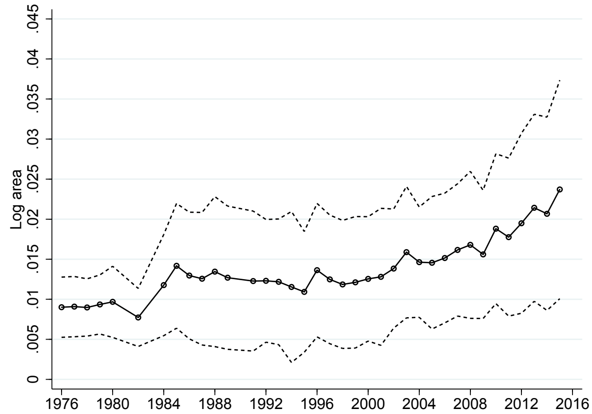

5.b: Density, instrumentation



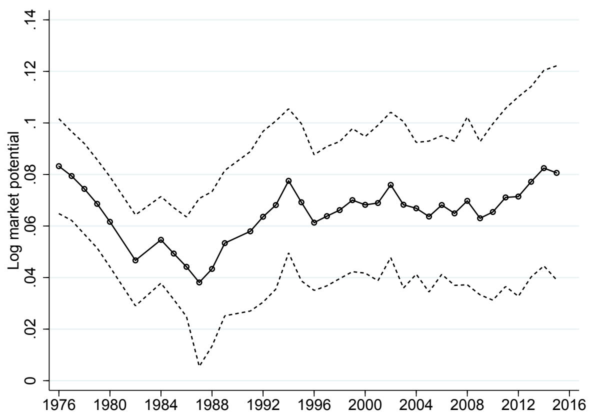

5.c: Land area, no instrumentation



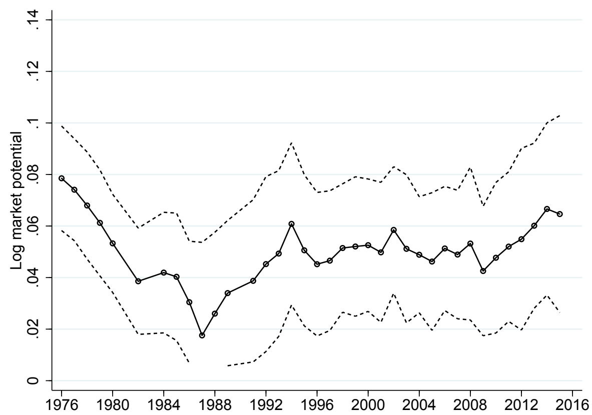

5.d: Land area, instrumentation




5.e: Market access, no instrumentation




5.f: Market access, instrumentation




*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots. Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

### 5.2 Decompositions of wage growth

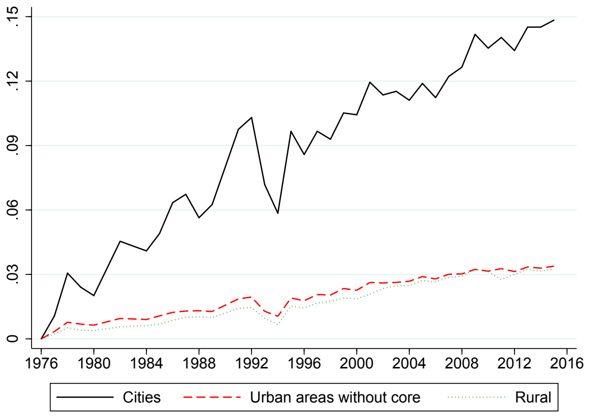
We now consider wage growth defined as the difference in average log-wage between any given year and 1976. First, we quantify the contributions to this growth of wage evolutions in the three location types and of the reallocation of workers across location types (equation 3). Figure 6.a shows that wage growth comes only from wage evolutions in the three location types whereas reallocation effects are negligible whatever the time horizon. Figure 6.b gives contributions related to wage evolutions for the different location types and shows that cities contribute the most.

Second, we quantify the contribution to city growth of the wage growth in the different cities and the reallocation of workers across cities (equation 4). Figure 6.c shows that city growth is mostly driven by wage evolutions in the different cities. The reallocation of workers has an influence that is negligible for short-run wage growth but it grows larger and becomes significant, while remaining small, for wage growth between 1976 and any year after 2006. Figure 6.d decomposes further the contribution of wage evolutions to city growth by quartile of city size, measured by employment in 1976. It shows that this contribution comes only from the cities in the fourth quartile, i.e. the largest cities. It is the growth in those locations that has mostly driven aggregate wage growth in France, rather than growth in smaller cities, urban areas without cores or rural places, or the reallocation of population between locations.

Figure 6: Decomposition of wage growth between 1976 and any given year

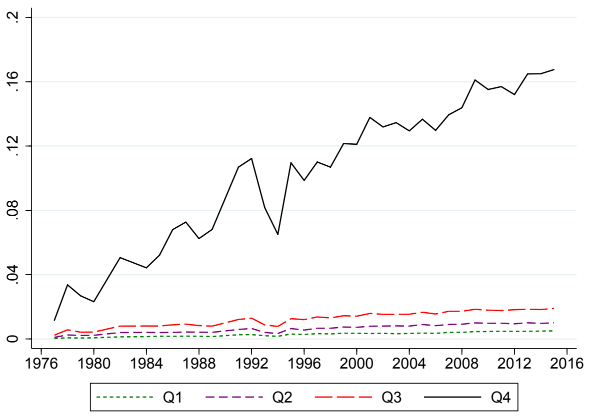
6.a: Overall wage growth


6.b: Wage contribution by location type




6.c: City wage growth


6.d: City wage contribution by city quartile




*Notes*: Panel a: "Wage growth": Average log-wage growth (relatively to 1976); "Wage contrib.": Contribution of wage evolutions in the three location types (rural, urban areas without a core and cities); "Proportion contrib.": Contribution of changes in the proportions of workers in the three location types.

We now evaluate the contributions to city wage growth of changes in values and returns to agglomeration variables. These contributions are computed as the sums of those obtained for cities (see equation 6), weighted by the city proportion of workers (among workers living in cities) at the initial date. Figure 7.a shows that the contribution of changes in values is negative. There are two main reasons for this result. First, time variations in agglomeration variables are rather small compared to cross-section differences across cities. Second, even if the population of most cities largely expands over the period, this often occurs together with a decrease in their density. In that case, an increase in agglomeration economies from land area is compensated by a decrease in agglomeration economies from density which is sometimes larger. In any case, the contribution of changes in values is pretty small, whatever the time horizon.

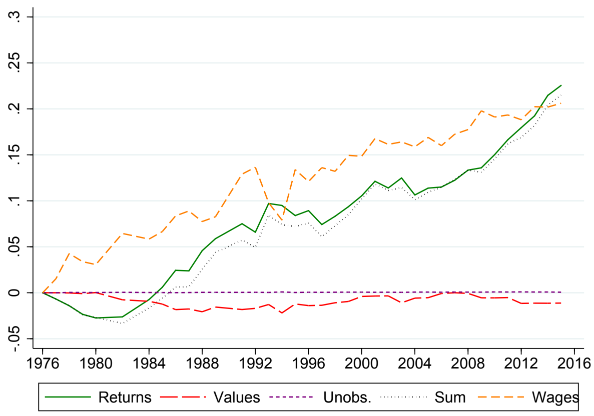
By contrast, changes in returns to agglomeration variables have a large positive impact on wage growth between 1976 and any year from 1985 onwards, which contrasts with the small negative impact before 1985.[11] This impact is increasing over time consistently with the wage increase observed in cities. Overall, changes in the returns to agglomeration is the main source of wage growth in France since the mid-eighties.

We can assess which agglomeration variables play the most important role in the contribution of changes in returns. Figure 7.b shows that the change in returns to density has the largest impact, followed by that of land area. The large impacts on medium-run city wage growth for density and land area come from both the significant increase in their returns, and large values compared to the reference city. By contrast, the change in returns to market access has a small negative impact on city wage growth between 1976 and any given year. This occurs because the return to market access is large in 1976 compared to that in other years, and values of market access are close to those of the reference city (i.e. there is not much variations in values across cities). It is the negative contribution of market access before 1985 that mostly explains the global negative contribution of changes in returns before that date observed in Figure 7.a.

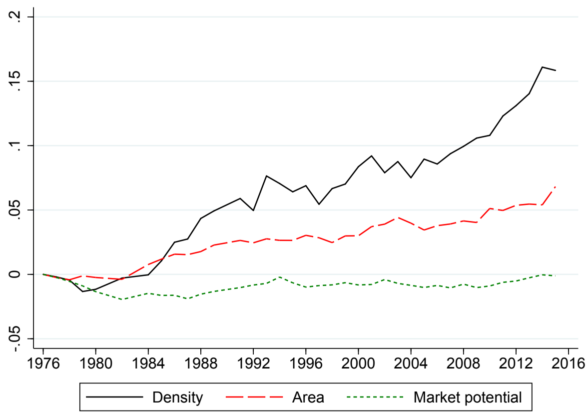
[11] We do not comment on the contribution of changes in city unobservables to city wage growth since it is close to zero by construction. Indeed, this contribution can be written as $\sum_c p_{c,t} \left(\eta_{c,t} - \eta_{c,t-1}\right) = \sum_c p_{c,t}\eta_{c,t} - \sum_c p_{c,t}\eta_{c,t-1}$. Since, time fixed effects are introduced in the second-stage specification of the model (equation 2), we have by construction $\sum_c p_{c,t}\eta_{c,t} = 0$, and $\sum_c p_{c,t}\eta_{c,t-1}$ is close to zero because $p_{c,t}$ does not vary much over time and is thus close to $p_{c,t-1}$, and by construction $\sum_c p_{c,t-1}\eta_{c,t-1} = 0$.

Figure 7: Decomposition of city wage growth between 1976 and any given year

7.a: Contributions to city wage growth




7.b: Contributions of changes in returns

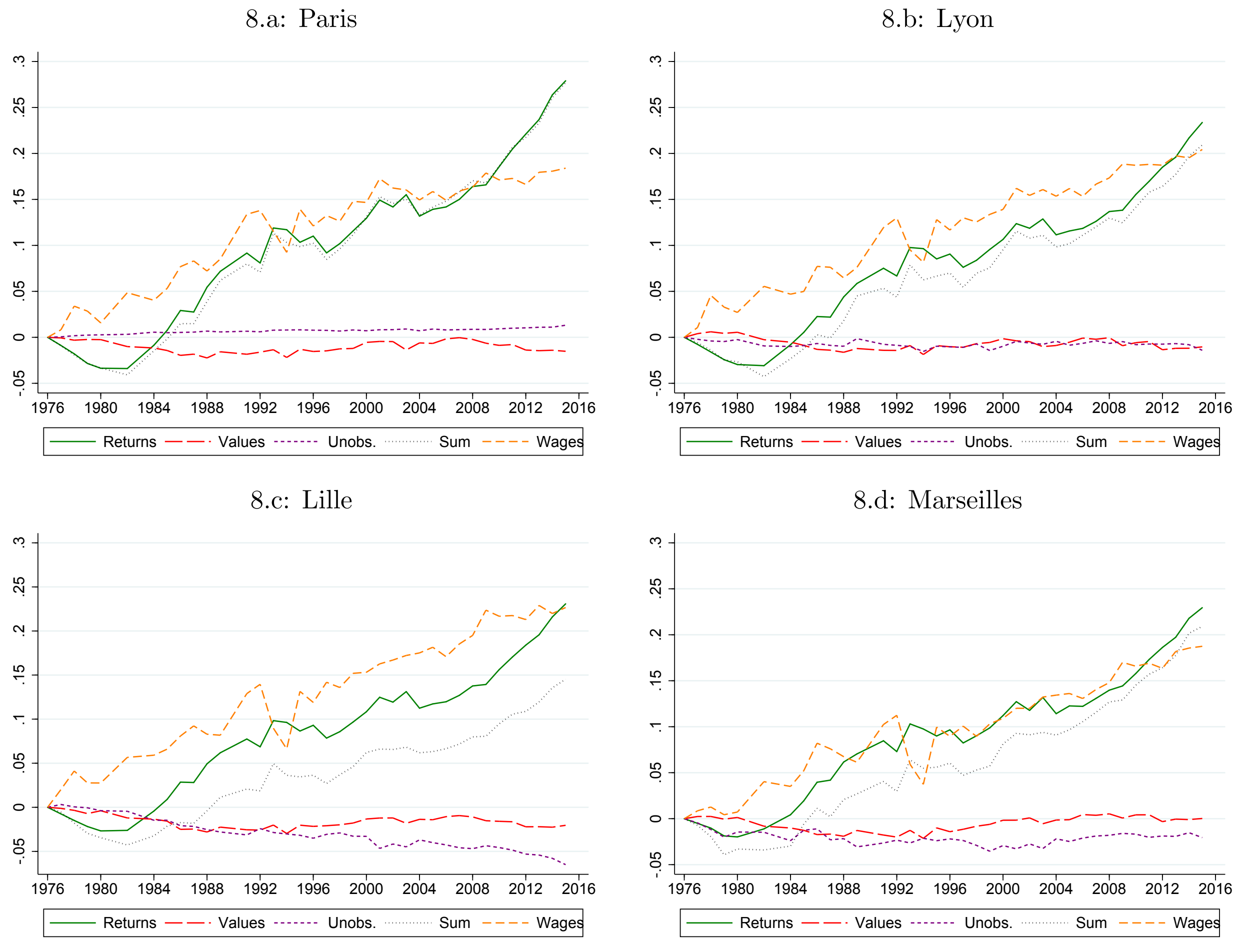



*Notes*: Panel a: "Wages": City average log-wage growth (relative to 1976); "Returns": Contributions of changes in returns of city variables to city wage growth; "Values": Contribution of changes in their values; "Unobs.": Contribution of changes in city unobservables; "Sum": Sum of these three contributions. Panel b: "Density" (resp. "Area" and "'Market Access": Contribution of changes in returns to density (resp. area and market access). Values are missing for 1981, 1983, 1990.

So far, we have presented results for the decomposition when aggregating all the cities, but it is also possible to consider the decomposition by city size group. For that purpose, we replicate the decomposition exercise separately for each quartile of city employment in 1976. Not surprisingly, Figure D.5 shows that the contribution of the change in returns to agglomeration variables increases with the city size quartile. Indeed, for the computation of this contribution, changes in returns are multiplied by values of density and area which are higher for cities in higher quartiles.

Finally, we separately consider the contributions of agglomeration variables to the wage growth in the four largest French cities, Paris, Lille, Lyon and Marseilles (Figures 8.a-8.d). The contribution of the changes in returns to agglomeration variables is the largest for Paris where density and land area are the largest in France (Figures 3.a and 3.b). Interestingly, even if Marseilles has grown a lot over the last 40 years, its contribution of the changes in values of agglomeration variables is not much different from that of other large cities. This is due to the decrease of its density that has gone together with the large increase in its land area. Finally, Lille has experienced a decrease in city unobservables, suggesting a decrease in productivity possibly due to the decline of textile, mining and steel industries.

Figure 8: Decomposition of wage growth between 1976 and any given year, for the four largest cities




*Notes*: "Returns": Contributions of changes in returns of city variables to log-wage growth; "Values": Contribution of changes in their values; "Unobs.": Contribution of changes in city unobservables; "Sum": Sum of these three contributions; "Wages": Average city log-wage growth.

# 6 Robustness checks

## 6.1 Alternative definitions of cities

In this section, we consider robustness checks when changing the way cities are defined since our approach is novel and not standard.

First, our delineation of cities varies over time and there are some fusions, disappearances and emergences of cities over the period that can be quite important. For instance Marseilles absorbs Aix-en-Provence during our study period, which induces a discrete large jump in its land area and density at the time of absorption. It is legitimate to wonder whether time variations in delineations affect the results. We conduct a first robustness check with a delineation of cities that is constant over time, and fixed to the one obtained in 2015. Figure D.6 shows that the time-varying profiles of estimates for coefficients for agglomeration variables are barely affected. Somehow, this is not surprising because these coefficients are estimated in second stage using cross-section variations across cities within each year, and these variations are much larger than the time variations induced by changes in the delineation of cities.

Moreover, the literature has proposed alternative ways of constructing cities. Whereas here cities are defined based on built-up density, Duranton (2015) or Bosker *et al.* (2021) consider commuting patterns and aggregate municipalities iteratively when they send a proportion of their commuters to the rest of the city above a given threshold. Recent official city definitions often mix the two perspectives using criteria based on both the built-up density and commuting patterns. This is the case for the definition of functional urban areas by OECD and the European Commission which has been implemented in many European countries. An urban centre is defined based on population or built-up density and municipalities are aggregated to that centre according to commuting flows. We conduct a robustness check when using the 2010 urban areas defined by INSEE.[12] Figure D.7 shows that the profiles of estimated coefficients are close to those in our benchmark except that, when instrumenting, the slope for estimated coefficients of density (resp. land area) is less steep (resp. steeper). This can be explained by different correlations between density and land area depending on the definition of cities, and different relationships between agglomeration variables and instruments.

Alternative time-varying delineations of cities based on different methodologies are not avail-

[12]There are past definitions of French urban areas but the methodology used to construct them is not consistent over time. This is why we consider the same 2010 definition at all dates.

able. Nevertheless, we can vary the scope of cities at the different dates by changing the bandwidth of the kernel used for smoothing built-up density in our delineation algorithm. When larger bandwidths are used, sparsely built-up pixels close to dense pixels and peripheral municipalities whose workers commute into the city centre can end up being included in the city. Nearby cities may also merge. To be as consistent as possible with official urban area definitions, we choose a rather large bandwidth of 2.1km for our benchmark delineations.

We conduct a robustness check using a smaller bandwidth of 1km to have a definition of cities more closely related to built-up continuity. Table B.2 shows that this change of bandwidth yields many more cities that are smaller on average, as expected. Estimated coefficients of density and land area still increase over time, whether or not agglomeration variables are instrumented, in line with results obtained with the 2.1km bandwidth (Figure D.8). Still, estimated density coefficients are smaller, suggesting that a 2.1km bandwidth is more appropriate to delineate cities relevant to measure agglomeration economies.

### 6.2 Dynamic agglomeration effects

We also conduct a robustness check considering dynamic agglomeration effects such that workers benefit from staying longer in larger cities. Following de la Roca and Puga (2017), we augment the wage specification with urban experience variables, i.e. the number of years spent in every city, with an effect that depends on both previous and current locations:

$$\begin{aligned} \ln w_{i,t} &= X_{i,t}\beta + 1_{\{(i,t)\in\mathcal{C}\}}\gamma_{c(i,t),t} + 1_{\{(i,t)\in\mathcal{U}\}}\gamma_t^{\mathcal{U}} + 1_{\{(i,t)\in\mathcal{R}\}}\gamma_t^{\mathcal{R}} + \mu_{s(i,t),t} \\ &+ \sum_{q,r=1}^{Q} 1_{\{(i,t)\in\mathcal{C}(r)\}}\Psi_q^r EXP_q + \sum_{q=1}^{Q}\sum_{k\in\{\mathcal{U},\mathcal{R}\}} 1_{\{(i,t)\in k\}}\Psi_q^k EXP_q \\ &+ \Psi^{\mathcal{U}} EXP_{\mathcal{U}} + \Psi^{\mathcal{R}} EXP_{\mathcal{R}} + u_i + \varepsilon_{i,t} \end{aligned} \quad (7)$$

where $\mathcal{C}(q)$ is the subset of cities in quartile of city size $q$, $EXP_{\mathcal{C}(q)}$ is the past experience in cities of this quartile, $EXP_{\mathcal{U}}$ is the past experience in urban areas without a core, $EXP_{\mathcal{R}}$ is the past experience in rural areas.[13] Parameters $\Psi^{\mathcal{U}}$ and $\Psi^{\mathcal{R}}$ capture the effects of past experience in respectively urban areas without a core and rural areas. It is implicitly assumed that these kinds of experience are fully transferable across locations. Dyadic parameters $\Psi_q^r$ (resp. $\Psi_q^k$) capture the effects of past experience in quartiles of cities $q$ depending on current quartile $r$

[13] A quartile in a given year is the unweighted quartile of city size for that year.

(resp. location $k$). Because these parameters depend on both past and current locations, it is allowed for past city experience to be only partially transferable to another quartile (resp. location type). Note that our specification is very general as dynamic effects are unconstrained, and in particular no functional forms is assumed for the role of city variables.

For the estimations, we limit our sample to individuals aged 18 or less in 1976 so that their past experience on the labour market is fully observed. Interestingly, the positive time trends for the estimated coefficients of density and land area remain, whether or not we instrument the agglomeration variables, but the magnitude of the effects are smaller (Figures D.9). This suggests the presence of a positive correlation between static and dynamic agglomeration effects, which is consistent with the literature (Combes and Gobillon, 2015).

### 6.3 Firm heterogeneity

A strand of the literature inspired from Abowd *et al.* (1999) considers establishment fixed effects rather than city fixed effects in wage specifications, and reconstruct city fixed effects as city averages of establishment fixed effects (Dauth *et al.*, 2022). A justification for this approach is that city fixed effects introduced directly into the wage specification are identified only from workers moving across cities, due to the presence of individual fixed effects. Biases may arise if moves occur between non-representative establishments in origin and destination cities (Card *et al.*, 2024).

A straightforward adaptation of this approach to our setting would consist in computing city-year averages of establishment fixed effects to recover time-varying city effects. A significant drawback is that city-year effects would be able to evolve over time only because of changes in the establishment composition of each city. This is an important restriction that is violated if there are changes in agglomeration economies that benefit surviving establishments. In particular, this can occur due to variations in both the values and returns to the agglomeration variables considered in this study. To address this issue, we extend the literature by considering the following wage specification that involves time-varying establishment effects:

$$\ln w_{i,t} = X_{i,t}\beta + u_i + v_{j(i,t),t} + \varepsilon_{i,t} \tag{8}$$

where $v_{j,t}$ is an establishment-year fixed effect and $j(i,t)$ is the establishment in which individual $i$ works in year $t$. In practice, establishment-year fixed effects are recovered by conducting an

OLS estimation. Identification is granted only within groups of establishment-year pairs well inter-connected by stayers and movers (Abowd *et al.*, 1999). As usual in the literature, we limit our attention to the group which establishment-year pairs gather the largest number of individual-year observations, although it represents here only 67% of our individual-year sample due to us considering time-varying establishment effects.

We construct city-industry-year effects as:

$$\tilde{\gamma}_{c,s,t} = \frac{\sum_{j \in (c,s,t)} N_{j,t} v_{j,t}}{\sum_{j \in (c,s,t)} N_{j,t}} \tag{9}$$

where $N_{j,t}$ is the number of individuals working in establishment $j$ at time $t$. When constructing these effects, we include the whole set of urban areas without a core and the whole rural area as two separate locations, and they are denoted respectively $c = \mathcal{U}$ and $c = \mathcal{R}$. Finally, consistently with equation (1), we recover location-year effects net of industry-year fixed effects by estimating the specification:

$$\tilde{\gamma}_{c,s,t} = 1_{\{c \in \mathcal{C}\}} \gamma_{c,t} + 1_{\{c = \mathcal{U}\}} \gamma_t^{\mathcal{U}} + 1_{\{c = \mathcal{R}\}} \gamma_t^{\mathcal{R}} + \mu_{s,t} + \nu_{c,s,t} \tag{10}$$

weighting by the city-establishment-year number of observations. The effects of agglomeration variables are then recovered from the estimation of equation (2) using our new set of estimated city-year effects as the dependent variable.

Interestingly, the positive time trends for the estimated coefficients of density and land area remain, whether or not we instrument the agglomeration variables. When instrumenting, values are slightly lower than in our benchmark case for estimated coefficients of density that now increase from 0 to 0.04 (Figures D.10). By contrast, values are slightly larger for estimated coefficients of land area since they increase from around 0.01 to 0.04.

## 7 Theoretical insights

In this section, we propose an urban model to assess how city land area and density are influenced by variations in the returns to agglomeration economies affecting wages. We can then quantify to what extent these equilibrium effects feed back into wage growth on top of the direct effect of changes in returns. Our framework starts with the standard monocentric city model with the specificity that wages are endogenous and depend on agglomeration economies. We characterize the equilibrium for the closed city where city population is exogenous, and then for its open version where population is endogenous. We conduct comparative statics to establish quantitative relationships between changes of city land area and density, and changes of their returns. We finally bring these relationships to the data. All developments and proofs are relegated in Appendix E.

## 7.1 The model

Consider a linear city $c$ made of locations $x$ such that all the jobs are exogenously located in a central business district (CBD) in $x = 0$. Workers are located on a segment $[0, \overline{x}_c]$ where $\overline{x}_c$ is the city fringe, and a worker located at distance $x$ commutes to the CBD paying a linear monetary cost $\tau_c x$. Every worker earns an endogenous wage $w_c$ that depends on agglomeration economies such that:

$$w_c = A_c \left(N_c/L_c\right)^{\beta} L_c^{\alpha}, \tag{11}$$

where $A_c$ is the city total factor productivity, and $L_c$ and $N_c$ are respectively the city land area and population such that $N_c > L_c > 1$. This imposes conditions on parameters at the equlibrium which is discussed below in Subsection 7.2.2. There are density agglomeration economies with elasticity parameter $\beta$ such that $0 < \beta < 1$, and land area agglomeration economies with elasticity parameter $\alpha$ such that $0 < \alpha < 1$.

An individual consumes a numeraire in quantity $z$ and land in quantity $\ell$ at price $R_c(x)$. Utility is Cobb-Douglas and given by $U(\ell, z) = B_c \ell^a z^{1-a}$ where $B_c$ captures city-specific consumption amenities, and the budget constraint is $w_c - \tau_c x = z + R_c(x)\,\ell$. Workers maximize their utility under budget constraint choosing their location, and how much numeraire and land they want to consume. The fringe is determined by the equality $R_c(\overline{x}_c) = \underline{R}$ where $\underline{R}$ is the agricultural land price. Since the city is linear, its fringe is such that $L_c = \overline{x}_c$, and the city population verifies the equilibrium equation:

$$N_c = \int_0^{\overline{x}} n_c(x)\, dx, \tag{12}$$

where $n_c(x) = 1/\ell$ is the population density at distance $x$.

## 7.2 Equilibrium and comparative statics

### 7.2.1 Closed cities

When city $c$ is closed, its population $N_c$ is fixed and only its land area $L_c$ adjusts. The model has a unique solution and it is possible to conduct comparative statics with respect to $\alpha$ and $\beta$, the elasticities of wages with respect to land area and population density:

$$\frac{\partial \log L_c}{\partial \log \alpha} = -\frac{\partial \log (N_c/L_c)}{\partial \log \alpha} = \frac{\alpha}{1+\beta-\alpha} \log L_c, \tag{13}$$

$$\frac{\partial \log L_c}{\partial \log \beta} = -\frac{\partial \log (N_c/L_c)}{\partial \log \beta} = \frac{\beta}{1+\beta-\alpha} \log \left(\frac{N_c}{L_c}\right), \tag{14}$$

$$\frac{\partial \log N_c}{\partial \log \alpha} = \frac{\partial \log N_c}{\partial \log \beta} = 0. \tag{15}$$

The elasticity of land area with respect to $\alpha$ (equation 13) is positive because of an income effect. Indeed, incomes increase due to additional land area agglomeration economies, which makes the aggregate land demand increase. Conversely, the elasticity of population density with respect to $\alpha$ is negative since population remains fixed whereas land consumption increases. The magnitude of these elasticities depends on land area $L_c$, $\alpha$ and $\beta$. Indeed, land area $L_c$ determines how much income is affected by a change in the intensity of land agglomeration economies. Moreover, a change in land area generates additional gains from an increase in land agglomeration economies (captured by $\alpha$), but also losses from a decrease in density agglomeration economies (captured by $\beta$). It is possible to comment on variations of land area and population density when $\beta$ varies (equation 14) in the same way. Interestingly, increasing the intensity of density agglomeration economies makes population density decrease. This is again due to the income effect that makes land area increase whereas population is held fixed.

We can then turn to variations of wages due to changes in the returns to land area and population density. Deriving the logarithm of the wage expression (11), we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \log L_c + \frac{\beta}{\alpha} \frac{\partial \log (N_c/L_c)}{\partial \log \alpha} + \frac{\partial \log L_c}{\partial \log \alpha}, \tag{16}$$

$$\frac{\partial \log w_c}{\partial \beta} = \log \left(\frac{N_c}{L_c}\right) + \frac{\alpha}{\beta} \frac{\partial \log L_c}{\partial \log \beta} + \frac{\partial \log (N_c/L_c)}{\partial \log \beta}. \tag{17}$$

There are direct effects due to changes in land area and density agglomeration economies (first right-hand side terms) and indirect effects due to changes in land area and population density (second and third right-hand side terms, respectively). Inserting equations (13), (14) and (15) into these expressions, we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \log L_c + \frac{\alpha - \beta}{1 + \beta - \alpha} \log L_c, \tag{18}$$

$$\frac{\partial \log w_c}{\partial \beta} = \log \left( \frac{N_c}{L_c} \right) + \frac{\alpha - \beta}{1 + \beta - \alpha} \log \left( \frac{N_c}{L_c} \right). \tag{19}$$

Our estimations give small values for $\alpha$ and $\beta$ (below 0.05). We can see from these two expressions that indirect effects due to changes in land area and population density (second right-hand side terms) are then negligible compared to direct effects due to changes in agglomeration economies (first right-hand side terms).

#### 7.2.2 Open cities

We can then turn to the open city case. Population is free to move across cities and, at the equilibrium, utility is the same in every city. We show that there is at most one stable equilibrium for every city when $\beta - a(1 + \beta - \alpha) < 0$, this condition being verified for parameters considered in the literature and found in our application. In that case, the utility in any city can be rewritten as a function of its population $u(N_c)$ that is inverse U-shaped. Indeed, agglomeration economies increase with population faster than agglomeration costs stemming from the crowding of the housing market up to a given value of city population (the optimum), whereas the opposite is true at larger population values. The equality $u(N_c) = \overline{u}$ then bears at most one stable solution: the equilibrium city population size larger than the optimal size. These properties are similar to those obtained for monocentric city models with agglomeration economies generated by gains from varieties or from the division of labor to perform tasks (see Duranton and Puga, 2004). Actually, for a city to be populated at equilibrium, its productivity, consumption amenities and commuting technology must be attractive enough so that $\overline{u}$ does not end up being above the maximum of the utility function $u(N_c)$. Finally, note that we imposed $N_c > L_c > 1$ for our formulation of agglomeration economies to make sense.

It is again possible to conduct comparative statics. We obtain when $\alpha$ varies (see Appendix E.2):

$$\frac{\partial \log L_c}{\partial \log \alpha} = \frac{\alpha}{1+\beta-\alpha}\left[\log L_c + \frac{N_c M_c}{L_c}\frac{\partial \log N_c}{\partial \log \alpha}\right], \tag{20}$$

$$\frac{\partial \log (N_c/L_c)}{\partial \log \alpha} = \frac{\alpha}{1+\beta-\alpha}\left[-\log L_c + \left(\frac{1+\beta-\alpha}{\alpha} - \frac{N_c M_c}{L_c}\right)\frac{\partial \log N_c}{\partial \log \alpha}\right], \tag{21}$$

where:

$$\frac{N_c M_c}{L_c} = \frac{a}{\lambda_c}\left(\frac{w_c - \tau_c L_c}{\tau_c L_c}\right) + \beta \text{ with } \lambda_c = \frac{1}{1-\underline{R}/R_c(0)}. \tag{22}$$

with $N_c M_c / L_c > 0$ because $\tau_c L_c$ is the maximum commuting cost paid in the city, which has to be lower than $w_c$. In expressions (20) and (21), the first right-hand side terms are the same as in the closed-city case, but there are now additional terms capturing migration effects. They involve the elasticity of population with respect to $\alpha$ which expression needs to be determined. Consider for now a city $c$ such that there is in-migration ($\partial \log N_c / \partial \log \alpha > 0$). The elasticity of land area is positively influenced by this in-migration since it creates additional land demand. The elasticity of population density has an ambiguous sign becasue there is both additional population and additional land demand. Typically, the elasticity of city population for a given city, say $c = 1$, verifies:

$$\frac{\partial \log N_1}{\partial \log \alpha} = \alpha \left(\frac{N_1 Q_1}{w_1 - \tau_1 L_1}\right)^{-1}\left(\sum_{c=1}^{C}\frac{w_c - \tau_c L_c}{Q_c}\right)^{-1}\sum_{c=1}^{C}\frac{w_c - \tau_c L_c}{Q_c}\left(\log L_c - \log L_1\right), \tag{23}$$

where:

$$\frac{N_c Q_c}{w_c - \tau_c L_c} = \beta - \frac{a}{\lambda_c}\left[1 + (\beta - \alpha)\frac{w_c}{\tau_c L_c}\right]. \tag{24}$$

Equation (23) shows that the elasticity of city-1 population depends on a weighted average of land area differences between city 1 and other cities. Indeed, in- or out-migration results from changes in land area agglomeration economies in every city.

We can then turn to the variations of wages. Inserting equations (20) into the expression for variations of wages with respect to $\alpha$ given by equation (16), we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \log L_c + \frac{\alpha - \beta}{1+\beta-\alpha}\log L_c + \left(\beta + \frac{\alpha-\beta}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\right)\frac{1}{\alpha}\frac{\partial \log N_c}{\partial \log \alpha}, \tag{25}$$

where the expression of $\frac{\partial \log N_c}{\partial \log \alpha}$ is given by equation (23). There is now a third term compared to the closed city case, that comes from migrations between cities affecting both city land area and density.

Expressions for elasticities of city land area and population density as well as variations of wages with respect to $\beta$ are very similar and are detailed in appendix. Interestingly, none of our expressions for elasticities depends on production and consumption amenities $A_c$ and $B_c$ that would be hard to quantify. Production amenities disappear because they are introduced multiplicatively in the wage function and the computation of elasticities makes intervene the derivative of log-wage (that involves the derivative of log-production amenity effect which is zero). Consumption amenities disappear because they enter multiplicatively the utility function, and the derivative of the between-city equilibrium equation then involves ratios of consumption amenity effects between city pairs that can be replaced by ratios of wages net of commuting costs (according to the between-city equilibrium equation).

### 7.3 Bringing the model to the data

Empirically, we estimate a log-wage equation at the individual level and then conduct a decomposition of the evolution of average log-wage for a given city $c$ between two dates $t-1$ and $t$, $\log w_{c,t} - \log w_{c,t-1}$. Indexing model parameters by $t$, we can isolate the evolution of average log-wages due to changes in agglomeration economies related to land area and population density from the rest:

$$\begin{aligned} \log w_{c,t} - \log w_{c,t-1} &= \log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) - \log w_{c,t-1}\left(\alpha_{t-1}, \beta_{t-1}, A_{t-1}, B_{t-1}\right), \\ &\quad + \left[\log w_{c,t} - \log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right)\right] \\ &\quad - \left[\log w_{c,t-1} - \log w_{c,t-1}\left(\alpha_{t-1}, \beta_{t-1}, A_{t-1}, B_{t-1}\right)\right], \end{aligned} \tag{26}$$

where:

$$\log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) = \log A_{c,t} + \beta_t \log\left(N_{c,t}/L_{c,t}\right) + \alpha_t \log L_{c,t} \tag{27}$$

is the log-wage equation specified in the model where $A_t = (A_{1,t}, ..., A_{C,t})'$ and $B_t = (B_{1,t}, ..., B_{C,t})'$. Note that wages are impacted by all city-specific total factor productivities and consumption amenities since they affect city land area and population at the equilibrium.

Considering that dates $t-1$ and $t$ are close, we can write that:

$$\log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) - \log w_{c,t-1}\left(\alpha_{t-1}, \beta_{t-1}, A_{t-1}, B_{t-1}\right) \approx d \log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) \tag{28}$$

In particular, we are interested in the evolutions of log-wages when the values of agglomeration parameters $\alpha$ and $\beta$ vary (and we want to leave aside their evolutions when city-specific total factor productivities and consumption amenities vary). Using equations (26) and (28), and a Taylor first-order approximation, it is possible to show that:

$$\log w_{c,t} - \log w_{c,t-1} = \frac{\partial \log w_{c,t}}{\partial \alpha} (\alpha_t - \alpha_{t-1}) + \frac{\partial \log w_{c,t}}{\partial \beta} (\beta_t - \beta_{t-1}) + r_{c,t}, \quad (29)$$

where $r_{c,t}$ is a residual that captures discrepancies between observed and theoretical wages, as well as theoretical wage variations due to changes in total factor productivities and consumption amenities.

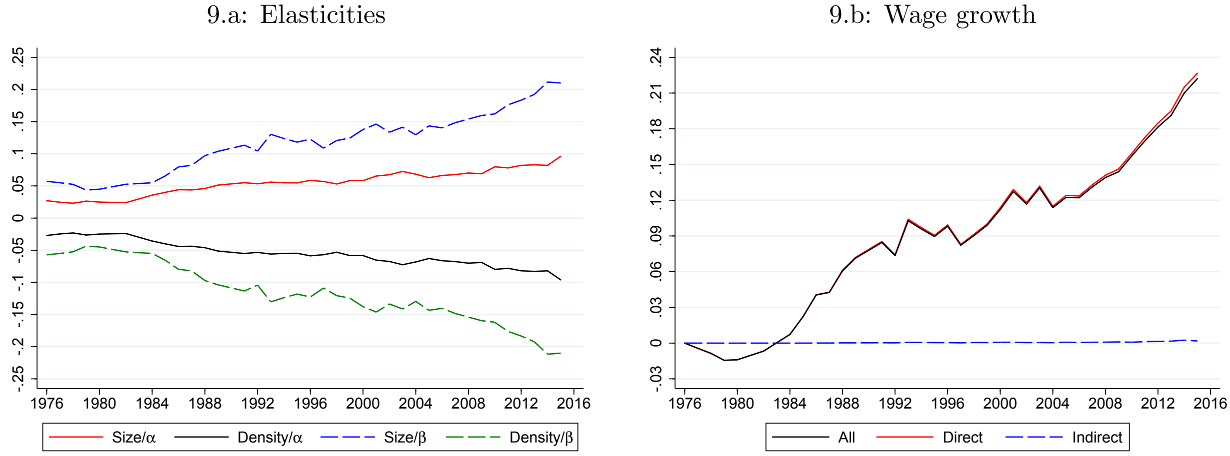
Equation (23) involves the term $Q_c / (w_c - \tau_c L_c)$ for every city, which depends only on quantities that can be measured in French data sets. As shown by expression (24), these quantities are the city population $N_c$, the land budget share a, the ratio between land prices at the fringe and at the center $\underline{R}/R_c(0)$, the share of commuting costs at the fringe $\tau_c L_c / w_c$, and agglomeration economies parameters $\alpha$ and $\beta$ that are recovered from the estimations. Therefore, the model allows the recovery of partial derivatives on the right-hand side of the decomposition (29), given by equations (18) and (19) in the closed city case, and equations (25) and (E.145) in the open city case.

Note that expressions make intervene $\log L_c$ that is affected by the choice of measurement units. In line with our empirical application, we consider city land area and density relatively to our reference city (i.e. rather than the theoretical objects $\log L_c$ and $\log(N_c/L_c)$, we consider $\log(L_c/L^*)$ and $\log(N_c/L_c/(N/L)^*)$ where $L_c$ and $N_c/L_c$ are values observed in the data, and $L^*$ and $(N/L)^*$ are empirical minimum values for land area and density across cities). Implicitly, it means that there are no agglomeration economies in the reference city, and that agglomeration economies start with values higher than those for the reference city.

For parameters related to agglomeration economies, $\alpha_t$ and $\beta_t$, we consider the values obtained from our estimations. For quantities $\tau_{c,t} L_{c,t} / w_{c,t}$, $\lambda_{c,t}$ and $a_t$, a first natural step is to consider that their values are the same for all cities at any date.[14] Interestingly, in that case, it is possible to check that the population-weighted averages of indirect migration effects on log-area, log-density and log-wages involved in equations (20), (21) and (25) are zero. In particular, this means that productivity increases in some cities due to positive changes of agglomeration

[14] We use $\tau_{c,t} L_{c,t} / w_{c,t} = 0.1$, $a_t = 0.3$, $\lambda_{c,t} = 1/0.9 = 1.11$.

Figure 9: Elasticities of agglomeration variables and wage growth predicted by the model




*Notes*: Panel a: Weighted averages of land area and density elasticities with respect to returns to agglomeration variables $\alpha$ and $\beta$, where the weight is the yearly number of employed workers. Values of these elasticities are equal in the cases of the open and closed monocentric city models. Panel b: Difference in log-wage between 1976 and any given year.

variables are compensated by productivity decreases in other cities due to negative changes of those variables.

Figure 9.a represents the land area and density elasticities weighted by the number of employed workers for the closed and open monocentric city models. They are identical in the two cases and quite low. This is consistent with agglomeration variables not varying much when changing their returns. It suggests that indirect effects of changes in returns to agglomeration variables on wage growth should be small, which is confirmed by Figure 9.b where the indirect effects on the log-wage difference between 1976 and any other year is close to zero. These calibration results are in line with our empirical findings.

## 8 Conclusion

In this paper, we assess the effect of urbanisation on the evolution of wages, focusing on the role of agglomeration economies. We separately consider the effects of changes in the values of agglomeration variables and the changes in their returns. We show that, even if some cities grew significantly, their growth was not enough to generate further aggregate labour earnings through agglomeration economies in a sizeable way. By contrast, we also document an increase in the returns to density and land area which greatly affected aggregate wage growth, primarily through large growth in big cities. Finally, we model a system of cities and show that changes in returns to agglomeration economies do not sufficiently affect city population density and land area to significantly influence aggregate labour earnings, which is consistent with our empirical findings.

Overall, disparities in city sizes and the emergence of urban giants spans centuries if not millennia. The path dependence in development due to the permanence of built-up areas makes city population adjusts slowly across the territory. Our results show that forty years are far from enough to generate population evolution across space that significantly impact wages. Population changes are small compared to cross-sectional disparities in population. Moreover, most of the French population lives in cities, and the growth of some cities may be counterbalanced by the decline of others. This means that gains in agglomeration economies for growing cities may be offset by losses in declining ones. National population growth could play a role in achieving urban growth without population loss in some cities, but natural and migratory balances have remained limited over the last fourty years.

Still, the country has experienced important structural changes over the last three centuries, particularly with transitions from agriculture to manufacturing, and then from manufacturing to services over the last fourty years. There has also been substantial improvement in transportation, allowing for further efficiency gains from spatial concentration. All these changes have influenced agglomeration economies and we showed that their intensity has greatly increased. We document that this increase, in turn, has impacted wages in a sizable way over just a few decades. Future research could investigate how different types of agglomeration economies have evolved and nourished this process. This could inform public authorities on margins to take action to further generate productivity and labour earnings growth.

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# Appendix

## A Additional data description

### A.1 Built-up information

The *Fichiers Fonciers* are provided by a governmental entity, the Center for Studies and Expertise on Risks, Environment, Mobility and Planning (*Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement*, CEREMA). The *BDTOPO* is provided by the French National Institute of Geography (*Institut National de l'Information Géographique et Forestière*, IGN-F). The *Fichiers Fonciers* include detailed information on land register, land use, and land property rights. For each land parcel, it gives the identifier and information on the buildings that sit on it. For each building, information includes the construction year, the footprint and height, but the last two variables are plagued with measurement errors. This is the reason why the data is complemented with the *BDTOPO* that provides vectorized information on both footprint and height for buildings with much more accuracy (but not the construction year). We match buildings in the *Fichiers Fonciers* and *BDTOPO* as follows. Using the parcel identifier in the *Fichiers Fonciers*, we get the parcel limits from a shapefile recording all parcels in France. We then consider that a building in *BDTOPO* belongs to a parcel in the *Fichiers Fonciers* if its centroid is located within its limits. When it is the case, we can match it with the buildings located in the parcel.

### A.2 Individual wage panel

The *DADS* data, which use in research has become widespread following Abowd *et al.* (1999), are collected from employers and self-employed in France for pensions, benefits, and tax proposes. Data include an individual identifier, the identifier of the municipality where the workplace is located, the occupation of the worker, the part-time/full-time status, the number of working days, the net wage (deflated by the consumer price index such that it is in constant euros), and the industry at the 4-digit level. Our main measure of earnings is the daily wage computed as the ratio between the net wage and the number of working days. We use an aggregated industry classification in 3-digit industries (NAF114). There are significant changes in the industry classification in 1993 and 2009 such that it is not possible to obtain a classification that is stable over time. Consequently, we use distinct industry classifications before 1993, between 1993 and

2003, and after 2009.

Information is available for jobs in manufacturing and services in the private and semi-public sectors for all employees born in October of even years over the 1976-2001 period, and for all employees born in October of even years or the $2^{nd}$, $3^{rd}$, $4^{th}$, $5^{th}$ of January, or the $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ of April, July or October over the 2002-2015 period. We restrict our attention to individuals aged 18-65 born in October of even years to avoid overweighting the recent period. We only keep their main job every year which is defined as the job with the highest net wage. We retain full-time jobs in the private sector such that duration and net wage are strictly positive. Jobs in the agriculture and fishery industry and in the banking industry are excluded.[15]

# B Additional descriptive statistics on cities

[15] Agriculture and fishery industry is normally not covered by the data. We exclude the remaining workers in that industry. An issue for the banking industry is that data are declared at the regional level rather than at the establishment one at the beginning of the panel. This is the reason why we drop that industry.

Table B.1: Descriptive statistics on delineated cities (i.e. urban areas with cores)

| Var | Min | p25 | p50 | mean | p75 | p95 | Max |
|---|---|---|---|---|---|---|---|
| Panel A : 1975 (286) | | | | | | | |
| Population | 172 | 14605 | 29392 | 108177 | 62066 | 257064 | 9083917 |
| Area | 4.68 | 42.83 | 65.40 | 113.63 | 101.52 | 272.92 | 2911.36 |
| Density | 10.04 | 243.65 | 519.73 | 652.52 | 908.69 | 1671.53 | 3120.16 |
| Panel B : 1982 (311) | | | | | | | |
| Population | 117 | 12385 | 26834 | 103116 | 57399 | 257262 | 9372229 |
| Area | 3.48 | 42 | 63 | 116.83 | 104.08 | 318.60 | 3377.16 |
| Density | 8.02 | 223.74 | 477.28 | 571.06 | 811.57 | 1352.46 | 2775.18 |
| Panel C : 1990 (309) | | | | | | | |
| Population | 153 | 13077 | 27987 | 108650 | 60157 | 266602 | 9862985 |
| Area | 8.32 | 43.92 | 70.64 | 126.52 | 113.56 | 327.55 | 3519.44 |
| Density | 7.49 | 234.32 | 466.01 | 553.16 | 784.48 | 1315.58 | 2802.43 |
| Panel D : 1999 (303) | | | | | | | |
| Population | 198 | 13511 | 27140 | 114972 | 62875 | 277733 | 10116852 |
| Area | 10.12 | 45.56 | 74.28 | 134.97 | 120.02 | 339.76 | 3647.48 |
| Density | 8.14 | 239.61 | 458.91 | 545.06 | 733.31 | 1297.33 | 2773.66 |
| Panel E : 2006 (297) | | | | | | | |
| Population | 81 | 14776 | 28474 | 122495 | 66407 | 295295 | 10666306 |
| Area | 5.60 | 46.12 | 73.48 | 140.88 | 120.60 | 425.29 | 3696.40 |
| Density | 6.91 | 247.74 | 457.40 | 547.12 | 750.77 | 1245.85 | 2885.59 |
| Panel F : 2015 (308) | | | | | | | |
| Population | 187 | 13068 | 27327 | 120231 | 66156 | 283045 | 11078022 |
| Area | 10.80 | 47.02 | 75.86 | 146.20 | 130.87 | 418.69 | 3759.88 |
| Density | 5.63 | 244.07 | 408.28 | 485.42 | 663.86 | 1091.40 | 2946.38 |

*Notes*: Each panel reports for a given census, the various moments of the distribution of population, land area, and density of delineated cities. The number of cities is given between brackets after the census date.

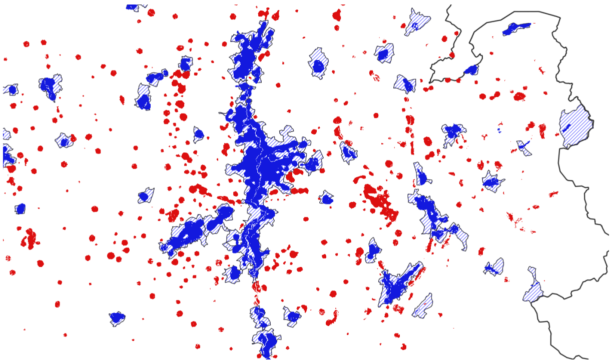
Table B.2: Descriptive statistics on delineated cities in 1975 and 2015

| Panel A: 1975, bandwidth 2.1km, 286 cities | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Min | p25 | p50 | mean | p75 | p95 | Max |
| Population | 172 | 14,605 | 29,392 | 10,817 | 62,066 | 257,064 | 9,083,917 |
| Area | 4 | 42 | 65 | 113 | 101 | 272 | 2,911 |
| Density | 10.04 | 243.65 | 519.73 | 652.52 | 908.69 | 1671.53 | 3120.16 |
| Panel B: 1975, bandwidth 1km, 565 cities | | | | | | | |
| | Min | p25 | Median | Mean | p75 | p95 | Max |
| Population | 462 | 5,564 | 11,825 | 55,037 | 32,269 | 176,757 | 8,593,972 |
| Area | 3 | 25 | 39 | 59 | 61 | 159 | 2,150 |
| Density | 10.04 | 186.20 | 361.09 | 564.32 | 760.54 | 1,670.70 | 3,995.78 |
| Panel C: 2015, bandwidth 2.1km, 308 cities | | | | | | | |
| | Min | p25 | p50 | mean | p75 | p95 | Max |
| Population | 187 | 13,068 | 27,327 | 120,231 | 66,156 | 283,045 | 11,078,022 |
| Area | 10 | 47 | 75 | 146 | 130 | 418 | 3,759 |
| Density | 5.63 | 244.07 | 408.28 | 485.42 | 663.86 | 1091.40 | 2946.38 |
| Panel D: 2015, bandwidth 1km, 573 cities | | | | | | | |
| | Min | p25 | Median | Mean | p75 | p95 | Max |
| Population | 225 | 5,564 | 12,291 | 63,603 | 33,089 | 176,131 | 10,636,760 |
| Area | 3 | 27 | 44 | 77 | 75 | 199 | 3,039 |
| Density | 6.17 | 160.56 | 317.51 | 432.61 | 604.07 | 1156.02 | 3500.09 |

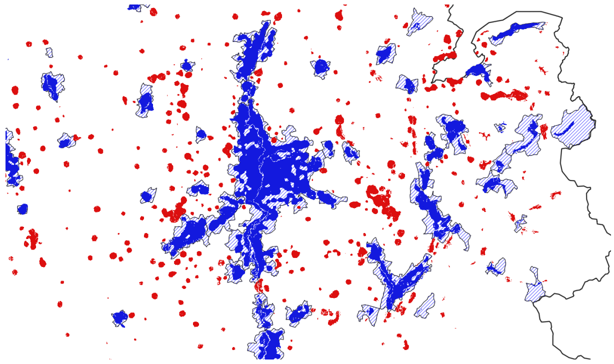
*Notes*: Each panel reports for the 1975 or 2015 census and different bandwidths used in the delineation algorithm, the various moments of the distribution of population, land area, and density of delineated cities. The number of cities is given between brackets after the census date and bandwidth.

Figure B.1: City delineations for Lyon, Lille and Marseilles, 1976 and 2015

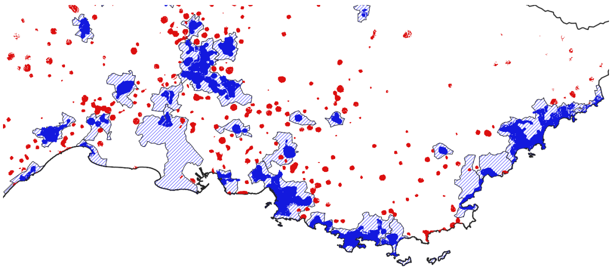
B.1.a: Lyon, 1976



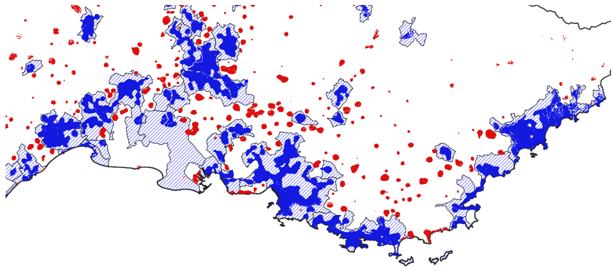
B.1.b: Lyon, 2015



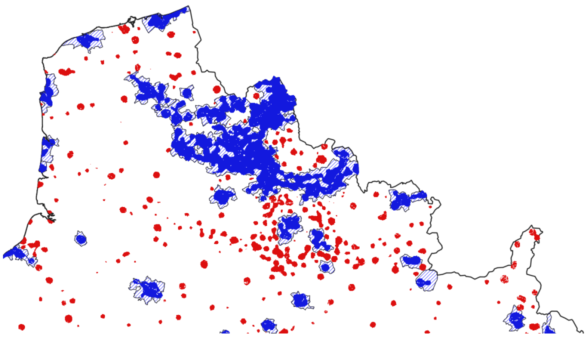
B.1.c: Marseilles, 1975



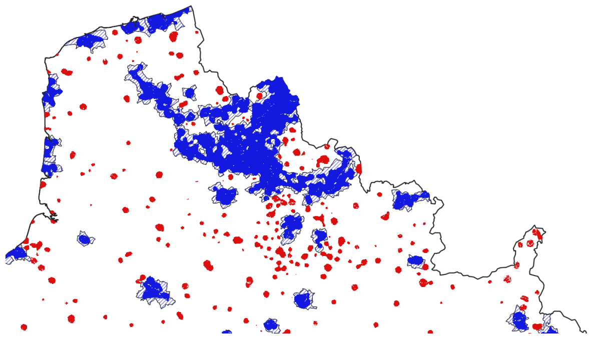
B.1.d: Marseilles, 2015



B.1.e: Lille, 1975



B.1.f: Lille, 2015



*Notes*: Urban areas obtained from our delineation algorithm separately run for 1976 and 2015 using a 2.1km bandwidth. Urban areas with cores (cities) are in blue and urban areas without a core are in red. Borders of municipalities that include part of a city are in black, and the area of municipalities not included in a delineated city but considered as part of it because more than 50% of its population is in it are in blue stripes.

## C Time-constant coefficients for agglomeration variables

In this Appendix, we discuss results when considering that coefficients of agglomeration variables are constant over time and we report their estimates in Table C.1. We first estimate the first-stage specification (1) when omitting individual fixed effects. In column (1), we regress the obtained city-year fixed effects on density and find a positive elasticity of wages that decreases when introducing land area as shown by column (2). The elasticity of wages with respect to density and land area are respectively 0.051 and 0.024, suggesting that there are agglomeration economies related to both variables. Introducing individual fixed effects in the first-stage regression (columns 5), these two elasticities decrease to 0.033 and 0.014 due to a positive sorting of individuals with larger unobserved skills into denser and larger cities. These estimates are in line with past studies (Combes and Gobillon, 2015).

If market access is added to the specification, the estimated elasticity of wage with respect to density is lower due to a positive correlation between density and market access, whether individuals fixed effects are excluded (column 3) or included (column 6). In the most complete specification that involves individual fixed effects, the wage elasticity for density, land area and market access are respectively 0.025, 0.014 and 0.065.

The explanatory power of the model is very high, with an $R^2$ close to 0.95 in the most complete specification, which justifies our focus on our three agglomeration variables. It is even higher than in the literature, which can be explained by the use of more consistent city delineations that vary over time.

Table C.1: Second stage OLS regression results

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Density | 0.084*** | 0.051*** | 0.044*** | 0.052*** | 0.033*** | 0.025*** |
| | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) | (0.001) |
| Area | | 0.024*** | 0.024*** | | 0.014*** | 0.014*** |
| | | (0.001) | (0.001) | | (0.001) | (0.001) |
| Market potential | | | 0.063*** | | | 0.065*** |
| | | | (0.003) | | | (0.003) |
| Individual FE | No | No | No | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| $R^2$ | 0.772 | 0.858 | 0.872 | 0.915 | 0.934 | 0.945 |
| N | 10974 | 10974 | 10970 | 10969 | 10969 | 10965 |

*Note*: Standard errors are in parentheses. Explanatory variables are all in logarithm. Regressions are weighted by the number of workers. *: $p < 0.1$, **: $p < 0.05$, ***: $p < 0.01$.

We also assess to what extent our estimates are affected by endogeneity issues. Table C.2 reports results when including individual fixed effects and instrumenting density, land area and market access with historical and soil variables. We start with a specification that includes only density and land area. Columns 1-3 show that, when we instrument with historical or soil variables, or both, the estimated coefficient for density is a bit larger but that for land area remains stable. As reported in columns 4-6, the estimated coefficient for density is a bit lower when adding and instrumenting market access. In the most complete specification where our three agglomeration variables are instrumented with both historical and soil instruments, the wage elasticity for density, land area and market access are respectively 0.031, 0.014 and 0.050. The fact that point estimates are not much affected by instrumentation is fully consistent with the literature.

Table C.2: Second stage IV regressions results

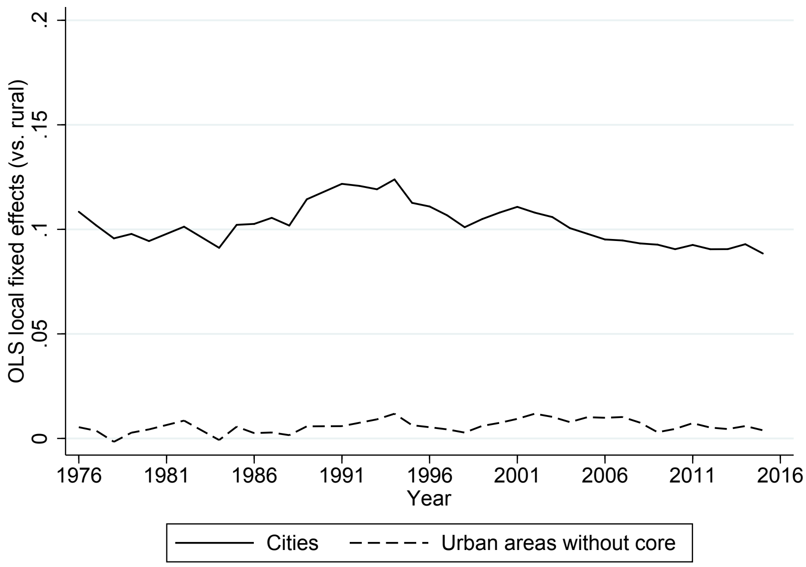
| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Density | 0.043*** | 0.049*** | 0.043*** | 0.027*** | 0.046*** | 0.031*** |
| | (0.002) | (0.002) | (0.002) | (0.003) | (0.003) | (0.002) |
| Area | 0.012*** | 0.013*** | 0.012*** | 0.016*** | 0.013*** | 0.014*** |
| | (0.001) | (0.001) | (0.001) | (0.001) | (0.001) | (0.001) |
| Market potential | | | | 0.050*** | 0.015*** | 0.050*** |
| | | | | (0.003) | (0.005) | (0.003) |
| Historical IV | Yes | No | Yes | Yes | No | Yes |
| Soil IV | No | Yes | Yes | No | Yes | Yes |
| KP F-stat. | 95.71 | 96.07 | 88.81 | 59.55 | 62.15 | 68.50 |
| Individual FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 10679 | 10921 | 10679 | 10679 | 10917 | 10679 |

*Note*: Standard errors are in parentheses. Explanatory variables are all in logarithm. Regressions are weighted by the number of workers. *: $p < 0.1$, **: $p < 0.05$, ***: $p < 0.01$. Historical instruments: logarithms of population densities in 1793, 1800, 1836 and 1856, and market potentials for the same years. Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

## D Variants and robustness checks

Figure D.1: OLS yearly effects of working in an urban area without a core or a city relatively to rural areas,

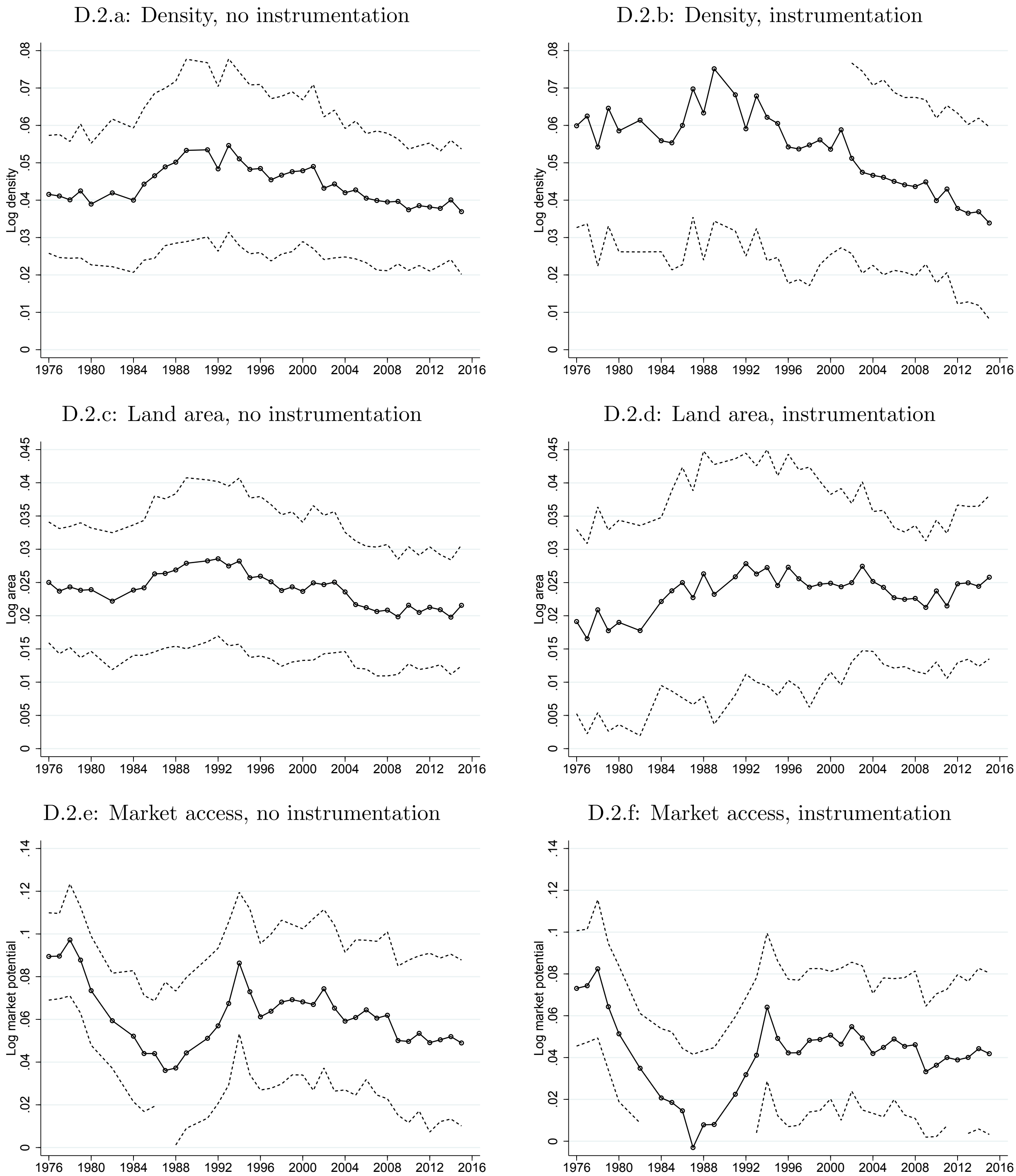
no individual fixed effects in the first-stage specification




*Notes*: Differences between yearly effects of being in an urban area without a core or in a city and yearly effects of being in a rural area. Yearly effects of being in a city are yearly averages of city-year fixed effects weighted by the yearly number of individuals working in cities.

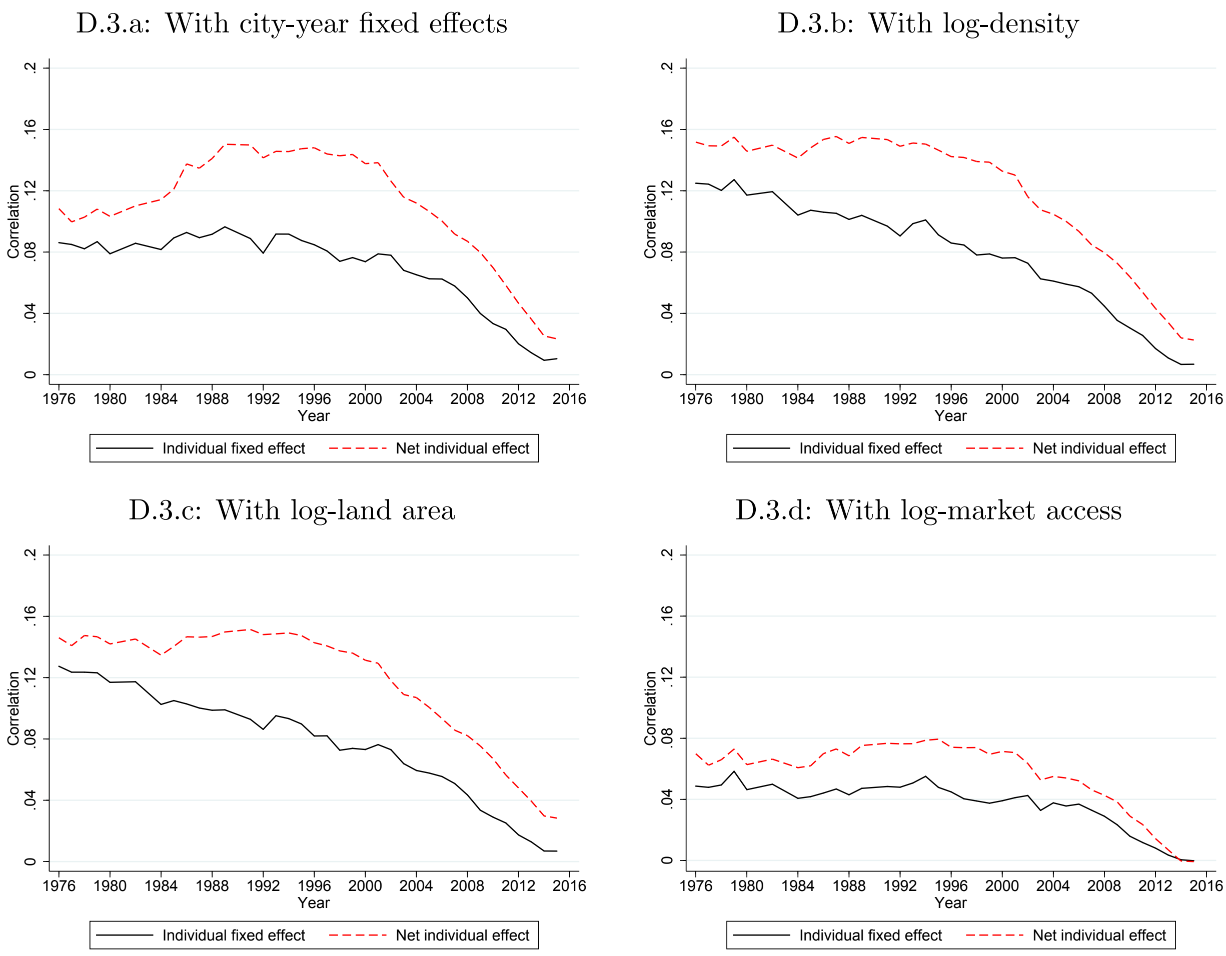
Figure D.2: Estimated yearly coefficients of city variables without individual fixes effects in the first-stage

specification, with and without instrumentation with historical and geological variables




*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

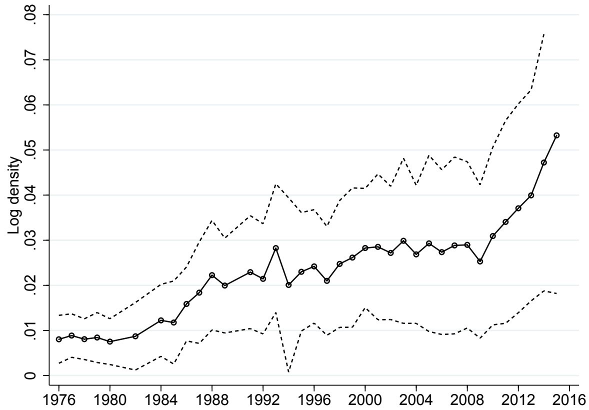
Figure D.3: Correlation between individual fixed effects and city-year fixed effects or city variables



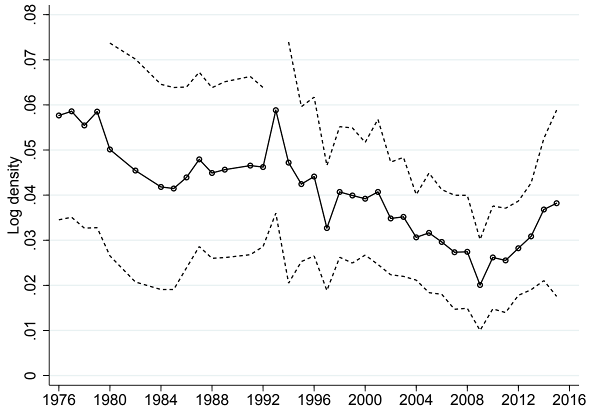

*Notes*: "Individual fixed effect": Correlation between the agglomeration variable provided in the panel title and individual fixed effects. "Net individual effect": Correlation between the agglomeration variable provided in the panel title and the net individual effects defined as individual averages of residuals obtained when regressing the sum of the individual fixed effect and squared age on age, squared age and year fixed effects. Observations are at the individual-year level.

Figure D.4: Estimated yearly coefficients of city variables with or without individual fixed effects in the first-stage specification, when restricting the sample to the first four observations of individuals appearing at least four times in the panel

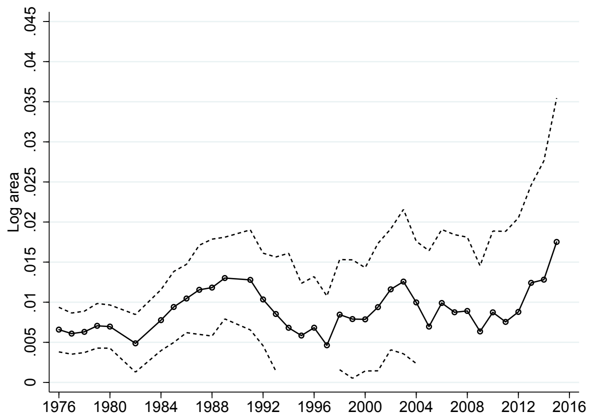
D.4.a: Density, with individual fixed effects



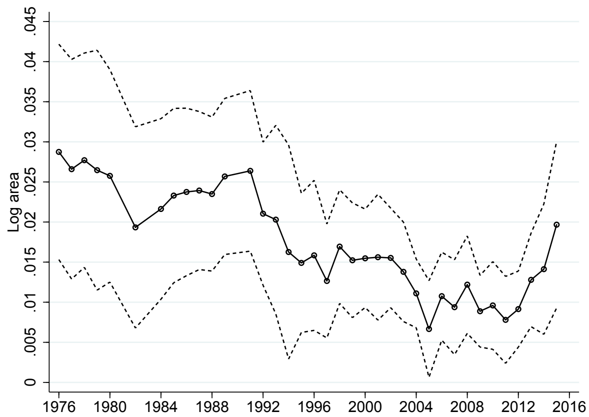

D.4.b: Density, without individual fixed effects



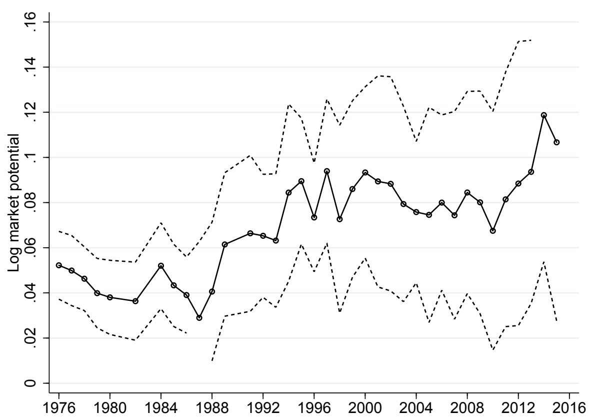

D.4.c: Land area, with individual fixed effects



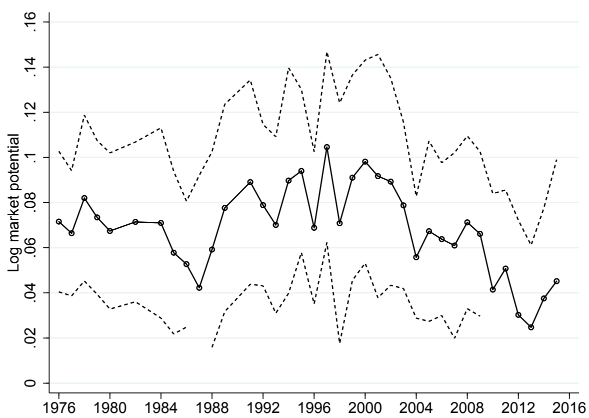

D.4.d: Land area, without individual fixed effects




D.4.e: Market access, with individual fixed effects

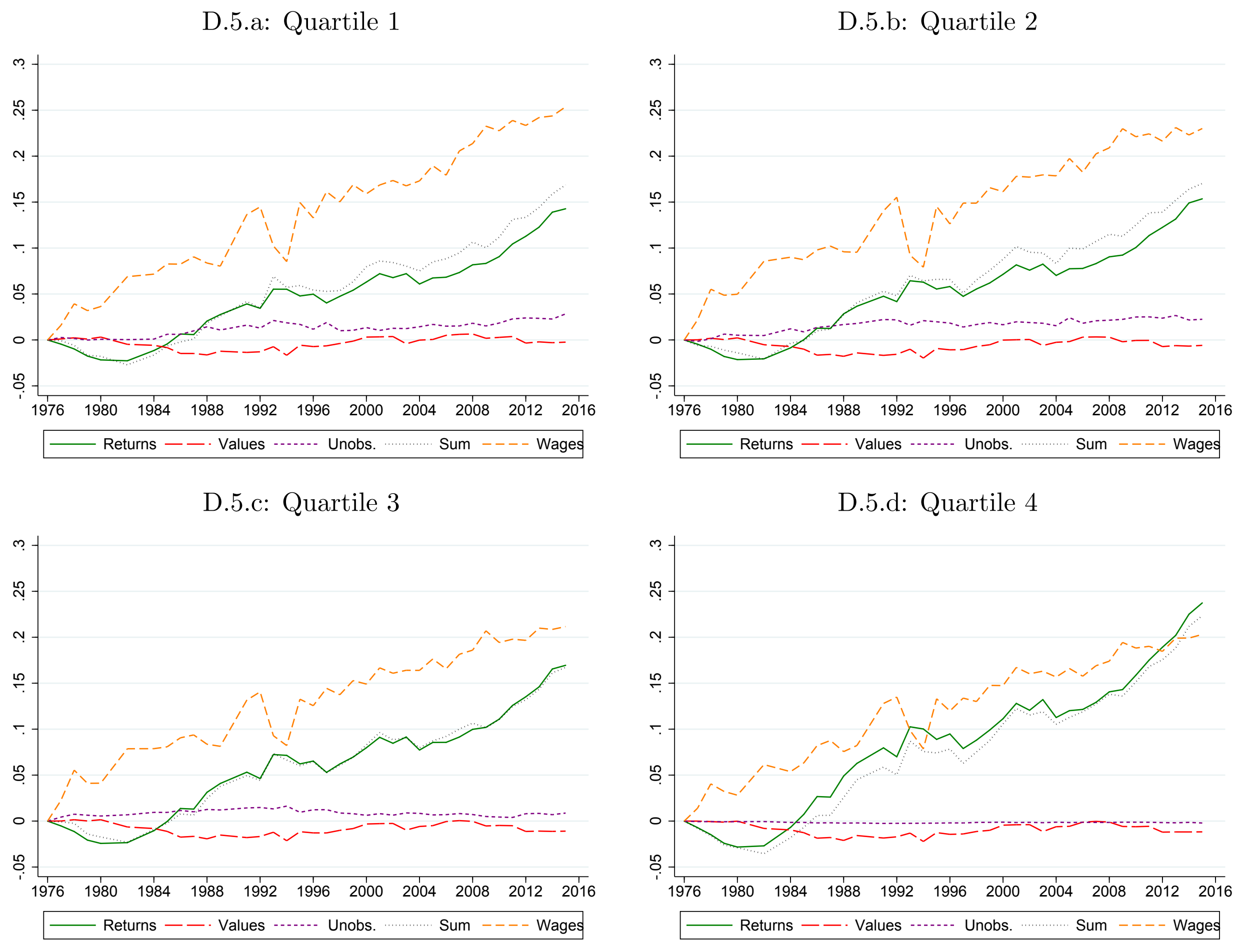



D.4.f: Market access, without individual fixed effects



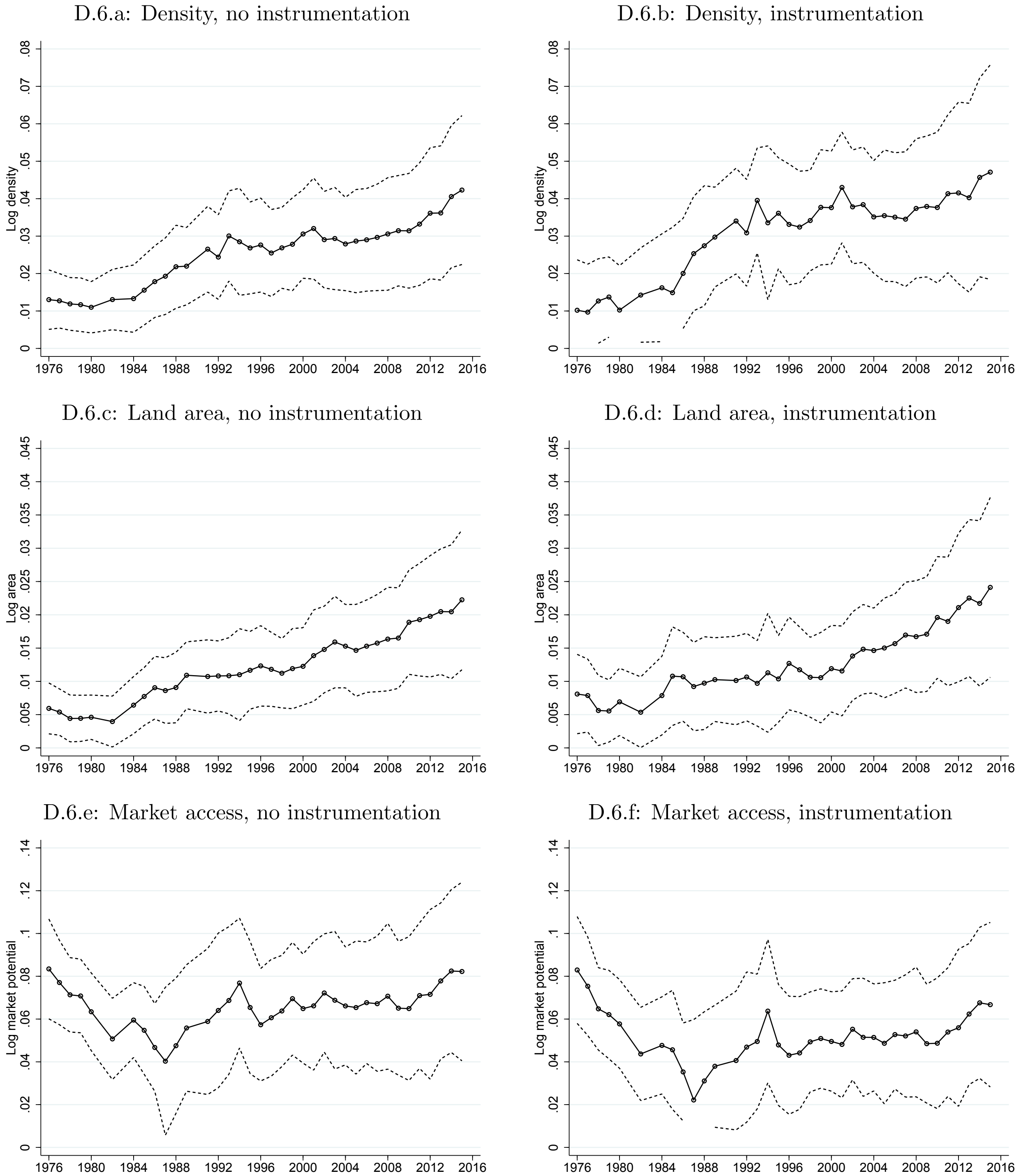

*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

Figure D.5: Decomposition of city wage growth between 1976 and year $t$, with $1976 \leqslant t \leqslant 2015$, by city employment quartile




*Notes*: "Returns": Contributions of changes in returns of city variables to log-wage growth; "Values": Contribution of changes in their values; "Unobs.": Contribution of changes in city unobservables; "Sum": Sum of these three contributions; "Wages": Log-wage growth.

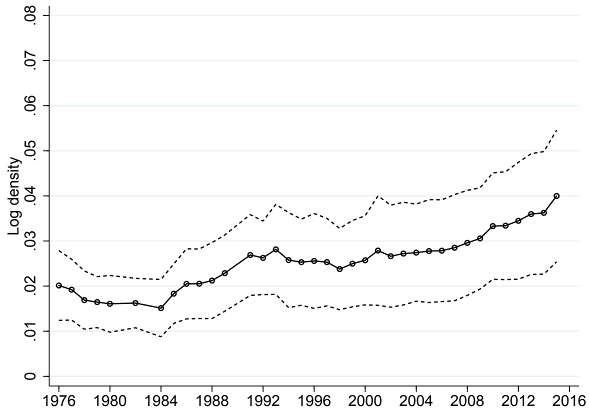
Figure D.6: Estimated yearly coefficients of city variables when there are individual fixed effects in the first-stage specification, 2015 delineation of cities for all years



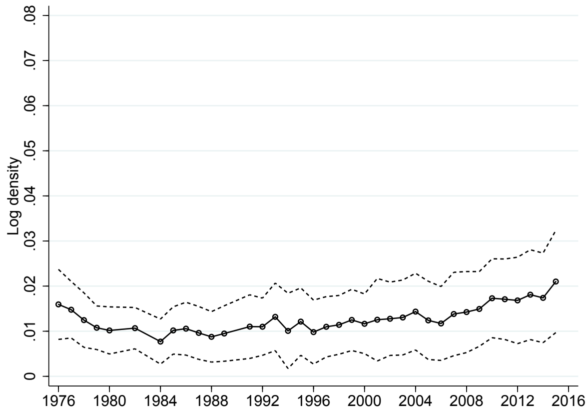

*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

Figure D.7: Estimated yearly coefficients of city variables when there are individual fixed effects in the first-stage specification, INSEE 2010 urban area definition of cities for all years

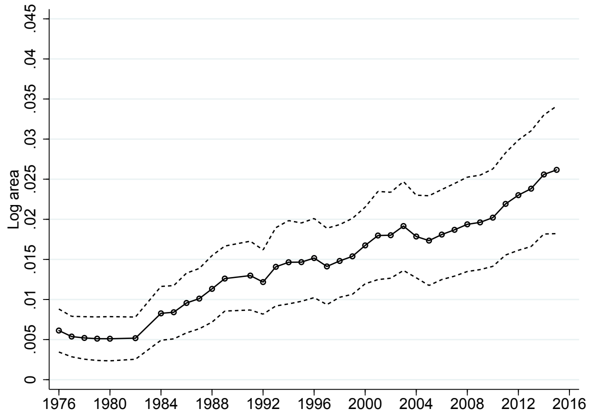
D.7.a: Density, no instrumentation



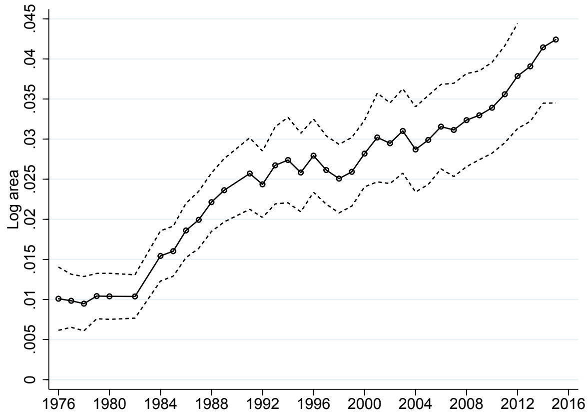

D.7.b: Density, instrumentation



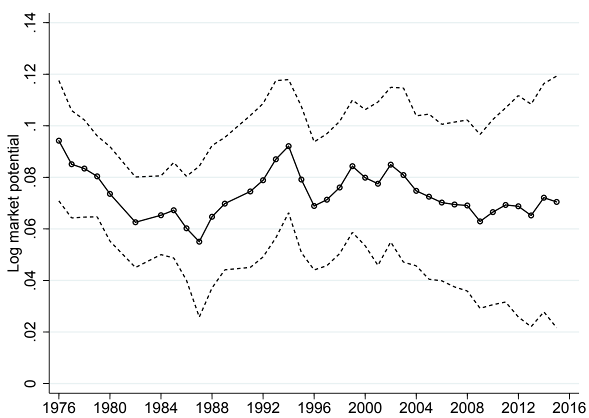

D.7.c: Land area, no instrumentation



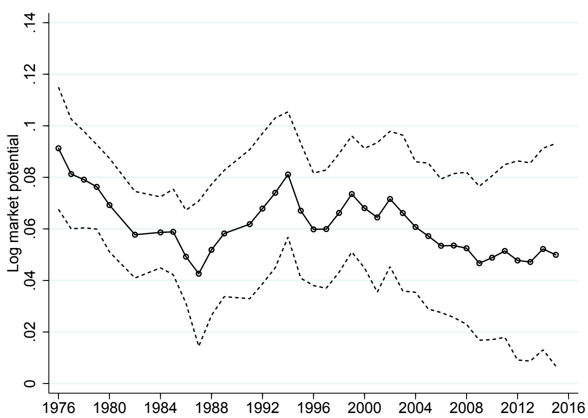

D.7.d: Land area, instrumentation




D.7.e: Market access, no instrumentation



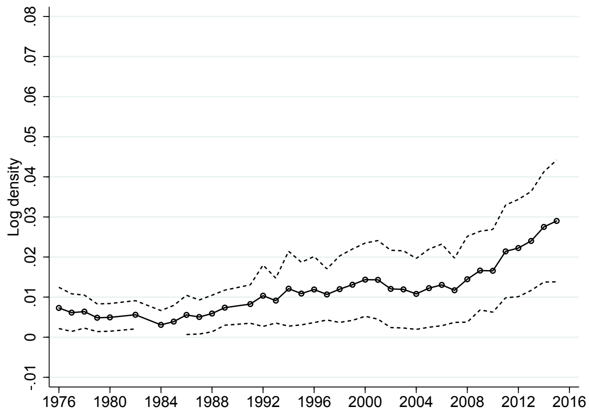

D.7.f: Market access, instrumentation



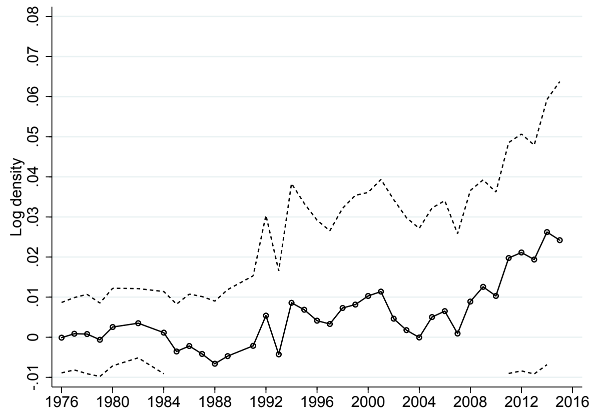

*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

Figure D.8: Estimated yearly coefficients of city variables when there are individual fixed effects in the first-stage specification, building volume densities in pixels smoothed using a 1km bandwidth

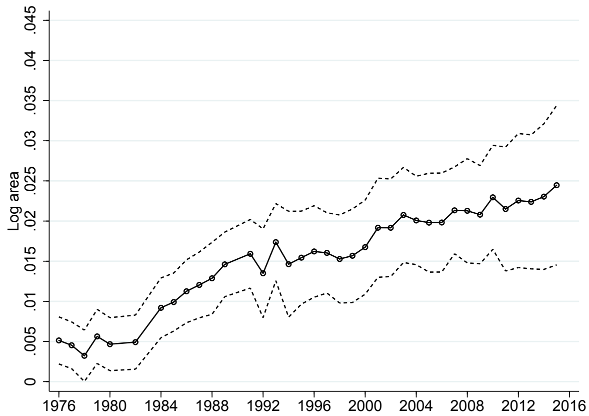
D.8.a: Density, no instrumentation



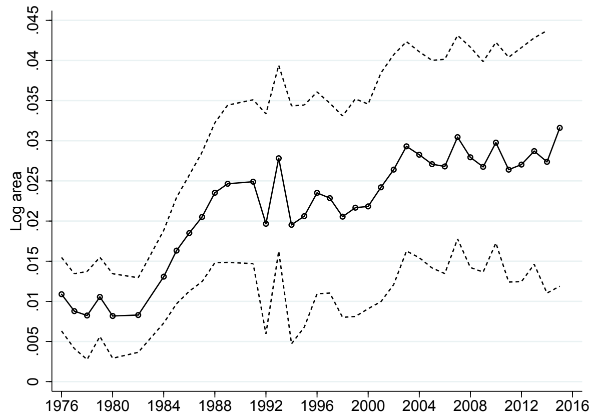

D.8.b: Density, instrumentation



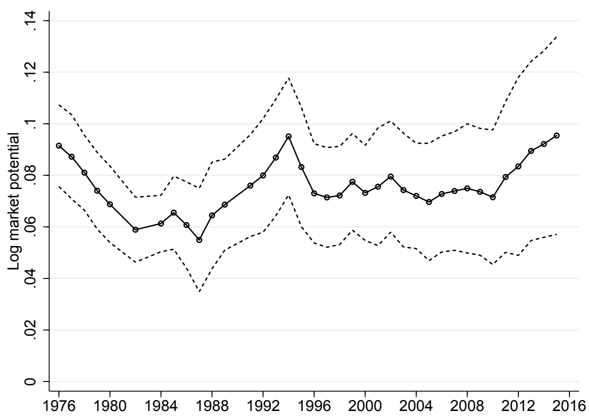

D.8.c: Area, no instrumentation



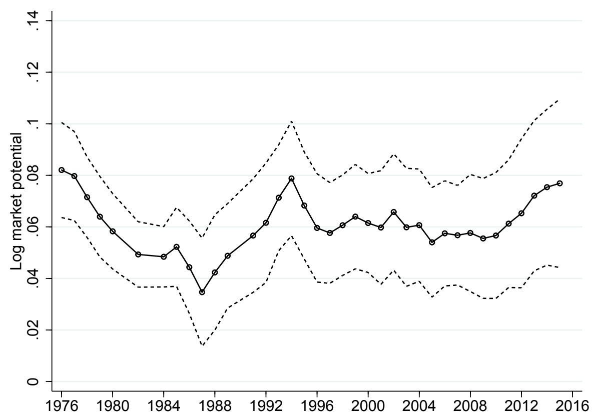

D.8.d: Area, instrumentation




D.8.e: Market access, no instrumentation



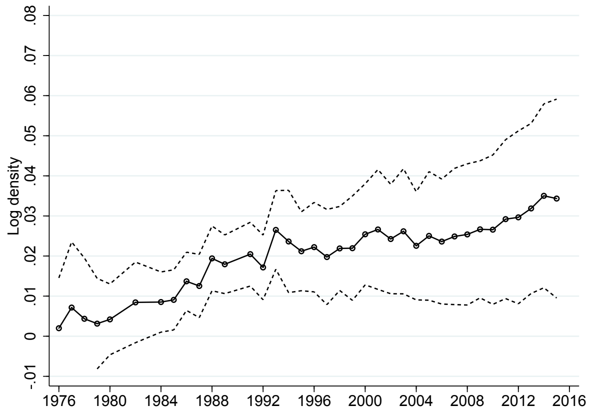

D.8.f: Market access, instrumentation



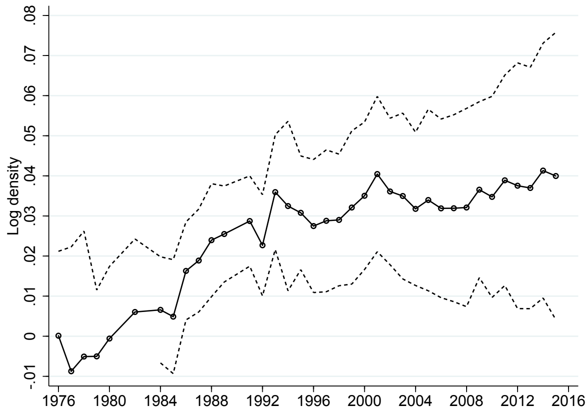

*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

Figure D.9: Estimated yearly coefficients of city variables when there are individual fixed effects and learning effects in the first-stage specification

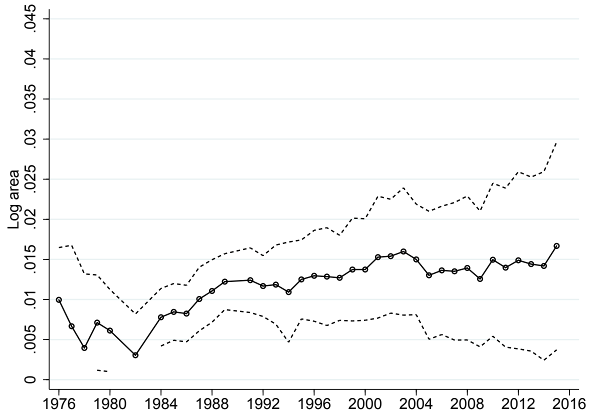
D.9.a: Density, no instrumentation



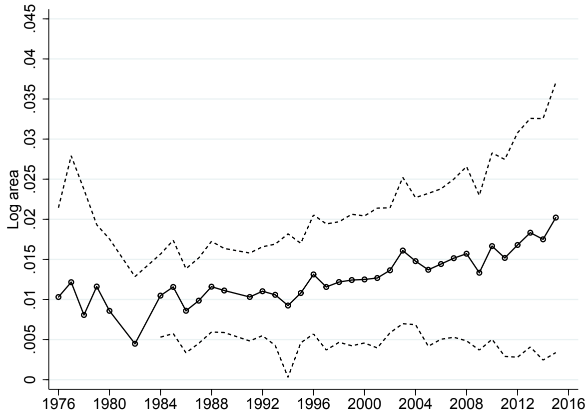

D.9.b: Density, instrumentation



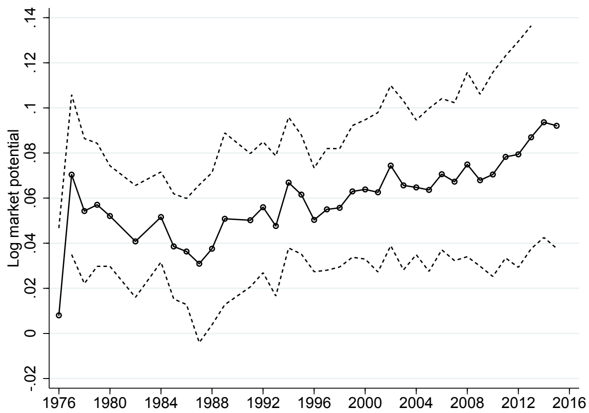

D.9.c: Land area, no instrumentation



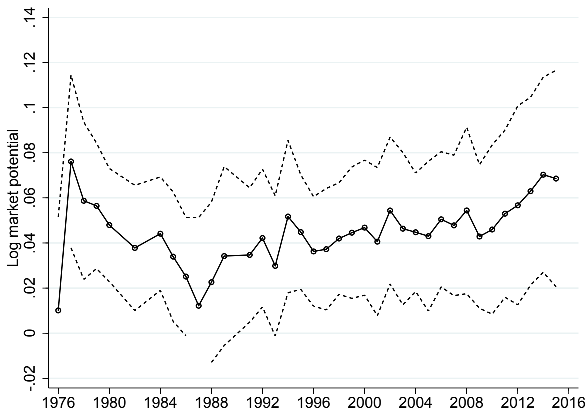

D.9.d: Land area, instrumentation




D.9.e: Market access, no instrumentation



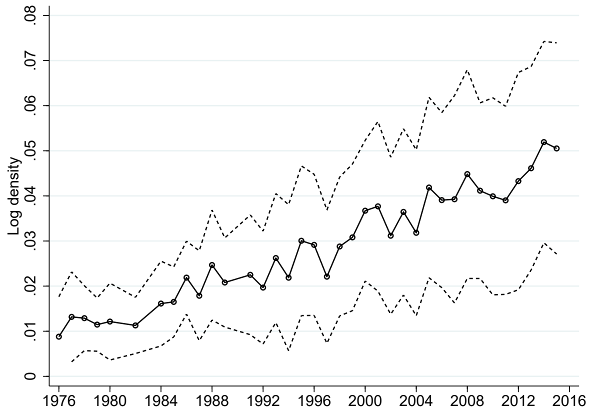

D.9.f: Market access, instrumentation



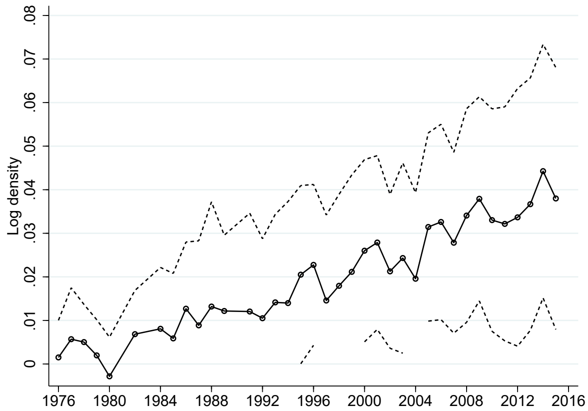

*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

Figure D.10: Estimated yearly coefficients of city variables when there are individual fixed effects and establishment-time fixed effects in the first-stage specification

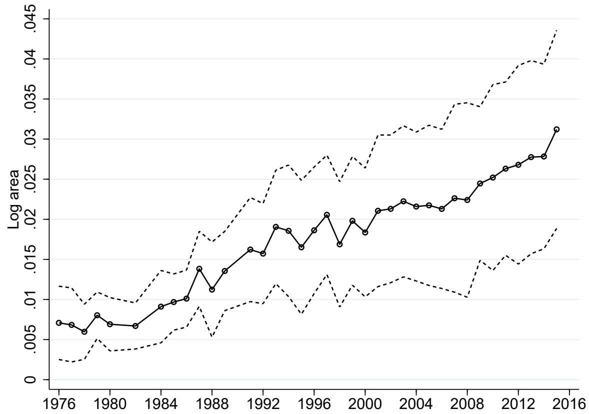
D.10.a: Density, no instrumentation



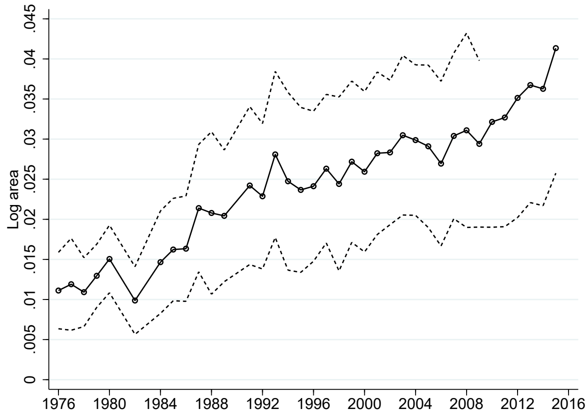

D.10.b: Density, instrumentation



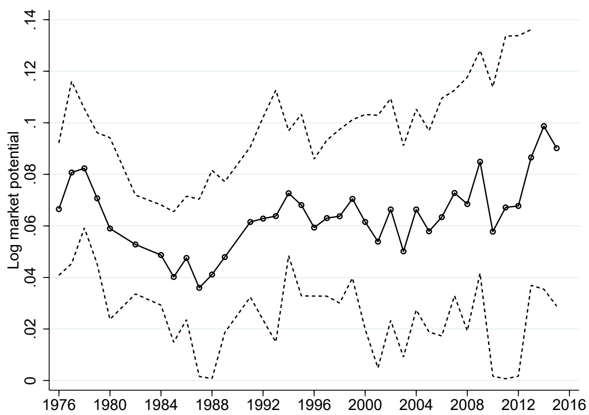

D.10.c: Land area, no instrumentation



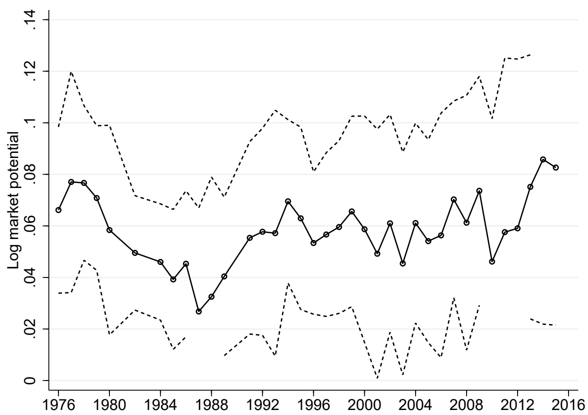

D.10.d: Land area, instrumentation




D.10.e: Market access, no instrumentation




D.10.f: Market access, instrumentation




*Notes*: Estimated coefficients are represented by bullet points and linked by a plain line, and bounds of confidence intervals are represented by dots (with interruptions if bound values are outside the y-axis grid). Figures b, d and f, historical instruments: logarithms of population densities in 1861, 1931, 1954 and 1856, and market accesses for the same years; Soil instruments: shares of the city area by levels of depth to rock, soil erodability, hydrogeological class, subsoil mineralogy, and topsoil organic carbon content.

# E Appendix: model

In this Appendix, we detail the monocentric city model and establish formulas given in the main text. Workers maximize their utility under budget constraint. The first order condition is given by:

$$R_c(x) = \frac{\partial U}{\partial \ell} \Big/ \frac{\partial U}{\partial z} \tag{E.30}$$

From this equation and the budget constraint, we get the optimal consumption quantities:

$$\ell_c(x) = a(w_c - \tau_c x)/R_c(x) \tag{E.31}$$

$$z_c(x) = (1-a)(w_c - \tau_c x) \tag{E.32}$$

At spatial equilibrium, all the individuals within the city get the same utility $\overline{u}$:

$$U(\ell_c(x), w_c - \tau_c x - R_c(x)\ell_c(x)) = \overline{u} \tag{E.33}$$

$$B_c[a(w_c - \tau_c x)/R_c(x)]^a [(1-a)(w_c - \tau_c x)]^{1-a} = \overline{u} \tag{E.34}$$

$$B_c(w_c - \tau_c x)/R_c(x)^a = \overline{u} \tag{E.35}$$

Deriving equation (E.33) with respect to $x$, we get:

$$\frac{\partial U}{\partial \ell}\frac{\partial \ell_c(x)}{\partial x} - \frac{\partial U}{\partial z}R_c(x)\frac{\partial \ell_c(x)}{\partial x} + \frac{\partial U}{\partial z}\left[-\tau_c - \frac{\partial R_c(x)}{\partial x}\ell_c(x)\right] = 0 \tag{E.36}$$

Using the first-order condition (E.30), the first two terms cancel out and we are left with the Alonso-Muth condition:

$$\frac{\partial R_c(x)}{\partial x} = -\frac{\tau_c}{\ell_c(x)} \tag{E.37}$$

The fringe is determined by the equality $R_c(\overline{x}_c) = \underline{R}$ where $\underline{R}$ is the agricultural land price. Land occupied by individuals is the segment $[0, \overline{x}_c]$ where $\overline{x}_c$ is the city fringe, such that $L_c = \overline{x}_c$, and city population verifies the equilibrium equation:

$$N_c = \int_0^{\overline{x}} n_c(x)\,dx = \int_0^{\overline{x}} \frac{1}{\ell_c(x)}dx = -\frac{1}{\tau_c}[R_c(\overline{x}) - R_c(0)] \tag{E.38}$$

where $n_c(x)$ is the population density at distance $x$ (equation to the ratio between land supply 1 divided by land demand per individual $\ell_c(x)$).

## E.1 Closed-city case

When city $c$ is closed, its population $N_c$ is fixed and only its land area $L_c = \overline{x}_c$ can vary. We conduct comparative statics with respect to a change in agglomeration economies parameter, $\alpha$ or $\beta$. Deriving equation (11), we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \log L_c + (\alpha - \beta) \frac{1}{L_c} \frac{\partial L_c}{\partial \alpha} \tag{E.39}$$

$$\frac{\partial \log w_c}{\partial \beta} = \log \left( \frac{N_c}{L_c} \right) + (\alpha - \beta) \frac{1}{L_c} \frac{\partial L_c}{\partial \beta} \tag{E.40}$$

Importantly, agglomeration economies vary not only because of the change in parameter, but also because of the resulting change in city land area that affects productivity through agglomeration economies (which is an equilibrium effect).

### E.1.1 Elasticities with respect to parameter $\alpha$

We first consider variations in $\alpha$, and then turn to variations in $\beta$. We derive the expression for $R_c(x)\,\ell_c(x)$ given by equation (E.31), which yields:

$$\ell_c(x) \frac{\partial R_c}{\partial \alpha} + R_c(x) \frac{\partial \ell_c}{\partial \alpha} = a \frac{\partial w_c}{\partial \alpha} \tag{E.41}$$

$$\frac{\partial \ell_c}{\partial \alpha} = \frac{1}{R_c(x)} \left[ a \frac{\partial w_c}{\partial \alpha} - \ell_c(x) \frac{\partial R_c}{\partial \alpha} \right] \tag{E.42}$$

$$= \frac{1}{R_c(x)} \left[ a \frac{\partial w_c}{\partial \alpha} - a (w_c - \tau_c x) \frac{1}{R_c(x)} \frac{\partial R_c}{\partial \alpha} \right] \tag{E.43}$$

Changes in land consumption are the sum of two terms: an income effect and a substitution effect (i.e. individuals substitute the composite good for land if land becomes too costly). This is explained at length by (Duranton and Handbury, 2023) in the case of a change in commuting costs due to workingfrom home.

In equilibrium, utility is equal in any given location $x$ and the center. From equation (E.35), this equality can be rewritten in the following way:

$$(w_c - \tau_c x) / R_c(x)^a = w_c / R_c(0)^a \tag{E.44}$$

We derive the land market clearing condition given by equation (E.38), holding $N$ fixed, since we are in the closed city case. We get:

$$\frac{\partial R_c(0)}{\partial \alpha} = \frac{\partial R_c(\overline{x}_c)}{\partial \alpha} \tag{E.45}$$

Finally, deriving the fringe condition $R_c(\overline{x}_c) = \underline{R}_c$, we obtain $\partial R_c(\overline{x}_c)/\partial\alpha = 0$, and thus:

$$\frac{\partial R_c(0)}{\partial \alpha} = 0 \tag{E.46}$$

Deriving the logarithm of expression (E.44) with respect to $\alpha$ and using the equality (E.46) gives:

$$\frac{1}{w_c - \tau_c x}\frac{\partial w_c}{\partial \alpha} - a\frac{1}{R_c(x)}\frac{\partial R_c}{\partial \alpha} = \frac{1}{w_c}\frac{\partial w_c}{\partial \alpha} \tag{E.47}$$

or equivalently:

$$\begin{aligned} a\frac{1}{R_c(x)}\frac{\partial R_c}{\partial \alpha} &= \left(\frac{1}{w_c - \tau_c x} - \frac{1}{w_c}\right)\frac{\partial w_c}{\partial \alpha} \\ &= \frac{\tau_c x}{w_c(w_c - \tau_c x)}\frac{\partial w_c}{\partial \alpha} \end{aligned} \tag{E.48}$$

Changes in wages due to changes in agglomeration economies are capitalised into land prices. The increase in land prices is larger in percentage as one gets further away from the CBD. Inserting expression (E.48) into equation (E.43) gives:

$$\frac{\partial \ell_c}{\partial \alpha} = \frac{1}{R_c(x)}\left(a\frac{\partial w_c}{\partial \alpha} - \frac{\tau_c x}{w_c}\frac{\partial w_c}{\partial \alpha}\right) = \frac{1}{R_c(x)}\left(a - \frac{\tau_c x}{w_c}\right)\frac{\partial w_c}{\partial \alpha} \tag{E.49}$$

Importantly, $\partial\ell_c/\partial\alpha$ is of the same sign as $\partial w_c/\partial\alpha$ as long as the share of commuting costs in wages $\tau_c x/w_c$ is lower than the share of land in spendings. Usually, one considers that $a \approx .3$ and commuting costs must thus be very large for the substitution effect to dominate.

We have $L_c = \overline{x}_c$, and thus: $\partial L_c/\partial\alpha = \partial\overline{x}_c/\partial\alpha$. Deriving the equality $R_c(\overline{x}_c) = \underline{R}_c$ and using the Alonso-Muth condition (E.37), we get:

$$\frac{\partial R_c(\overline{x}_c)}{\partial \alpha} + \frac{\partial \overline{x}_c}{\partial \alpha}\frac{\partial R(\overline{x}_c)}{\partial x} = 0 \tag{E.50}$$

$$\frac{\partial R_c(\overline{x}_c)}{\partial \alpha} - \frac{\tau_c}{\ell_c(\overline{x}_c)}\frac{\partial \overline{x}_c}{\partial \alpha} = 0 \tag{E.51}$$

Then, using that fact that $L_c = \overline{x}_c$, as well as equations (E.48) and (E.31), we get:

$$\begin{aligned}
\frac{\partial L_c}{\partial \alpha} &= \frac{\ell_c(\overline{x}_c)}{\tau_c}\frac{\partial R_c(\overline{x}_c)}{\partial \alpha} && \text{(E.52)}\\
\frac{\partial L_c}{\partial \alpha} &= \frac{R_c(\overline{x}_c)\,\ell_c(\overline{x}_c)\,\overline{x}_c}{w_c(w_c - \tau_c\overline{x}_c)}\frac{1}{a}\frac{\partial w_c}{\partial \alpha} && \text{(E.53)}\\
\frac{\partial L_c}{\partial \alpha} &= \frac{L_c}{w_c}\frac{\partial w_c}{\partial \alpha} && \text{(E.54)}
\end{aligned}$$

Importantly, whereas land consumption in some locations within the city may vary in the opposite way of wages as $a$ increases (for specific values of the parameters), aggregate land consumption always varies in the same way. Put differently, at the aggregate level, the substitution effect is dominated by the income effect. Interestingly, equation (E.54) can also be obtained by deriving the logarithm of the equality between utilities in the center and at the fringe given by equation (E.44). Indeed, derivation of its logarithm gives:

$$\begin{aligned}
\frac{1}{w_c - \tau_c L_c}\left(\frac{\partial w_c}{\partial \alpha} - \tau_c\frac{\partial L_c}{\partial \alpha}\right) &= \frac{1}{w_c}\frac{\partial w_c}{\partial \alpha} && \text{(E.55)}\\
\frac{\partial w_c}{\partial \alpha} - \tau_c\frac{\partial L_c}{\partial \alpha} &= \left(1 - \frac{\tau_c L_c}{w_c}\right)\frac{\partial w_c}{\partial \alpha} && \text{(E.56)}\\
-\tau_c\frac{\partial L_c}{\partial \alpha} &= -\frac{\tau_c L_c}{w_c}\frac{\partial w_c}{\partial \alpha} && \text{(E.57)}\\
\frac{\partial L_c}{\partial \alpha} &= \frac{L_c}{w_c}\frac{\partial w_c}{\partial \alpha} && \text{(E.58)}
\end{aligned}$$

Then, inserting expression (E.54) into equation (E.39), we obtain:

$$\begin{aligned}
\frac{1}{w_c}\frac{\partial w_c}{\partial \alpha} &= \log L_c + (\alpha - \beta)\frac{1}{L_c}\frac{L_c}{w_c}\frac{\partial w_c}{\partial \alpha} && \text{(E.59)}\\
[1 + (\beta - \alpha)]\frac{1}{w_c}\frac{\partial w_c}{\partial \alpha} &= \log L_c && \text{(E.60)}
\end{aligned}$$

Since $\alpha < 1$, $\beta > 0$ and $L_c > 1$, we have $\partial w_c/\partial\alpha > 0$, i.e. wages increase as agglomeration economies with respect to city land area increase (while holding population constant). From equations (E.54) and (E.60), we get variations in city land area:

$$\begin{aligned}
\frac{\partial L_c}{\partial \alpha} &= \frac{1}{1 + \beta - \alpha}L_c \log L_c && \text{(E.61)}\\
\frac{\partial \log L_c}{\partial \log \alpha} &= \frac{\alpha}{1 + \beta - \alpha}\log L_c && \text{(E.62)}
\end{aligned}$$

City land area varies to a larger extent when the intensity of density agglomeration economies $\beta$ is smaller and the intensity of land agglomeration economies $\alpha$ is larger. In particular, as land area increases, population density decreases (since population is constant) and this lowers density agglomeration economies. The larger $\beta$, the larger the loss.

It is then easy to establish a relationship for the variations of density with $\alpha$ since population is fixed. We have, using (E.62):

$$\frac{\partial \log \left(N_c/L_c\right)}{\partial \log \alpha} = -\frac{\partial \log L_c}{\partial \log \alpha} = -\frac{\alpha}{1+\beta-\alpha} \log L_c \tag{E.63}$$

We can then turn to variations of wages. Inserting expressions (E.63) into equation (E.39), we get:

$$\begin{aligned} \frac{\partial \log w_c}{\partial \alpha} &= \log L_c + \frac{1}{\alpha}\left(\alpha-\beta\right)\frac{\partial \log L_c}{\partial \log \alpha} \\ &= \log L_c + \frac{\alpha-\beta}{1+\beta-\alpha} \log L_c \end{aligned}$$

### E.1.2 Elasticities with respect to parameter $\beta$

We now consider a change in $\beta$. The only difference when establishing a formula for variations in city land area comes from a difference in the formula of wage variations. By analogy, we have similarly to equation (E.54):

$$\frac{\partial L_c}{\partial \beta} = \frac{L_c}{w_c}\frac{\partial w_c}{\partial \beta} \tag{E.64}$$

Inserting expression (E.64) into equation (E.40) yields:

$$\frac{1}{w_c}\frac{\partial w_c}{\partial \beta} = \log\left(\frac{N_c}{L_c}\right) + \left(\alpha-\beta\right)\frac{1}{w_c}\frac{\partial w_c}{\partial \beta} \tag{E.65}$$

or equivalently:

$$\left[1+\left(\beta-\alpha\right)\right]\frac{1}{w_c}\frac{\partial w_c}{\partial \beta} = \log\left(\frac{N_c}{L_c}\right) \tag{E.66}$$

From equations (E.64) and (E.66), we get variations in city land area:

$$\frac{\partial L_c}{\partial \beta} = \frac{1}{1+\beta-\alpha} L_c \log\left(\frac{N_c}{L_c}\right) \tag{E.67}$$

$$\frac{\partial \log L_c}{\partial \log \beta} = \frac{\beta}{1+\beta-\alpha} \log\left(\frac{N_c}{L_c}\right) \tag{E.68}$$

and finally, we get:

$$\frac{\partial \log\left(N_c/L_c\right)}{\partial \log \beta} = -\frac{\partial \log L_c}{\partial \log \beta} = -\frac{\beta}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right) \tag{E.69}$$

We turn again to variations of wages. Inserting expressions (E.69) into equation (E.40), we get:

$$\begin{aligned}\frac{\partial \log w_c}{\partial \beta} &= \log\left(\frac{N_c}{L_c}\right) + \frac{1}{\beta}\left(\alpha-\beta\right)\frac{\partial \log L_c}{\partial \log \beta} \\ &= \log\left(\frac{N_c}{L_c}\right) + \frac{\alpha-\beta}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right)\end{aligned}$$

## E.2 Open-city case

We now consider an economy with $C$ cities denoted by $c \in \{1, 2, ..., C\}$. We allow city population to vary due to migrations between cities. We conduct comparative statics with respect to a change in income parameter, $\alpha$ or $\beta$. Deriving equation (11), we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \beta\frac{\partial \log\left(N_c/L_c\right)}{\partial \alpha} + \log L_c + \alpha\frac{\partial \log L_c}{\partial \alpha} \tag{E.70}$$

$$\frac{\partial \log w_c}{\partial \beta} = \beta\frac{\partial \log\left(N_c/L_c\right)}{\partial \beta} + \log\left(\frac{N_c}{L_c}\right) + \alpha\frac{\partial \log L_c}{\partial \beta} \tag{E.71}$$

Compared to the closed city case, there are additional effects resulting from the adjustment of city population to a variation in the value of an agglomeration economies parameter. The change of city population affects productivity through a change in density agglomeration economies. As before, we conduct the rest of the exercise for variations in $\alpha$ and then turn to variations in $\beta$.

Utility should be the same for any two cities at equilibrium, in particular at the fringe. Using the expression of indirect utility given by equation (E.35) evaluated at the fringe $\overline{x}_c = L_c$ and the equality $R_c\left(L_c\right) = \underline{R}$ (agricultural land price being assumed to be the same at the fringe of every city), we get:

$$B_c\left(w_c - \tau L_c\right) = B_1\left(w_1 - \tau_1 L_1\right) \tag{E.72}$$

Using the equality (E.44) for the fringe and the city center, as well as expression (E.38), we also get:

$$\left(w_c - \tau_c L_c\right)/R_c\left(L_c\right)^a = w_c/R_c\left(0\right)^a \tag{E.73}$$

$$\left(w_c - \tau_c L_c\right)/\underline{R}^a = w_c/\left(\underline{R} + \tau_c N_c\right)^a \tag{E.74}$$

We then end up with a system of $3C$ equations for $3C$ unknowns $(w_c, L_c, N_c)$ for $c \in \{1, ..., C\}$:

$$
\begin{aligned}
B_1 (w_1 - \tau_1 L_1) &= B_c (w_c - \tau_c L_c) \text{ for } c \in \{2, ..., C\} && \text{(E.75)} \\
\frac{w_c - \tau_c L_c}{\underline{R}^a} &= \frac{w_c}{(\underline{R} + \tau_c N_c)^a} \text{ for } c \in \{1, ..., C\} && \text{(E.76)} \\
\Sigma_{c=1}^{C} N_c &= N && \text{(E.77)} \\
w_c &= A_c (N_c/L_c)^{\beta} L_c^{\alpha} \text{ for } c \in \{1, ..., C\} && \text{(E.78)}
\end{aligned}
$$

(with parameters considered to be such that we have: $N_c > L_c > 1$).

### E.2.1 Determination of the equilibrium

To determine the existence and unicity of stable equilibria, we first rewrite the equilibrium condition across cities as a utility function that depends only of city population $u(N_c)$, such that $u(N_c) = \overline{u}$ where $\overline{u}$ is the utility level at equilibrium in every city. We then show that the utility function $u(\cdot)$ is concave, which yields that it has at most one stable equilibrium at a value above its optimum. As the level of function $u(\cdot)$ can be re-scaled changing the values of production and consumption amenities, it is possible to consider values of these amenities such that the stable equilibrium exists.

We now derive the expression of utility function $u(N_c)$. From the within-city equilibrium conditions (E.76), we get the two equalities:

$$
\begin{aligned}
B_c w_c &= (\underline{R} + \tau_c N_c)^a \, \overline{u} && \text{(E.79)} \\
B_c (w_c - \tau_c L_c) &= \underline{R}^a \overline{u} && \text{(E.80)}
\end{aligned}
$$

Subtracting the second equation from the first one gives:

$$
\left[ (\underline{R} + \tau_c N_c)^a - \underline{R}^a \right]^{-1} B_c \tau_c L_c = \overline{u} \tag{E.81}
$$

We want to express city area at the equilibrium as a function of the equilibrium population. Using expressions (11), within-city equilibrium condition (E.76) can be rewritten as:

$$L_c = \left[1-\left(\frac{\underline{R}}{\underline{R}+\tau_c N_c}\right)^a\right]\frac{w_c}{\tau_c} \tag{E.82}$$

$$= \left(\frac{A_c}{\tau_c}\right)^{1/(1+\beta-\alpha)}\left[1-\left(\frac{\underline{R}}{\underline{R}+\tau_c N_c}\right)^a\right]^{1/(1+\beta-\alpha)} N_c^{\beta/(1+\beta-\alpha)} \tag{E.83}$$

Inserting this expression into equation (E.81) yields:

$$\left[(\underline{R}+\tau_c N_c)^a - \underline{R}^a\right]^{-1} B_c\tau_c \left(\frac{A_c}{\tau_c}\right)^{1/(1+\beta-\alpha)}\left[1-\left(\frac{\underline{R}}{\underline{R}+\tau_c N_c}\right)^a\right]^{1/(1+\beta-\alpha)} N_c^{\beta/(1+\beta-\alpha)} = u \tag{E.84}$$

$$\left[(\underline{R}+\tau_c N_c)^a - \underline{R}^a\right]^{(\alpha-\beta)} N_c^{\beta}\left(\underline{R}+\tau_c N_c\right)^{-a} = (B_c\tau_c)^{\alpha-\beta-1}\frac{\tau_c}{A_c}u^{1+\beta-\alpha} \tag{E.85}$$

This is a quite intricate equation for equilibria and the question is whether there is a unique stable equilibrium (and under which conditions).

We denote the logarithm of the left-hand side as $L\left(N_c\right)$, which verifies:

$$L\left(N\right) = (\alpha-\beta)\log\left[(\underline{R}+\tau N)^a - \underline{R}^a\right] + \beta\log N - a\log\left(\underline{R}+\tau N\right) \tag{E.86}$$

Deriving this expression with respect to $N$ gives:

$$\frac{\partial L}{\partial N} = (\alpha-\beta)\frac{\tau a\left(\underline{R}+\tau N\right)^{a-1}}{(\underline{R}+\tau N)^a-\underline{R}^a} + \frac{\beta}{N} - \frac{\tau a}{\underline{R}+\tau N} \tag{E.87}$$

$$= \frac{\tau a\left(\alpha-\beta\right)N\left(\underline{R}+\tau N\right)^a + \beta\left(\underline{R}+\tau N\right)\left[(\underline{R}+\tau N)^a-\underline{R}^a\right] - \tau a N\left[(\underline{R}+\tau N)^a-\underline{R}^a\right]}{\left[(\underline{R}+\tau N)^a-\underline{R}^a\right]\left(\underline{R}+\tau N\right)N} \tag{E.88}$$

The numerator of this expression, denoted $NUM$, verifies:

$$NUM = \tau a\left(\alpha-\beta\right)N\left(\underline{R}+\tau N\right)^a + \beta\left(\underline{R}+\tau N\right)\left[(\underline{R}+\tau N)^a-\underline{R}^a\right] - a\tau N\left[(\underline{R}+\tau N)^a-\underline{R}^a\right] \tag{E.89}$$

$$NUM/\underline{R}^{a+1} = a\left(\alpha-\beta\right)\frac{\tau N}{\underline{R}} + \left[\beta\left(1+\frac{\tau N}{\underline{R}}\right) - a\left(1+\beta-\alpha\right)\frac{\tau N}{\underline{R}}\right]\left[\left(1+\frac{\tau N}{\underline{R}}\right)^a - 1\right] \tag{E.90}$$

Consider the case where $N \to 0$. We have:

$$NUM/\underline{R}^{a+1} = a\left(\alpha-\beta\right)\frac{\tau N}{\underline{R}} + \left[\beta\left(1+\frac{\tau N}{\underline{R}}\right) - a\left(1+\beta-\alpha\right)\frac{\tau N}{\underline{R}}\right]\left[\left(1+a\frac{\tau N}{\underline{R}} + o\left(\frac{\tau N}{\underline{R}}\right)\right) - 1\right] \tag{E.91}$$

$$NUM/\underline{R}^{a+1} = a(\alpha-\beta)\frac{\tau N}{\underline{R}} + a\beta\frac{\tau N}{\underline{R}} + o\left(\frac{\tau N}{\underline{R}}\right) \tag{E.92}$$

$$NUM/\underline{R}^{a+1} \approx a\alpha\frac{\tau N}{\underline{R}} \tag{E.93}$$

and for $N$ close to zero, $NUM$ is strictly positive. Now consider the case where $N \to +\infty$:

$$NUM/\underline{R}^{a+1} \approx \left(\frac{\tau N}{\underline{R}}\right)^a (\beta - a(1+\beta-\alpha))\frac{\tau N}{\underline{R}} \tag{E.94}$$

and for $N$ large enough, $NUM$ is strictly negative.

We now show that $NUM$ is monotonically increasing and then decreasing. Denoting $x = \tau N/\underline{R}$, we have:

$$NUM(x)/\underline{R}^{a+1} = a(\alpha-\beta)x + [\beta(1+x) - a(1+\beta-\alpha)x]\left[(1+x)^a - 1\right] \tag{E.95}$$

$$\begin{aligned}\frac{\partial NUM(x)/\underline{R}^{a+1}}{\partial x} &= a(\alpha-\beta) + [\beta - a(1+\beta-\alpha)]\left[(1+x)^a - 1\right] \\ &\quad + a\left[\beta(1+x) + a(1+\beta-\alpha) - a(1+\beta-\alpha)(1+x)\right](1+x)^{a-1} \qquad \text{(E.96)} \\ &= a\alpha + (1+a)[\beta - a(1+\beta-\alpha)]\left[(1+x)^a - 1\right] \\ &\quad + a^2(1+\beta-\alpha)\left[(1+x)^{a-1} - 1\right] \qquad \text{(E.97)}\end{aligned}$$

$$\begin{aligned}\frac{\partial^2 NUM(x)/\underline{R}^{a+1}}{\partial x^2} &= a(1+a)[\beta - a(1+\beta-\alpha)](1+x)^{a-1} \\ &\quad + a^2(a-1)(1+\beta-\alpha)(1+x)^{a-2} \qquad \text{(E.98)}\end{aligned}$$

From equation (E.98), we get that a necessary condition for $\partial^2 NUM/\partial x^2 < 0$ is that $\beta - a(1+\beta-\alpha) < 0$ and $a < 1$. This occurs for wide ranges of values of parameters around those considered in the literature and found in our application, ie. around $a = .3$, $\alpha = .01$ and $\beta = .03$. In that case, $\partial NUM/\partial x$ is strictly decreasing. As we have from equation (E.97) that $\partial NUM(0)/\partial x = a\alpha > 0$ and $\lim_{x\to+\infty} \partial NUM(x)/\partial x = -\infty$, there is a unique value $\widetilde{x}$ such that $\partial NUM(0)/\partial x = 0$ with $NUM$ being increasing from 0 to $\widetilde{x}$, and then decreasing. Since $NUM(\widetilde{x}) = 0$, $NUM$ is positive on the $[0, \widetilde{x}]$ interval. Moreover, since $NUM(x) \to -\infty$ under the assumption that $\beta - a(1+\beta-\alpha) < 0$ (see equation E.95), there is a unique $\widetilde{\widetilde{x}} > \widetilde{x}$ such that $NUM\left(\widetilde{\widetilde{x}}\right) = 0$, and $NUM$ is positive on the $\left[0, \widetilde{\widetilde{x}}\right]$ interval and negative on the interval $\left[\widetilde{\widetilde{x}}, +\infty\right[$. Since by definition $NUM$ is the numerator of the derivative of $L$ and the denominator is positive, we deduce that $L$ is bell-shaped. This yields that there is at most a single stable equilibrium for each city (i.e. if it exists, it occurs at the value of $N$ such that $NUM(N) < 0$ and equation (E.85) is verified). Still, depending on the values of parameters, some cities may be empty.

### E.2.2 Elasticities with respect to parameter $\alpha$

Deriving expressions (E.75) and (E.77), as well as the logarithm of expression (E.76) with respect to $\alpha$ gives:

$$B_1\left(\frac{\partial w_1}{\partial\alpha}-\tau_c\frac{\partial L_1}{\partial\alpha}\right) = B_c\left(\frac{\partial w_c}{\partial\alpha}-\tau_c\frac{\partial L_c}{\partial\alpha}\right) \tag{E.99}$$

$$\frac{1}{w_c-\tau L_c}\left[\frac{\partial w_c}{\partial\alpha}-\tau_c\frac{\partial L_c}{\partial\alpha}\right] = \frac{1}{w_c}\frac{\partial w_c}{\partial\alpha}-\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial\alpha} \tag{E.100}$$

$$\sum_{c=1}^{C}\frac{\partial N_c}{\partial\alpha} = 0 \tag{E.101}$$

We are first going to insert the expression for the change in agglomeration economies (E.70) into the within-city equilibrium derivative (E.100):

$$\frac{w_c}{w_c-\tau_c L_c}\frac{1}{w_c}\frac{\partial w_c}{\partial\alpha}-\frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial\alpha} = \frac{1}{w_c}\frac{\partial w_c}{\partial\alpha} -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial\alpha} \tag{E.102}$$

$$\frac{\tau_c L_c}{w_c-\tau_c L_c}\frac{1}{w_c}\frac{\partial w_c}{\partial\alpha}-\frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_j}{\partial\alpha} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_j}{\partial\alpha} \tag{E.103}$$

$$\frac{\tau_c L_c}{w_c-\tau_c L_c}\left[\beta\frac{1}{N_c}\frac{\partial N_c}{\partial\alpha}+\log L_c+(\alpha-\beta)\frac{1}{L_c}\frac{\partial L_c}{\partial\alpha}\right]-\frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial\alpha} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial\alpha} \tag{E.104}$$

$$\beta\frac{\tau_c L_c}{w_c-\tau_c L_c}\frac{1}{N_c}\frac{\partial N_c}{\partial\alpha}+\frac{\tau_c L_c}{w_c-\tau_c L_c}\log L_c+(\alpha-\beta-1)\frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial\alpha} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial\alpha} \tag{E.105}$$

$$(1+\beta-\alpha)\frac{\partial L_c}{\partial\alpha} = L_c\log L_c +M_c\frac{\partial N_c}{\partial\alpha} \tag{E.106}$$

where

$$M_c = a\frac{w_c-\tau_c L_c}{\underline{R}+\tau_c N_c}+\beta\frac{L_c}{N_c} \tag{E.107}$$

and finally, rearranging the terms, we get:

$$\frac{\partial\log L_c}{\partial\log\alpha} = \frac{\alpha}{1+\beta-\alpha}\log L_c+\frac{1}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial\log N_c}{\partial\log\alpha} \tag{E.108}$$

This expression for the variation of city land area is similar to the one obtained in the closed city case that is given by equation (E.62), except that there is now the additional term $\frac{\alpha}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial N_c}{\partial \alpha}$ with $M_c > 0$ due to migrations between cities. In particular, $M_c$ captures the effect of increasing land prices that makes land less attractive if city population increases (since $M_c$ is smaller when $R_c(0) = \underline{R} + \tau_c N_c$ is larger), and the additional effect of density agglomeration economies that makes people want to consume more land as their income is higher. In fact, the migration term $\partial N_c / \partial \alpha$ can be positive or negative, depending on whether cities become more or less attractive with respect to each other when land agglomeration economies change. We can then insert the expression for the change in agglomeration economies (E.70) into the between-city equilibrium derivative (E.99):

$$B_1 \left[ \beta \frac{w_1}{N_1} \frac{\partial N_1}{\partial \alpha} + w_1 \log L_1 + (\alpha - \beta) \frac{w_1}{L_1} \frac{\partial L_1}{\partial \alpha} - \tau_1 \frac{\partial L_1}{\partial \alpha} \right]$$
$$= B_c \left[ \beta \frac{w_c}{N_c} \frac{\partial N_c}{\partial \alpha} + w_c \log L_c + (\alpha - \beta) \frac{w_c}{L_c} \frac{\partial L_c}{\partial \alpha} - \tau_c \frac{\partial L_c}{\partial \alpha} \right] \tag{E.109}$$

$$B_1 \left[ \beta \frac{w_1}{N_1} \frac{\partial N_1}{\partial \alpha} + w_1 \log L_1 + \left[ (\alpha - \beta) w_1 - \tau_1 L_1 \right] \frac{1}{L_1} \frac{\partial L_1}{\partial \alpha} \right]$$
$$= B_c \left[ \beta \frac{w_c}{N_c} \frac{\partial N_c}{\partial \alpha} + w_c \log L_c + \left[ (\alpha - \beta) w_c - \tau_c L_c \right] \frac{1}{L_c} \frac{\partial L_c}{\partial \alpha} \right] \tag{E.110}$$

Inserting the expression of city land area (E.108) into this equation, we get:

$$B_1 \left[ \beta \frac{w_1}{N_1} \frac{\partial N_1}{\partial \alpha} + w_1 \log L_1 + \frac{(\alpha - \beta) w_1 - \tau_1 L_1}{1 + \beta - \alpha} \frac{1}{L_1} \left( L_1 \log L_1 + M_1 \frac{\partial N_1}{\partial \alpha} \right) \right]$$
$$= B_c \left[ \beta \frac{w_c}{N_c} \frac{\partial N_c}{\partial \alpha} + w_c \log L_c + \frac{(\alpha - \beta) w_c - \tau_c L_c}{1 + \beta - \alpha} \frac{1}{L_c} \left( L_c \log L_c + M_c \frac{\partial N_c}{\partial \alpha} \right) \right] \tag{E.111}$$

$$B_1 \left[ \left( \beta \frac{w_1}{N_1} + \frac{(\alpha - \beta) w_1 - \tau_1 L_1}{1 + \beta - \alpha} \frac{M_1}{L_1} \right) \frac{\partial N_1}{\partial \alpha} + \frac{w_1 - \tau_1 L_1}{1 + \beta - \alpha} \log L_1 \right]$$
$$= B_c \left[ \left( \beta \frac{w_c}{N_c} + \frac{(\alpha - \beta) w_c - \tau_c L_c}{1 + \beta - \alpha} \frac{M_c}{L_c} \right) \frac{\partial N_c}{\partial \alpha} + \frac{w_c - \tau_c L_c}{1 + \beta - \alpha} \log L_c \right] \tag{E.112}$$

$$B_1 \left[ \left( \beta (1 + \beta - \alpha) \frac{w_1}{N_1} - \left[ \tau_1 L_1 + (\beta - \alpha) w_1 \right] \frac{M_1}{L_1} \right) \frac{\partial N_1}{\partial \alpha} + (w_1 - \tau_1 L_1) \log L_1 \right]$$
$$= B_c \left[ \left( \beta (1 + \beta - \alpha) \frac{w_c}{N_c} - \left[ \tau_c L_c + (\beta - \alpha) w_c \right] \frac{M_c}{L_c} \right) \frac{\partial N_c}{\partial \alpha} + (w_c - \tau_c L_c) \log L_c \right] \tag{E.113}$$

We define $Q_c$ with the following equation:

$$Q_c = \beta (1 + \beta - \alpha) \frac{w_c}{N_c} - \left[ \tau_c L_c + (\beta - \alpha) w_c \right] \frac{M_c}{L_c} \tag{E.114}$$

The term $Q_c$ captures the influence of in/out migration on individual utility. It is the sum of two terms. The first one is positive and captures the effect of an increase in density agglomeration economies. The second one can be either positive or negative, and comes from the change in city land area due to the in/out migration of workers. A negative effect comes from the increase in commuting costs. An additional effect, which can be positive or negative comes from the difference in the changes of density and land area agglomeration economies.

We consider that parameters are such that, for every $c$, we have $Q_c \neq 0$. Substituting expression (E.114) into equation (E.113), and using equality (E.75) to make ratios of consumption amenity effects disappear, gives:

$$B_1\left[Q_1\frac{\partial N_1}{\partial\alpha} + (w_1-\tau_1 L_1)\log L_1\right] = B_c\left[Q_c\frac{\partial N_c}{\partial\alpha} + (w_c-\tau_c L_c)\log L_c\right] \tag{E.115}$$

$$\frac{B_1 Q_1}{B_c Q_c}\frac{\partial N_1}{\partial\alpha} = \frac{\partial N_c}{\partial\alpha} + \frac{w_c-\tau_c L_c}{Q_c}\log L_c - \frac{B_1}{B_c}\frac{w_1-\tau_1 L_1}{Q_c}\log L_1 \tag{E.116}$$

$$\frac{w_c-\tau_c L_c}{w_1-\tau_1 L_1}\frac{Q_1}{Q_c}\frac{\partial N_1}{\partial\alpha} = \frac{\partial N_c}{\partial\alpha} + \frac{w_c-\tau_c L_c}{Q_c}(\log L_c - \log L_1) \tag{E.117}$$

$$\tag{E.118}$$

Summing over all $c$ and using the population derivative given by equation (E.101), we obtain:

$$\frac{Q_1}{w_1-\tau_1 L_1}\left(\sum_{c=1}^{C}\frac{w_c-\tau_c L_c}{Q_c}\right)\frac{\partial N_1}{\partial\alpha} = \sum_{c=1}^{C}\frac{w_c-\tau_c L_c}{Q_c}(\log L_c - \log L_1) \tag{E.119}$$

$$\frac{\partial \log N_1}{\partial\log\alpha} = \alpha\frac{w_1-\tau_1 L_1}{N_1 Q_1}\left(\sum_{c=1}^{C}\frac{w_c-\tau_c L_c}{Q_c}\right)^{-1}\sum_{c=1}^{C}\frac{w_c-\tau_c L_c}{Q_c}(\log L_c - \log L_1) \tag{E.120}$$

Hence, the change in city-1 population is a weighted average of differences in initial land area between city 1 and every city. From expression (E.108), we can also deduce variations for population density. We have:

$$\frac{\partial\log(N_c/L_c)}{\partial\log\alpha} = \frac{\partial\log N_c}{\partial\log\alpha} - \frac{\partial\log L_c}{\partial\log\alpha} \tag{E.121}$$

$$= \frac{\partial\log N_c}{\partial\log\alpha} - \frac{\alpha}{1+\beta-\alpha}\log L_c - \frac{\alpha}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial\log N_c}{\partial\log\alpha} \tag{E.122}$$

$$= -\frac{\alpha}{1+\beta-\alpha}\log L_c + \left(1-\frac{\alpha}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\right)\frac{\partial\log N_c}{\partial\log\alpha} \tag{E.123}$$

and we can use equation (E.120) to develop this expression and get an expression for this elasticity that can be computed in our empirical analysis.

We now turn to variations of wages. Inserting expressions (E.108) into equation (E.70), we get:

$$\frac{\partial \log w_c}{\partial \alpha} = \log L_c + \frac{\beta}{\alpha}\frac{\partial \log N_c}{\partial \log \alpha} + \frac{\alpha-\beta}{\alpha}\frac{\partial \log L_c}{\partial \log \alpha} \quad \text{(E.124)}$$

$$= \log L_c + \frac{\beta}{\alpha}\frac{\partial \log N_c}{\partial \log \alpha} + \frac{\alpha-\beta}{\alpha}\left(\frac{\alpha}{1+\beta-\alpha}\log L_c + \frac{1}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial \log N_c}{\partial \log \alpha}\right) \quad \text{(E.125)}$$

$$= \log L_c + \frac{\alpha-\beta}{1+\beta-\alpha}\log L_c + \left(\beta + \frac{\alpha-\beta}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\right)\frac{1}{\alpha}\frac{\partial \log N_c}{\partial \log \alpha} \quad \text{(E.126)}$$

where the expression of $\frac{\partial \log N_c}{\partial \log \alpha}$ is given by equation (E.120).

### E.2.3 Elasticities with respect to parameter $\beta$

We then consider a change in $\beta$. We are first going to insert the expression for the change in wages (E.71) into the expression of the with-city equilibrium derivative (E.100) considered when deriving with respect to $\beta$ rather than $\alpha$. We obtain:

$$\frac{w_c}{w_c-\tau_c L_c}\frac{1}{w_c}\frac{\partial w_c}{\partial \beta} - \frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial \beta} = \frac{1}{w_c}\frac{\partial w_c}{\partial \beta} - \frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial \beta} \quad \text{(E.127)}$$

$$\frac{\tau_c L_c}{w_c-\tau_c L_c}\frac{1}{w_c}\frac{\partial w_c}{\partial \beta} - \frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_j}{\partial \beta} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_j}{\partial \beta} \quad \text{(E.128)}$$

$$\frac{\tau_c L_c}{w_c-\tau_c L_c}\left[\beta\frac{\partial \log(N_c/L_c)}{\partial \beta} + \log\left(\frac{N_c}{L_c}\right) + \alpha\frac{\partial \log L_c}{\partial \beta}\right] - \frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial \beta} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial \beta} \quad \text{(E.129)}$$

$$\beta\frac{\tau_c L_c}{w_c-\tau_c L_c}\frac{1}{N_c}\frac{\partial N_c}{\partial \beta} + \frac{\tau_c L_c}{w_c-\tau_c L_c}\log\left(\frac{N_c}{L_c}\right) + (\alpha-\beta-1)\frac{\tau_c}{w_c-\tau_c L_c}\frac{\partial L_c}{\partial \beta} = -\frac{\tau_c a}{\underline{R}+\tau_c N_c}\frac{\partial N_c}{\partial \beta} \quad \text{(E.130)}$$

$$(1+\beta-\alpha)\frac{\partial L_c}{\partial \beta} = L_c \log\left(\frac{N_c}{L_c}\right) + M_c\frac{\partial N_c}{\partial \beta} \quad \text{(E.131)}$$

and finally, rearranging the terms, we get:

$$\frac{\partial \log L_c}{\partial \log \beta} = \frac{\beta}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right) + \frac{\beta}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial \log N_c}{\partial \beta} \quad \text{(E.132)}$$

This equation is similar to equation (E.108) except for the presence of $\log(N_c/L_c)$ rather than $\log(L_c)$ in the first right-hand term, and the presence of parameter $\beta$ at the numerator of the two right-hand side terms rather than $\alpha$.

We now compute the expression corresponding to equation (E.120) when considering variations in $\beta$ rather than $\alpha$. The counterpart of equation (E.99) is:

$$B_1\left(\frac{\partial w_1}{\partial\beta}-\tau_1\frac{\partial L_1}{\partial\beta}\right)=B_c\left(\frac{\partial w_c}{\partial\beta}-\tau_c\frac{\partial L_c}{\partial\beta}\right) \tag{E.133}$$

Inserting equation (E.71) into this expression, we obtain:

$$\begin{aligned} & B_1\left[\beta\frac{w_1}{N_1}\frac{\partial N_1}{\partial\beta}+w_1\log\left(\frac{N_1}{L_1}\right)+(\alpha-\beta)\frac{w_1}{L_1}\frac{\partial L_1}{\partial\beta}-\tau_1\frac{\partial L_1}{\partial\beta}\right] \\ = \;& B_c\left[\beta\frac{w_c}{N_c}\frac{\partial N_c}{\partial\beta}+w_c\log\left(\frac{N_c}{L_c}\right)+(\alpha-\beta)\frac{w_c}{L_c}\frac{\partial L_c}{\partial\beta}-\tau_1\frac{\partial L_c}{\partial\beta}\right] \end{aligned} \tag{E.134}$$

$$\begin{aligned} & B_1\left[\beta\frac{w_1}{N_1}\frac{\partial N_1}{\partial\beta}+w_1\log\left(\frac{N_1}{L_1}\right)+\left[(\alpha-\beta)\frac{w_1}{L_1}-\tau_1\right]\frac{\partial L_1}{\partial\beta}\right] \\ = \;& B_c\left[\beta\frac{w_c}{N_c}\frac{\partial N_c}{\partial\beta}+w_c\log\left(\frac{N_c}{L_c}\right)+\left[(\alpha-\beta)\frac{w_c}{L_c}-\tau_1\right]\frac{\partial L_c}{\partial\beta}\right] \end{aligned} \tag{E.135}$$

Inserting the expression of city land area (E.132) into this equation, we get:

$$B_1\left[\beta\frac{w_1}{N_1}\frac{\partial N_1}{\partial\beta}+w_1\log\left(\frac{N_1}{L_1}\right)+\left[(\alpha-\beta)\frac{w_1}{L_1}-\tau_c\right]\left[\frac{L_1}{1+\beta-\alpha}\log\left(\frac{N_1}{L_1}\right)+\frac{1}{1+\beta-\alpha}M_1\frac{\partial N_1}{\partial\beta}\right]\right] \tag{E.136}$$

$$=B_c\left[\beta\frac{w_c}{N_c}\frac{\partial N_c}{\partial\beta}+w_c\log\left(\frac{N_c}{L_c}\right)+\left[(\alpha-\beta)\frac{w_c}{L_c}-\tau_c\right]\left[\frac{L_c}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right)+\frac{1}{1+\beta-\alpha}M_c\frac{\partial N_c}{\partial\beta}\right]\right] \tag{E.137}$$

$$B_1\left[\left(\beta\frac{w_1}{N_1}+\frac{(\alpha-\beta)\,w_1-\tau_1L_1}{1+\beta-\alpha}\frac{M_1}{L_1}\right)\frac{\partial N_1}{\partial\beta}+\frac{w_1-\tau_1L_1}{1+\beta-\alpha}\log\left(\frac{N_1}{L_1}\right)\right] \tag{E.138}$$

$$=B_c\left[\left(\beta\frac{w_c}{N_c}+\frac{(\alpha-\beta)\,w_c-\tau_cL_c}{1+\beta-\alpha}\frac{M_c}{L_c}\right)\frac{\partial N_c}{\partial\beta}+\frac{w_c-\tau_cL_c}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right)\right] \tag{E.139}$$

$$B_1\left[\left(\beta\,(1+\beta-\alpha)\,\frac{w_1}{N_1}-[\tau_1L_1+(\beta-\alpha)\,w_1]\,\frac{M_1}{L_1}\right)\frac{\partial N_1}{\partial\beta}+(w_1-\tau_1L_1)\log\left(\frac{N_1}{L_1}\right)\right] \tag{E.140}$$

$$=B_c\left[\left(\beta\,(1+\beta-\alpha)\,\frac{w_c}{N_c}-[\tau_cL_c+(\beta-\alpha)\,w_c]\,\frac{M_c}{L_c}\right)\frac{\partial N_c}{\partial\beta}+(w_c-\tau_cL_c)\log\left(\frac{N_c}{L_c}\right)\right] \tag{E.141}$$

The other developments are straightforward and follow those when there are variations in $\alpha$. We then end up with the expression:

$$\frac{\partial\log N_1}{\partial\log\beta}=\beta\frac{w_1-\tau_1L_1}{N_1Q_1}\left(\sum_{c=1}^{C}\frac{w_c-\tau_cL_c}{Q_c}\right)^{-1}\sum_{c=1}^{C}\frac{w_c-\tau_cL_c}{Q_c}\left[\log\left(\frac{N_c}{L_c}\right)-\log\left(\frac{N_1}{L_1}\right)\right] \tag{E.142}$$

This expression is similar to the one obtained when there are variations in $\alpha$ that is given by equation (E.120), except for terms in brackets on the right-hand side that are of the form $\log(N_c/L_c)$ rather than $\log(L_c)$, and the whole expression on the right-hand side is multiplied by $\beta$ rather than $\alpha$.

We finally turn to variations of wages. Inserting expressions (E.132) into equation (E.71), we get:

$$\frac{\partial \log w_c}{\partial \beta} = \frac{\partial \log N_c}{\partial \log \beta} + \log\left(\frac{N_c}{L_c}\right) + \frac{\alpha-\beta}{\beta}\frac{\partial \log L_c}{\partial \log \beta} \tag{E.143}$$

$$= \log\left(\frac{N_c}{L_c}\right) + \frac{\partial \log N_c}{\partial \log \beta}$$

$$+\frac{\alpha-\beta}{\beta}\left[\frac{\beta}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right) + \frac{1}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\frac{\partial \log N_c}{\partial \log \beta}\right] \tag{E.144}$$

$$= \log\left(\frac{N_c}{L_c}\right) + \frac{\alpha-\beta}{1+\beta-\alpha}\log\left(\frac{N_c}{L_c}\right) + \left(\beta + \frac{\alpha-\beta}{1+\beta-\alpha}\frac{N_c M_c}{L_c}\right)\frac{1}{\beta}\frac{\partial \log N_c}{\partial \log \beta} \tag{E.145}$$

where the expression of $\partial \log N_c / \partial \log \beta$ is given by equation (E.142). This expression is very similar to the one obtained when deriving with respect to $\alpha$ that is given by equation (E.126). Once the derivative of city populations have been replaced by their expressions, the difference is that terms $\log L_c$ are replaced by terms $\log\left(N_c/L_c\right)$.

## E.3 Computation of expressions

### E.3.1 Decomposition

We now explain how we get the decomposition of interest provided in the main text. In this subsection, model parameters are indexed by year $t$ as we are interested in wage evolution over time and parameters can change. Considering that dates $t-1$ and $t$ are close, we can write that:

$$\log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) - \log w_{c,t-1}\left(\alpha_{t-1}, \beta_{t-1}, A_{t-1}, B_{t-1}\right) \tag{E.146}$$

$$\approx d \log w_{c,t}\left(\alpha_t, \beta_t, A_t, B_t\right) \tag{E.147}$$

$$= \frac{\partial \log w_{c,t}}{\partial \alpha} d\alpha_t + \frac{\partial \log w_{c,t}}{\partial \beta} d\beta_t + \frac{\partial \log w_{c,t}}{\partial A_t} dA_t + \frac{\partial \log w_{c,t}}{\partial B_t} dB_t \tag{E.148}$$

$$\approx \frac{\partial \log w_{c,t}}{\partial \alpha}\left(\alpha_t - \alpha_{t-1}\right) + \frac{\partial \log w_{c,t}}{\partial \beta}\left(\beta_t - \beta_{t-1}\right) + \frac{\partial \log w_{c,t}}{\partial A}\left(A_t - A_{t-1}\right)$$

$$+\frac{\partial \log w_{c,t}}{\partial B}\left(B_t - B_{t-1}\right) \tag{E.149}$$

where $\frac{\partial \log w_{c,t}}{\partial A} = \left(\frac{\partial \log w_{c,t}}{\partial A_1}, \ldots, \frac{\partial \log w_{c,t}}{\partial A_C}\right)$ and $\frac{\partial \log w_{c,t}}{\partial B} = \left(\frac{\partial \log w_{c,t}}{\partial B_1}, \ldots, \frac{\partial \log w_{c,t}}{\partial B_C}\right)$.

In particular, we are interested in the evolution of log-wage when the values of agglomeration parameters $\alpha$ and $\beta$ vary. Hence, inserting expression (E.149) into equation (26), we obtain our decomposition of interest given by equation (29) where $\frac{\partial \log w_{c,t}}{\partial A}\left(A_t - A_{t-1}\right) + \frac{\partial \log w_{c,t}}{\partial B}\left(B_t - B_{t-1}\right)$ enters the residual $r_{c,t}$.

### E.3.2 Expressions

We need to bring expressions (E.108), (E.132), (E.120) and (E.142) to the data. For that purpose, we are first going to rewrite them as functions of quantities for which we can find an empirical counterpart. We have values in the data for $N_j$ and $L_j$, and we are able to recover estimates for $\alpha$ and $\beta$. We need values for the quantities $N_c M_c / L_c$ and $(w_c - \tau_c L_c)/Q_c$. Using expression (E.107), we get:

$$\frac{N_c M_c}{L_c} = a \frac{N_c}{L_c} \frac{w_c - \tau_c L_c}{\underline{R} + \tau_c N_c} + \beta \tag{E.150}$$

This expression makes intervene $R_c(0) = \underline{R} + \tau_c N_c$ that can be rewritten such that:

$$R_c(0) = \frac{R_c(0)}{\tau_c N_c} \tau_c N_c = \lambda_c \tau_c N_c \tag{E.151}$$

where:

$$\lambda_c = \frac{R_c(0)}{R_c(0) - \underline{R}} = \frac{1}{1 - \underline{R}/R_c(0)} \tag{E.152}$$

and provided that the ratio $\underline{R}/R_c(0)$ can be computed from the data, we can compute $\lambda_c$. Inserting expression (E.151) into equation (E.150), we get:

$$\begin{aligned} \frac{N_c M_c}{L_c} &= a \frac{N_c}{L_c} \frac{w_c - \tau_c L_c}{\lambda_c \tau_c N_c} + \beta \\ &= \frac{a}{\lambda_c} \left( \frac{w_c}{\tau_c L_c} - 1 \right) + \beta \end{aligned} \tag{E.153}$$

Provided that the ratio $\tau_c L_c / w_c$ can be computed from the data, we can compute $N_c M_c / L_c$.

Inserting expressions (E.150) and (E.151) into equation (E.114), we obtain:

$$\begin{aligned} N_c Q_c &= \beta(1 + \beta - \alpha) w_c - [\tau_c L_c + (\beta - \alpha) w_c] \frac{N_c}{L_c} \left( a \frac{w_c - \tau_c L_c}{\lambda_c \tau_c N_c} + \beta \frac{L_c}{N_c} \right) \\ &= \beta(1 + \beta - \alpha) w_c - [\tau_c L_c + (\beta - \alpha) w_c] \left( a \frac{w_c - \tau_c L_c}{\lambda_c \tau_c L_c} + \beta \right) \\ &= \beta(w_c - \tau_c L_c) - [\tau_c L_c + (\beta - \alpha) w_c] \frac{a}{\lambda_c \tau_c L_c} (w_c - \tau_c L_c) \end{aligned} \tag{E.154}$$

Hence:

$$\frac{Q_c}{w_c - \tau_c L_c} = \frac{1}{N_c} \left[ \beta - \frac{a}{\lambda_c} \left[ 1 + (\beta - \alpha) \frac{w_c}{\tau_c L_c} \right] \right] \tag{E.155}$$

and this expression can be computed for given values for parameters, $\lambda_c$ and $\tau_c L_c / w_c$, but also for $N_c$.

To sum up, we are able to compute the elasticities of land area and population density with respect to $\alpha$ and $\beta$ from estimated parameters for $\alpha$ and $\beta$, the housing budget share $a$, the city share of costliest transport cost in wages $\tau_c L_c / w_c$, the city ratio between land prices at the fringe and at the center $\underline{R}/R_c(0)$, and city land area and population $L_c$ and $N_c$.

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