Structural Change, Land Use and Urban Expansion

Nicolas Coeurdacier
SciencesPo Paris, CEPR

Florian Oswald
SciencesPo Paris

Marc Teignier
Serra Húnter Fellow,
University of Barcelona

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Abstract

How do cities grow in the process of structural transformation? To answer this question, we develop a multi-sector spatial equilibrium model with endogenous land use: land is used either for agriculture or housing. Urban land, densely populated due to commuting frictions, expands out of agricultural land. With rising productivity, the reallocation of workers away from agriculture frees up land for cities to expand, limiting the increase in land values despite higher income and increasing urban population. Due to the reallocation of land use, the area of cities expands at a fast rate and urban density persistently declines, as in the data over a long period. Quantitative predictions of the joint evolution of density and land values across time and space are confronted with historical data assembled for France over 180 years.

Keywords: Structural Change, Land Use, Productivity Growth, Urban Density.
JEL-codes: O41, R14, O11

1 Introduction

Since the early years of the industrial revolution, the population massively migrated from rural areas towards cities. This widespread phenomenon of urbanization went together with the reallocation of workers away from the agricultural sector towards manufacturing and service sectors—a phenomenon of structural change. How do cities grow when these well-known phenomena occur? Cities can become denser for a given area—growth at the intensive margin. They can also become larger in surface to accommodate more workers—via growth at the extensive margin. Over a long period, cities have been growing essentially in area, at such a fast speed that their average density has been falling. In other words, over time, cities expanded faster in area than in population. We precisely document this stylized fact for France since 1870 but it is also documented on a global scale in Angel et al. (2010). In France, the population of the main cities has been multiplied by almost 4 since 1870, while their area increased by a factor of 30: the average urban density has thus been divided by a substantial factor of about 8. This paper shows that this persistent decline in density, despite the process of urbanization, is well explained by the most conventional theories of structural change with non-homothetic preferences and augmented with endogenous land use—whereby land can be used for agriculture or urban housing.

A crucial insight of our theory is to consider that the value of agricultural land at the urban fringe determines the opportunity cost of expanding the area of cities for housing purposes. With low agricultural productivity, agricultural goods and farmland are expensive. High agricultural land values make cities initially small in area and very dense as households cannot afford large homes—a manifestation of the 'food problem' (Schultz (1953)). With structural change driven by rising productivity, workers move away from rural areas towards cities, freeing up agricultural land. As the value of land at the urban fringe falls and households start being able to buy larger homes with increasing incomes, cities expand in area at a fast rate. Together with the reallocation of workers across sectors, reallocation of land use occurs—from agricultural use to urban use. We document that for France, since 1840, about 15% of French land has been converted away from agricultural use. As long as the transitory process of reallocation away from agriculture continues, cities grow faster in area than population and average urban density keeps falling with urban expansion. Thus, our theory provides a novel mechanism explaining urban sprawl and suburbanization. This complements the traditional Urban Economics view that cities have sprawled following improvements in commuting technologies, which have allowed households to live further away from their workplace.

Our framework also provides novel predictions regarding the historical evolution of land values. When productivity is low and agricultural goods are in high demand for subsistence needs, the value of farmland is high relative to income. With economic development, structural change frees up farmland for urban expansion. The value of agricultural land as share of income falls and, over time, the share of urban land value rises significantly. These predictions are in line with the data as shown in Piketty and Zucman (2014). Moreover, despite rising housing demand, the fast expansion of cities at the extensive margin due to structural change initially limits the increase in urban land rents and housing prices. When the reallocation of workers out of agriculture slows down, so does the reallocation of land use at the fringe of cities. If workers' productivity increases further, the value of land must adjust to prevent further expansion of cities with rising housing demand. Land values start to increase at a faster rate. Our theory thus predicts relatively flat land and housing values for decades before shooting up—a prediction which resembles very much the data for France and most advanced economies as best illustrated in Knoll et al. (2017). Therefore, our theory provides novel insights on the joint evolution of the density of cities and land values along the process of economic development. It also helps understanding how the structure of cities, e.g. their urban extent and density, evolves with the process of structural transformation. It sheds new light on the origins of urban sprawl in the process of economic development—a central matter in the artificialization of soils and their environmental impact (IPCC (2018)).

The contribution of our paper is threefold. First, we document new stylized facts on land use and urban expansion for France since the mid-nineteenth century. In particular, using historical maps and satellite data for the more recent period, we document the historical decline of the density of French cities. Between 1870 and 1950, the average density was divided by about 3 and again by about 2.5 until 1975—the thirty years post-World War II being characterized in France by faster structural change and *rural exodus* (Mendras (1970), Bairoch (1989), Toutain (1993)). Together with the slowdown of structural change in the more recent decades, average urban density did not fall much since. These facts, together with the historical evolution of urban and agricultural land values in France, motivate our theory.

The second contribution is to develop a spatial general equilibrium model of structural change with endogenous land use. The production side features three sectors: rural, urban and housing. The rural (urban) sector produces agricultural (non-agricultural) tradable goods, the production of the agricultural good being more land intensive. The housing sector produces location-specific housing units using the urban good and land in the process. Land is in fixed supply and land use is rivalrous: land is either used for agriculture or for housing. Following the traditional monocentric model after Alonso et al. (1964), Muth (1969), and Mills (1967), urban land use (i.e. cities) emerges endogenously due to commuting costs for workers: urban land is more densely populated than rural land and the urban fringe corresponds to the longest commute of a worker producing urban goods. Due to commuting frictions, urban workers are thus compensated with a higher wage than rural workers. Importantly, the rental price of land at the fringe of the city must be equalized across potential usages—the marginal productivity of land in the rural sector determining the opportunity cost of expanding further urban land. The last important components of our theory are the drivers of structural change. Structural change is driven by the combination of non-homothetic preferences on the demand side, particularly a subsistence consumption for the rural good, and increasing agricultural productivity on the supply side. This generates transitory dynamics with rising productivity in agriculture that are at the heart of our story: in the old times, due to low agricultural productivity, land is scarce with high values of farmland with respect to income. Moreover, households devote a large fraction of their resources to feed themselves and cannot afford large homes. Few urban workers are concentrated on a small area and urban land is highly densely populated. Later on, with agricultural development, farmland is getting less valuable, accommodating rising demand for housing of more numerous urban workers. The city sprawls and average urban density falls through two channels: the fall in the rental price of farmland at the urban fringe and the increasing share of spending towards housing. Note that this decline in urban density occurs even without improvements in commuting technology.

We account for the latter, more standard, mechanism by incorporating a model of commuting mode choice into our theory. Building upon LeRoy and Sonstelie (1983) and DeSalvo and Huq (1996), individuals optimally choose their commuting mode based on their opportunity cost of time and location. More specifically, as this opportunity cost increases with rising urban productivity, workers optimally choose faster commuting modes and live further away from the city center: the city expands at the expense of rural land. Thus, although the mechanisms are entirely different, both urban *and* rural productivity growth lead to sprawling and suburbanization together with a decline in average urban density. However, the implications for density across urban locations are different. Increasing urban productivity and faster commutes lead to a reallocation of urban workers away from the center towards the city fringe. As a consequence, central density falls more than average urban density since suburban density increases. To the contrary, increasing agricultural productivity and structural change lead to the addition of lower and lower density settlements at the fringe of cities: suburban density falls more than the average urban density. While central density did fall since the mid-nineteenth century, historical data for Paris shows that it fell less than the average urban density. This suggests that both channels—the structural change and the commuting speed channels—have been playing a role in driving the density decline.

In a third contribution, we develop a quantitative version of our spatial equilibrium model applied to the French context since 1840. The quantitative model includes multiple regions, with one city per region surrounded by agricultural land. Labor and goods are perfectly mobile across regions, which differ in their urban and rural productivity. Using data from various historical sources, we measure sectoral factors of production and productivities since 1840 and calibrate the model to fit the process of structural change in France. Historical spatial data on farmland values and urban population discipline the spatial distribution of urban and rural productivity. To account for the use of faster commutes over time, we make use of a tractable parametrization of commuting costs and calibrate the elasticities of commuting speed to urban income and commuting distance using individual commuting data. We show that the model's predictions match relatively well the joint evolution of population density and land values over time and space. Using novel cross-sectional data on local farmland values, we find that cities surrounded by high farmland values are relatively denser—a prediction at the heart of our mechanisms. Quantitatively, the elasticity of urban density with respect to the farmland price found in the data is in line with its model counterpart. We also disentangle the relative importance of falling commuting costs relative to our novel mechanism based on structural change in explaining the persistent decline in urban density, emphasizing further the quantitative importance of improvements in agricultural productivity for the expansion of cities.

Related literature. The paper relates to several strands of literature in macroeconomics and spatial economics. From a macro perspective, it relates to the literature linking productivity changes and land values, starting with Ricardo (1817). This traditional view would imply that a fixed factor such as land should continuously rise in value with economic development (see, among others, Nichols (1970) and Grossman and Steger (2017) for a recent contribution). However, such a prediction would not fit well the measurement of housing prices and land values over a long period as in Piketty and Zucman (2014) and Knoll et al. (2017) (see also Davis and Heathcote (2007) for related U.S. evidence). An alternative view developed in Miles and Sefton (2020) argues that the rise in land and housing prices can be mitigated by improvements in commuting technologies, which allow cities to expand outwards. Our approach, in the tradition of the theory of structural change, also argues that land used to be scarce and valuable while agricultural productivity was low, but that improvements in technology alleviate pressure on land, decreasing its value. In a sense, our theory reconciles these different views in a unified framework. From a theoretical perspective, we contribute to the literature on structural change, surveyed in Herrendorf et al. (2014), by considering a spatial dimension—adding endogenous land use and a housing sector—in the most conventional multi-sector model with non-homothetic preferences (Kongsamut et al. (2001), Gollin et al. (2007), Herrendorf et al. (2013), Boppart (2014), Comin et al. (2021), Alder et al. (2021)). Structural change and urbanization are known to be tightly linked (Lewis (1954)). Gollin et al. (2016) shows that not only economic development but also natural resources rents lead to urbanization. However, the literature has rarely investigated the spatial dimension of structural change, largely abstracting from spatial frictions. Michaels et al. (2012), Eckert and Peters (2022) and Budí-Ors and Pijoan-Mas (2022) are notable exceptions. The crucial difference to those is the ability of our framework to replicate the evolution of population density within locations, putting emphasis on the internal structure and density of cities, while their focus is more on the distribution of population and the sectoral specialization across regions. We also emphasize the implications for land values across time and space, largely absent in these studies. We also show how commuting frictions and location-specific land values generate a sizeable wedge between the workers marginal productivities in the rural and urban sector, an 'agricultural productivity gap' (Gollin et al. (2014))—a complementary explanation to urban-rural wage gaps, different from migration costs or selection of migrants towards cities (Restuccia et al. (2008), Lagakos and Waugh (2013), Young (2013)).

Our paper also contributes to the literature in spatial economics on urban expansion surveyed in Duranton and Puga (2014, 2015). An important feature is the presence of commuting frictions shaping the population density across space (Alonso et al. (1964); Muth (1969); Mills (1967)). We expand this literature by adding endogenous sectoral allocation of factors and a general equilibrium structure at the heart of the macro literature. Importantly, and contrary to the bare bones urban monocentric model, land is in fixed supply and the price of land at the boundary of the city becomes an endogenous object which is itself affected by the process of structural change. The most related work to our approach developed in Brueckner (1990) shows how location-specific land values pin down rural-urban migrations and the extent of urbanization in a spatial equilibrium (see also Brueckner and Lall (2015) for a survey). However, without the drivers of structural change and endogenous land values at the urban fringe as in our framework, this approach stays relatively silent regarding the long-run dynamics of urbanization and land values. In this latter dimension, our work relates to the literature measuring and explaining land values across space (see Glaeser et al. (2005), Albouy (2016), Albouy et al. (2018) and Combes et al. (2018) for recent contributions). In particular, we show that the dispersion of land values across space and the scarcity of land in some locations depend very much on the extent of economic development and structural change. Our approach also provides an alternative mechanism generating substantial sprawling of cities in line with economic development. More specifically, it explains why, over time, most cities expand faster in area than in population as documented on a global scale by Angel et al. (2010). In the French context, we also relate to the historical measurement of urban land use in Combes et al. (2021). Our story is complementary to the usual explanations based on the improvement of commuting technologies and/or the relocation of economic activity within cities (see references in Glaeser and Kahn (2004) and Heblich et al. (2018), Redding (2021) for recent contributions). Lastly, our paper contributes to the literature on quantitative spatial economics surveyed in Redding and Rossi-Hansberg (2017) (see also Ahlfeldt et al. (2015)) by emphasizing the extensive margin of cities.

The paper is organized as follows. Section 2 provides motivating empirical evidence on land use, land values, urban expansion and population density across space over a long period in France. Section 3 provides a baseline spatial general equilibrium model of land use and structural change which enlightens the main mechanisms. Section 4 develops a quantitative version calibrated to French historical data. Section 5 concludes.

2 Historical Evidence from France

2.1 Land use and Employment in Agriculture

Data. Using various sources described in Appendix A, we assemble aggregate data on employment shares in agriculture and agricultural land use in France since 1840. Historical data on land use in agriculture are available roughly every 30 years (or less) until the 1980s and then at higher frequency. They are largely extracted from secondary sources based on the Agricultural Census (Recensement Agricole), and cross-checked with various alternative historical sources (Toutain (1993) among others). Post-1950, data are from the Ministry of Agriculture.

Employment. As all countries going through structural transformation, France exhibits significant reallocation of labor away from agriculture over the period, from about 60% employed in agriculture in 1840 to about 2.5% today (Figure 1). The process of structural change accelerated significantly over the period 1945-1975: in 1945, 36% of the working population are still in agriculture and this number falls below 10% in 1975. In this sense, France is somewhat peculiar relative to the other advanced economies: it is still a largely agrarian economy right after World War II—much more than the U.K. or the U.S. This measurement is described in detail in Appendix A.1.2.

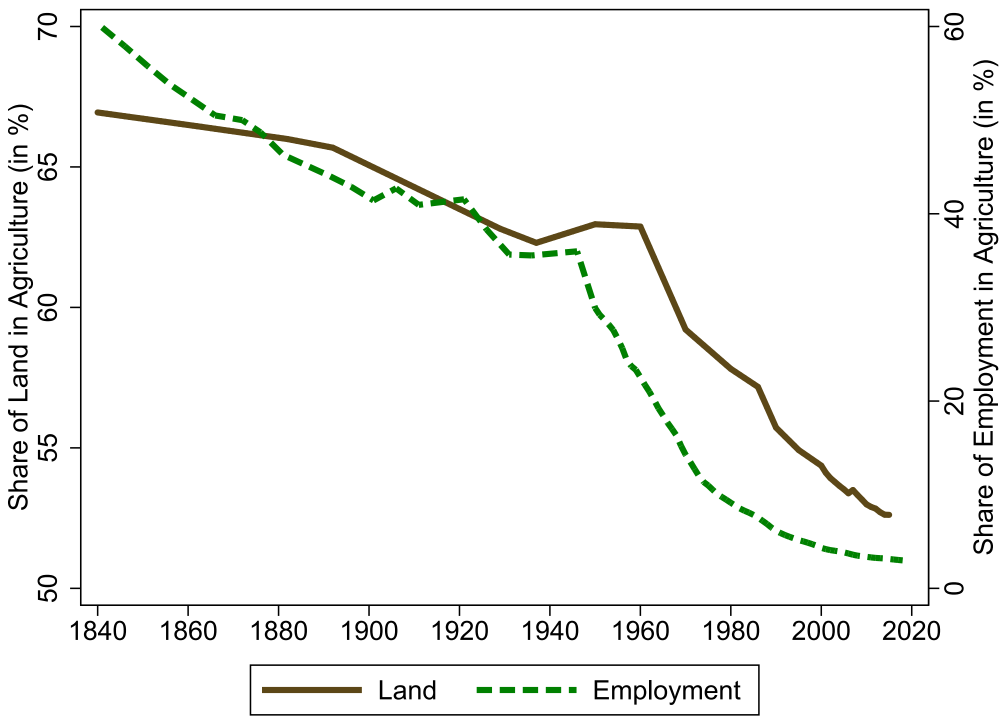


Figure 1: Land use and labor reallocation in France (1840-2015).

Notes: The solid line shows the share of French land used for agriculture (left axis). The dashed line shows the share of workers in the agricultural sector (right axis). *Source*: See Appendix A.1.1.

Land use. Although measurement is sometimes difficult for the very early periods, one can confidently argue that, in the aggregate, the share of French land used for agriculture fell significantly since 1840 (Figure 1).[1] Our preferred estimates are that about two thirds of French land was used for agriculture in 1840. In 2015, this number decreased to 52%. In other words, about 15% of French land use has been reallocated away from agriculture since 1840. While this might not seem quantitatively important, it is substantial from the perspective of urban expansion. 15% of the French territory is actually more than the total amount of land with artificial use in France nowadays, which is about 9% of total land. While it is difficult to assess with certainty what usage former agricultural land has been put to over such a long period, it is likely that a significant fraction of this land has been artificialized, allowing cities to expand. More precise data on land use over the period 1982-2015 show that the surface of artificialized soil increased by about 2 million hectares, or 3.7% of the French territory. This represents roughly 70% of the quantity of land converted away from agriculture over the same period.[2] The measurement of cities area (presented below) provides

[1] The main issue is the definition of agricultural land. Forests were part of agricultural land in the 19th century but not later. Given their use as natural amenity, we exclude them throughout even though forest exploitation for wood production is arguably of agricultural nature. The allocation of grazing fields is also not entirely consistent across years before World War II. See Appendix A.1.1 for details.

[2] Since 1982, data on land use beyond agricultural land use are available on a regular basis from the Enquêtes Teruti and Teruti-Lucas. The rest of agricultural land is to a large extent converted into forests and woods. Forests were accounting for about 18% of French land in 1882 (Agricultural Census) compared to about 30% in 2015 (Enquête Teruti-Lucas)—growing out of agricultural land but also rocky land, moors and sparse vegetation areas.

further compelling evidence that a significant fraction of agricultural land was reallocated towards urban land use. Data on agricultural land use are detailed in Appendix A.1.1.

2.2 Urban Expansion

Data. We use historical maps, aerial photographs and satellite data to measure the area of the main French cities at different dates: 1866 (military maps, e.g. carte d'Etat Major), 1950 (maps and/or photographs), and every ten to fifteen years after 1975 using satellite data from the Global Human Settlement Layer (GHSL) project. One caveat is that we cannot have any area measurement between 1866 and 1950. Data and procedure for the measurement of urban extent across French cities are detailed in Appendix A.2. Measurement of the urban extent using maps in 1866 and 1950 is performed for the 100 most populated cities in the initial period. For a given city, the urban extent ends when the land is not continuously built upon. For the satellite data, it is delimited by grid cells where the fraction of built up land is below 30% and a requirement that cells are connected.[3] By way of example, Figures A.7 and A.8 in Appendix A.2.1 show the area measurement for a medium-size French city, Reims, in 1866 and 1950 using maps. Figure A.18 shows the same city in 2016 viewed from the sky, with an area of about 57 km^2—about 20 times larger than its 1866 counterpart. This last figure also clearly shows how the city is surrounded by agricultural land—a crucial element for our story where urban land expands out of farmland. This feature is not specific to Reims. Recent satellite observations from the Corine Land Cover project—detailed in Appendix A.3.1—show that our sample of cities is surrounded mainly by agricultural land: apart from their coastal part and water bodies, two thirds of land use in the near surroundings of cities is agricultural.[4]

Using Census data, we relate the measured land area occupied by cities to the corresponding population. Data for the first available Census in 1876 are used for the initial period of study. Census data defines population at the municipality level ('commune') and an urban area can incorporate more than one municipality. In 1876, this is not a concern as the main 'commune' of the city is the whole city population. In later periods, one needs to group municipalities into an urban area. Post 1975, GHSL data combines satellite images with Census data on population. This directly provides the population of every grid cell of our measured urban area, circumventing the issue. However, for the 1950 period in between, the different municipalities that are part of our measured areas must be selected. This is done on a case by case basis, looking at the map of each of the 100 largest urban areas. This way, we make sure that the population of the area incorporates all the corresponding

[3]For maps/photos, the urban fringe is visible by a stark color change between the built and non-built part. For the satellite data, measurement is not very sensitive to alternative built up thresholds (see Appendix A.2.5). Figures A.11 and A.12 in the same Appendix illustrate how GHSL data are used to delineate the urban boundaries of Marseille and Bordeaux. While measurement error when delineating the urban area is unavoidable at the city level (some farmland might be included or some urban detached-houses with a large garden excluded), it is less of an issue when averaging across the 100 cities. We also double-check the quality of photo/map measurement in the most recent period relative to satellite data measurement (see Appendix A.2.5). The cross-sectional correlation between both measures is very high. We also cross check our measures with Angel et al. (2010) for Paris and find very similar results.

[4]The rest is made of forest/moors and discontinuous urban land (e.g. leisure/transport infrastructure, industrial/commercial sites, ...)—both categories in roughly equal proportions. See details in Appendix A.3.1.

municipalities' population. The procedure is detailed and discussed in Appendix A.2.2.[5]

The area and population of French cities. Not surprisingly, more populated cities are larger in area at a given date. However, in the cross-section, the urban area increases strictly less than one for one with urban population: more populated cities are denser on average.[6] This stands in contrast with their evolution in the time-series. Over time, cities have been increasing much faster in area than in population. Let us give some order of magnitude and describe the average evolution over time for the 100 most populated French cities in 1876. Figure 2 shows the evolution of total area and population of these 100 cities over the period considered—both variables being normalized to 1 to show the increase in size. Since 1870, the area of cities has been multiplied by a factor close to 30 on average. This is a substantial increase. Between 1870 and 1950, the area of cities was roughly multiplied by a factor of 6. Between 1950 and today, the area of cities was multiplied again by a factor of 5 on average—the fastest rate of increase being observed over the period 1950-1975. For comparison, the population of these cities has been multiplied by a factor close to 4 since 1870.[7] As urban area increased at a much faster rate than urban population, the average urban density significantly declined over the period.

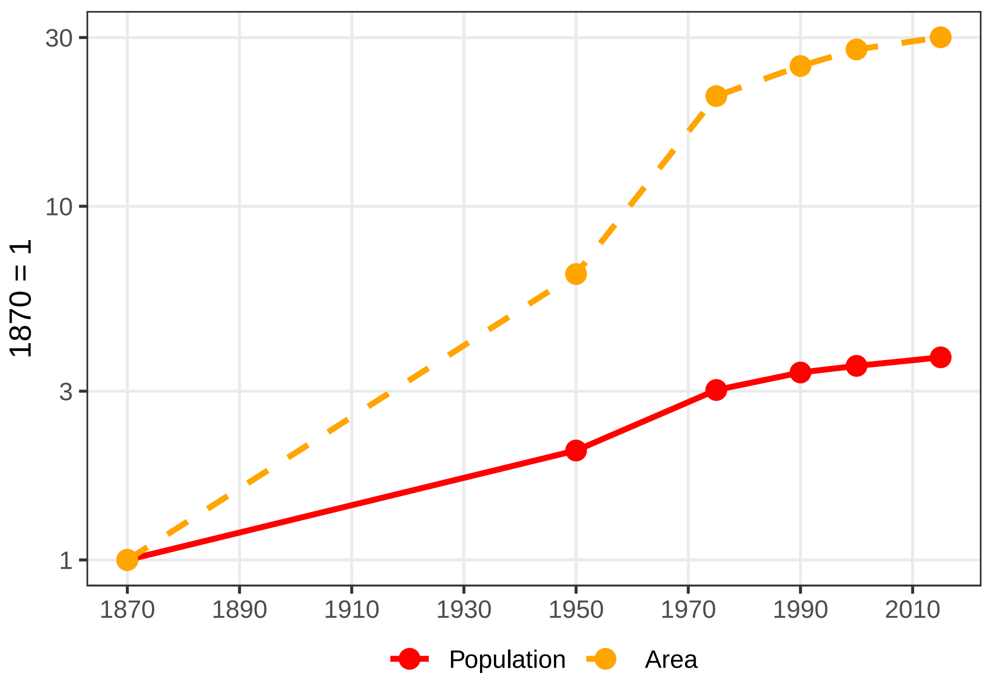


Figure 2: Urban area and population of the 100 largest cities in France (1870-2015).

Notes: The dashed line shows the total urban area of the 100 cities relative to the initial period (sum of all the urban areas) . The bottom solid line shows the total population relative to the initial period in the same cities. Both area and population are normalized to unity in the initial period. *Source*: See Appendix A.2.

[5] In 1950, only the largest cities, particularly Paris, are the result of the agglomeration of several 'communes'.

[6] In the cross-section, at a given date, a 10% increase in the population of a city corresponds to approximately a 8.5% increase in its area and this elasticity varies fairly little across the different time periods.

[7] French population was multiplied by a bit less than 2 over the entire period. Due to the reallocation of people way from rural areas towards cities, we get roughly a factor 4 over the period.

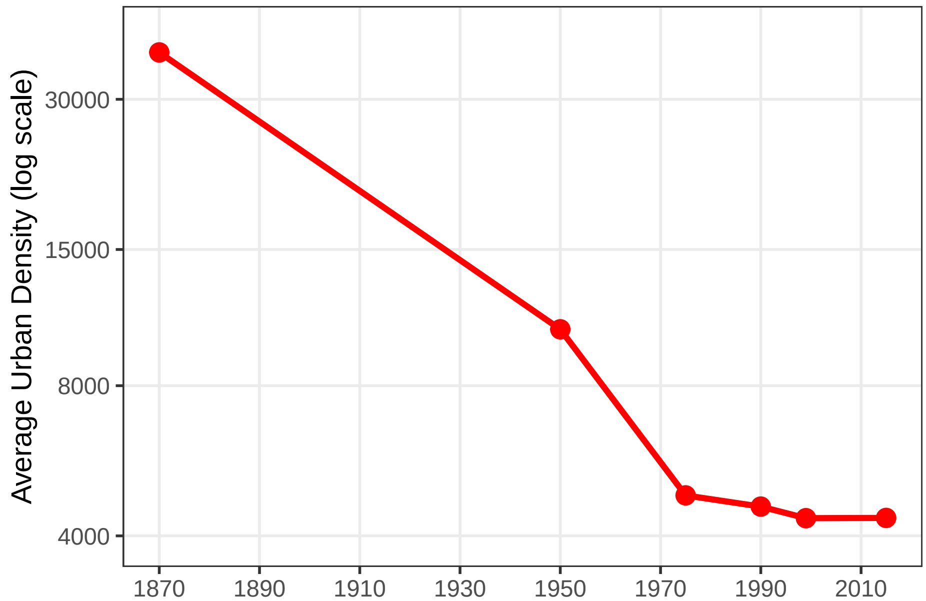


Figure 3: The historical decline in urban density.

Notes: The solid line shows the urban density averaged across the top 100 French cities (weighted average with 1975 population weights). *Source*: Etat major, IGN, GHSL and Census. See Appendix A.2 for details.

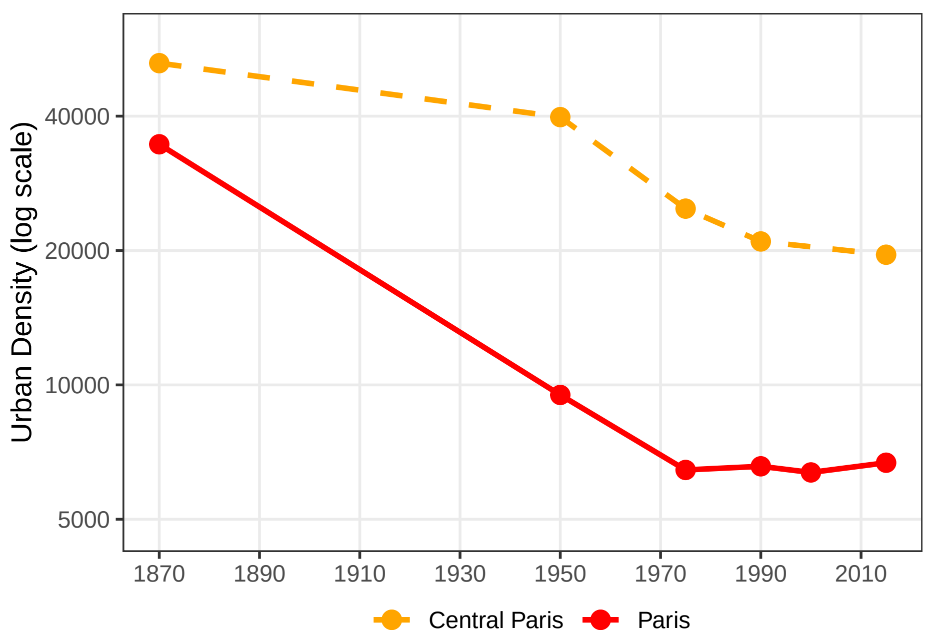


Figure 4: The historical decline in urban and central density in Paris.

Notes: The solid line shows the average urban density in Paris; the dashed line shows the density in Central Paris (districts 1 to 6). *Source*: Etat major, IGN, GHSL and Census.

The density of French cities. Using population and area of cities at the different dates, one can measure the evolution of urban densities across the different cities over 150 years. While in the cross-section larger cities are denser, the density of French cities declined over time—area expanding at a faster rate than population. This is shown in Figure 3 for the population-weighted average of density across the 100 largest French cities. The average urban density fell massively over the period: it has been divided by a factor of roughly 8. Urban density fell at the fastest rate over the period 1950-1975 and barely falls thereafter. Thus, urban density fell the most over the period when people massively left rural areas and the employment share in agriculture fell the most. The later slowdown of the decline in density coincides with the slowdown in the rate of structural change.

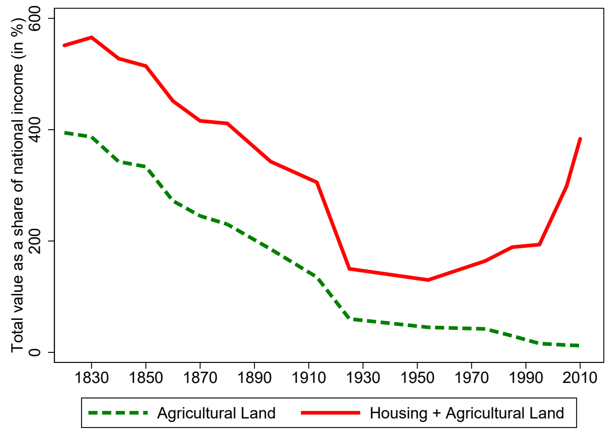
Ideally, one would like to explore how density evolved in different locations of a city (within-city variations). This would provide information on whether density fell in the central locations or in the outskirts of the city. Unfortunately, for most cities we are not able to differentiate the central density to the suburban one as most cities expand the area of their main historical 'commune', particularly so over the period 1870-1950. Thus, we cannot measure the historical population in different parts of a city. However, it can be done for Paris which is divided into several districts. Figure 4 shows the evolution of the density of Central Paris relative to the average urban density of the metropolitan area: the central density of Paris did fall over time but significantly less than the average density of the city. This suggests that the decline in average urban density is not only due to a reallocation of urban residents away from dense centers but also due to the addition of less and less dense suburban areas at the city fringe over time.

2.3 Land values

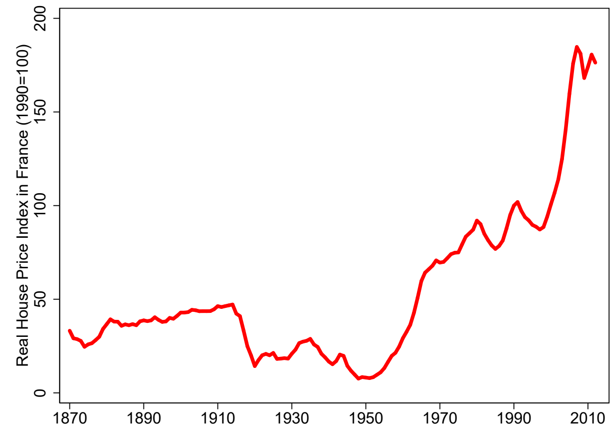
Data. Data on land and housing values (over income) for France over a long period can be found in Piketty and Zucman (2014).[8] Historical data for the real housing price index for France are provided in Knoll et al. (2017).

Historical evolution. Figure 5a describes the evolution of the aggregate value of French land over income since 1820. The fall in the value of housing and land wealth (as a share of income) in the pre-World War II period is essentially driven by a declining value of farmland. While farmland was expensive relative to income in the nineteenth century, today it is relatively cheap. This is confirmed by data on average farmland prices: since 1850, the average value of an agricultural field (per unit of land) as a share of per capita income has been divided by a factor of 15 in France. This fact is at the heart of our story: structural change puts downward pressure on farmland values—allowing cities to expand at a fast rate. As a consequence, there is an important reallocation of land values across usage, from agricultural land towards housing (or urban) land. While the value of agricultural land accounted for more than 70% of housing and land wealth in 1820, it accounts for only 3% in 2010. Lastly, despite the falling value of farmland as a share of income, the total

[8] Using various data sources, we also computed a measure of farmland prices per unit of land. Our estimates are consistent with Piketty and Zucman (2014).



(a) Agricultural Land and Housing Wealth.



(b) Real House Price Index.

Figure 5: Land and Housing Values in France.

Notes: The left plot shows agricultural wealth as a share of French national income in % (dashed) and the sum of agricultural and housing wealth as a share of national income in % (solid). The right plot shows the housing price index deflated by the CPI. Data are from Piketty and Zucman (2014) (panel 5a) and Knoll et al. (2017) (panel 5b).

value of housing and land wealth (as a share of income) grows at an increasing rate after 1950.

This steep increase, arguably driven by the increasing value of urban land where most of the population is concentrated, echoes the findings of Knoll et al. (2017).[9] They show that for developed countries, including France, housing prices have been quite stable until the 1950s before rising at an increasing pace—a *hockey-stick* shape of housing prices as shown in Figure 5b.

To sum-up, our historical data shows a set of salient facts over the last 180 years: beyond the well-known reallocation of labor away from agriculture, land has been reallocated away from agricultural use. Migrations away from the rural areas were accompanied with urban expansion both in area and population. However, given that urban area grew at a significantly faster pace than urban population, the average urban density massively declined over the period, particularly so in the decades following World War II. Together with this process of structural change, the value of farmland as a share of income shrank significantly to the benefit of non-agricultural (urban) land.

These stylized facts motivate our subsequent theoretical analysis where we introduce a spatial dimension together with endogenous land use to the most standard theory of structural change with non-homothetic preferences.

3 A Baseline Theory

We present the baseline spatial equilibrium model to highlight the main mechanisms. After presenting the environment, we derive the equilibrium conditions and define the equilibrium formally.

[9] Bonnet et al. (2019) show that this increase in the price of housing is largely driven by the price of land and not by the capital and structure component.

3.1 Environment Description

We consider an economy producing an urban good (u) and a rural good (r). The urban good is thought of as a composite of manufacturing goods and services, while the rural good represents an agricultural good. The urban good is also used in the production of housing services. Goods and factor markets are perfectly competitive. Both goods are perfectly tradable.

Factor Endowments. The economy is endowed with land and a continuum of ex-ante identical workers, both in fixed supply. Each worker is endowed with one unit of labor and we denote by L the total population of workers. Land area is denoted S. Land can be used to produce the rural good or for residential purposes. The production of the urban good takes place in the city, while the production of the rural good, being more land intensive, takes place in the rural area. We assume that production of the urban good takes place in only one location $\ell = 0$, which is similar to the Central Business District (CBD) in a standard urban model, where space is given by the interval $[0, S]$. Workers' residence ℓ can lie anywhere in the interval $[0, S]$.

Technology. The production of the urban good only uses labor as input. One unit of labor produces θ_u units of the urban good

$$Y_u = \theta_u L_u,$$

where L_u denotes the number of workers working in the urban sector.

The production of the rural good uses labor and land according to the following constant returns to scale technology,

$$Y_r = \theta_r (L_r)^\alpha (S_r)^{1-\alpha},$$

where L_r denotes the number of workers in the rural sector, S_r the amount of land used for production and θ_r a Hicks-neutral productivity parameter. $0 < \alpha < 1$ is the intensity of labor use.

Remark. The important technology assumption is that the rural sector is more land intensive than the urban one, $1 - \alpha > 0$, implying stronger decreasing returns to scale to labor in this sector.

The production of housing space is provided by land developers, which can use more or less intensively the land for residential purposes. In each location ℓ, developers supply housing space $H(\ell)$ per unit of land with a convex cost, $\frac{H(\ell)^{1+1/\epsilon}}{1+1/\epsilon}$ with $\epsilon > 0$, paid in units of the numeraire.[10]

Preferences. Preferences over urban and rural goods are non-homothetic as in Kongsamut et al. (2001) and Herrendorf et al. (2013) among others. Consider a worker living in a location ℓ. Denote $c_r(\ell)$ the consumption of rural (agricultural) goods, $c_u(\ell)$ the consumption of urban goods (used a numeraire) and $h(\ell)$ the consumption of housing. The composite consumption good is

$$C(\ell) = \left(c_r(\ell) - \underline{c}\right)^{\nu(1-\gamma)} \left(c_u(\ell) + \underline{s}\right)^{(1-\nu)(1-\gamma)} h(\ell)^\gamma \tag{1}$$

[10] The urban good is used as an intermediary input for the production of housing space. Some equivalent formulation holds for a Cobb-Douglas production function of housing (see Combes et al. (2018)).

where $\underline{c}$ denotes the minimum consumption level for the rural good, and where $\underline{s}$ stands for the initial endowment of the urban good. Preference parameters ν and γ belong to $(0, 1)$. Workers derive utility only from consumption. The utility of a household in location ℓ is equivalent to $C(\ell)$.

Spatial Structure. Workers face spatial frictions $\tau(\ell)$ when commuting to work in the urban sector. A worker residing in location ℓ and working in the urban sector earns a wage *net of spatial frictions* equal to $w(\ell) = w_u - \tau(\ell)$, with w_u denoting the urban wage, $\tau(0) = 0$, and $\partial\tau(\ell)/\partial\ell \geq 0$. The commuting cost $\tau(\ell)$ incorporates all spatial frictions which lower disposable income available for consumption when living further away from the location of production. It includes time-costs of commuting as well as the effective spending on transportation.

Since spatial frictions increase with ℓ, urban workers locate as close as possible to $\ell = 0$. If one denotes $\ell = \phi < S$ the furthest away location of an urban worker, ϕ is endogenous in our framework and represents the fringe of the city. Workers residing in locations beyond ϕ produce the rural good, which does not involve spatial frictions, as rural workers do not commute.

As described in detail in Section 3.2, the commuting cost, $\tau(\ell)$, is partly endogenous in our framework, because urban households adjust their mode of commuting m depending on their location ℓ and opportunity cost of time (wage rate w_u). We use the functional form $\tau(\ell) = a \cdot (w_u \ell)^{\xi}$, $a > 0$ and $\xi \in (0, 1)$, for which we provide a micro-foundation through this commuting choice model. This modeling approach helps mapping commuting costs into observables from commuting data but results do not depend qualitatively on the micro-foundation as long as commuting costs are increasing and concave in the opportunity cost of time and commuting distance.

Remarks. The spatial structure calls for a number of important remarks. First, if it were possible for all workers to locate at $\ell = 0$, there would be no spatial frictions. Second, one should note that for $\ell \leq \phi$, land will be used for residential purposes to host urban workers. As a consequence, land available for rural production would also be maximized if all workers could locate at $\ell = 0$. This case would correspond to an entirely 'vertical' city, where land use and spatial frictions are irrelevant. We view this extreme case as a standard two-sector model of structural transformation. Last, the spatial frictions $\tau(\ell)$ do not involve traffic congestion in the baseline economy.

3.2 Household Optimization Conditions

We consider ex-ante identical workers simultaneously choosing their consumption expenditures, their location, and their commuting mode taking all prices as given.

Commuting Choice Optimization. Commuting costs in location ℓ, $\tau(\ell)$, are the sum of spending on commuting using transport mode m, $f(m)$, and time-costs proportional to $w_u \cdot t(\ell)$, where $t(\ell)$ denotes the time spent on daily commutes of an individual located in ℓ, such that

$$\tau(\ell) = f(m) + \zeta w_u \cdot t(\ell), \tag{2}$$

where $0 < \zeta \leq 1$ represents the valuation of commuting time in terms of foregone wages. Transportation modes m are continuously ordered by their speed, as in DeSalvo and Huq (1996), such that m denotes both the mode and the speed of commute. The commuting time (both ways) is therefore, $t(\ell) = \frac{2\ell}{m}$. Faster commutes are more expensive and $f(m)$ is increasing in m. For tractability, we use the following functional form, $f(m) = \frac{c_\tau}{\eta_m} m^{\eta_m}$, with $\eta_m > 0$ and c_τ a cost parameter measuring the efficiency of the commuting technology. This expression for commuting costs facilitates parametrization and preserves some tractability, while elucidating the main mechanisms.[11]

At any given moment in time, prevailing technology offers different transportation modes ordered by their respective speed m. An individual in location ℓ chooses the mode of transportation of speed m in order to minimize the commuting costs $\tau(\ell)$. By equalizing the marginal cost of a higher speed m to its marginal benefits in terms foregone wage, the optimal chosen mode/speed satisfies,

$$m = \left(\frac{2\zeta w_u}{c_\tau}\right)^{1-\xi} \cdot \ell^{1-\xi}, \tag{3}$$

where $\xi \equiv \frac{\eta_m}{1+\eta_m} \in (0, 1)$. Individuals living further away choose faster commuting modes. The speed of commuting also increases with the wage rate as a higher wage increases the opportunity cost of time. Using Equations (2) and (3), we get that equilibrium commuting costs satisfy,

$$\tau(\ell) = a \cdot (w_u \ell)^{\xi}, \tag{4}$$

where $a \equiv \left(\frac{1+\eta_m}{\eta_m}\right) c_\tau^{\frac{1}{1+\eta_m}} (2\zeta)^{\frac{\eta_m}{1+\eta_m}} > 0$. Commuting costs increase with the wage rate (the opportunity cost of time) and the commuting distance with constant elasticities.[12] Since individuals optimally choose the commuting speed, the elasticity ξ of commuting costs to the wage rate is strictly smaller than unity. This is important as it implies that, for a given residential location, the share of resources devoted to commuting falls with rising urban productivity and wages. In equilibrium, this makes individuals willing to live further away in order to enjoy larger homes. This is the channel through which rising urban productivity leads to faster commutes and suburbanization. Our derivation of commuting costs also enlightens the calibration as the elasticity of commuting costs to commuting distance (resp. income) is directly tied to the elasticity of commuting speed to commuting distance (resp. income), which have data counterparts (Equation (3)).

Budget Constraint and Expenditures. Consumers earn a wage income net of spatial frictions $w(\ell)$ in location ℓ. Given the spatial structure, $w(\ell) = w_u - \tau(\ell)$ for $\ell \leq \phi$ and $w(\ell) = w_r$ for

[11]The cost $f(m)$ has several possible interpretations. At a more macro level, it can represent the fixed cost of installing public transportation, where a faster mode is more expensive (a train line versus the horse drawn omnibus). At a more individual level, it represents the cost of buying an individual mean of transportation—a bike being cheaper than an automobile. However, this reduced-form approach sets aside the possibility that the implemented commuting technologies and their speed depend in a more sophisticated way on the equilibrium allocation in the city (e.g. traffic congestion or the construction of transport infrastructures may depend on the spatial allocation of urban residents).

[12]Commuting costs also fall with a better commuting technology (lower a). a is alike a relative price of commuting: if technology improves relatively faster in the commuting sector, the relative price a (in terms of urban goods) falls. Our baseline simulations will hold a fixed focusing on urban productivity as the main driver of faster commutes.

$\ell > \phi$, where w_r denotes the wage rate in the rural sector. Consumers also earn land rents, r. Land rents are redistributed lump-sum equally and are thus assumed to be independent of location. The budget constraint of a worker in location ℓ satisfies

$$pc_r(\ell) + c_u(\ell) + q(\ell)h(\ell) = w(\ell) + r, \tag{5}$$

with $q(\ell)$ the rental price per unit of housing (henceforth the housing price) in location ℓ.

Maximizing utility (Equation (1)) subject to the budget constraint (Equation (5)) yields the following consumption expenditures,

$$pc_r(\ell) = (1-\gamma)\nu(w(\ell) + r + \underline{s} - p\underline{c}) + p\underline{c} \tag{6}$$

$$c_u(\ell) = (1-\gamma)(1-\nu)(w(\ell) + r + \underline{s} - p\underline{c}) - \underline{s} \tag{7}$$

$$q(\ell)h(\ell) = \gamma(w(\ell) + r + \underline{s} - p\underline{c}). \tag{8}$$

Due to the presence of subsistence needs ($\underline{c} > 0$), individuals reallocate consumption away from the rural good with rising income, increasing the consumption share of the urban good and housing. The reallocation of demand towards the urban good is stronger when $\underline{s} > 0$.

Mobility Equations and Sorting. Since the rural and the urban good are perfectly tradable, urban workers, which would all prefer locations closer to $\ell = 0$, compete for these locations. Adjustment of housing prices through the price of land makes sure that households remain indifferent across different locations. Using Equations (6)-(8), this implies the following mobility Equation, where consumption is equalized to $\overline{C}$ across locations ℓ,

$$\overline{C} = C(\ell) = \kappa \frac{w(\ell) + r + \underline{s} - p\underline{c}}{q(\ell)^\gamma}, \tag{9}$$

with κ constant across locations, equal to $((1-\gamma)\nu)^{(1-\gamma)\nu}((1-\gamma)(1-\nu))^{(1-\gamma)(1-\nu)}\gamma^\gamma/p^{\nu(1-\gamma)}$.

The mobility Equation (9) implies that $\left(\frac{w(\ell)+r+\underline{s}-p\underline{c}}{q(\ell)^\gamma}\right)$ is constant across locations. This holds within urban locations ($\ell \leq \phi$), within (identical) rural locations as well as when comparing an urban and rural worker. Since workers in the rural sector do not face spatial frictions and live in ex-post identical locations, $\ell \geq \phi$, the price of housing must be the same across these locations. We denote by q_r the price of housing in the rural sector, where $q_r = q(\ell \geq \phi)$. A worker in the rural sector earns a wage w_r, receives land rents r and faces the same housing price $q_r = q(\phi)$ than an urban worker at the fringe. Therefore we have

$$w(\phi) = w_r = w_u - \tau(\phi). \tag{10}$$

In other words, the urban worker at the urban fringe must have the same wage net of commuting frictions than a rural worker—commuting frictions generating an urban-rural wage gap. Equation (10) is essential to understand the spatial allocation of workers: higher spatial frictions at the fringe

ϕ reduce incentives of rural households to move to the city.

Within city locations ($\ell \leq \phi$), the housing price adjusts such that workers are indifferent across locations. Using Equations (9) and (10), we get a housing rental price gradient:

$$q(\ell) = q_r \left(\frac{w(\ell) + r + \underline{s} - p\underline{c}}{w(\phi) + r + \underline{s} - p\underline{c}} \right)^{1/\gamma} = q_r \left(\frac{w(\ell) + r + \underline{s} - p\underline{c}}{w_r + r + \underline{s} - p\underline{c}} \right)^{1/\gamma}. \tag{11}$$

Within the city, $q(\ell)$ is falling with ℓ to compensate workers who live in worse locations. For ℓ above ϕ, the housing price is constant, equal to q_r. A crucial difference compared to the standard urban model is that the fringe price q_r is endogenously determined in our general equilibrium model.

3.3 Producers' Optimization Conditions

Goods' producers choose the amount of labor, and land for the rural producer, while land developers choose the supply of housing space in each location ℓ, to maximize profits, taking all prices as given.

Urban and Rural Factor Payments. Perfect competition ensures that the urban wage is

$$w_u = \theta_u, \tag{12}$$

in terms of units of the urban good, which is used as numeraire.

Rural workers and land are paid their marginal productivities. Defining p as the relative price of the rural good in terms of the numeraire urban good,

$$w_r = \alpha p \theta_r \left(\frac{S_r}{L_r} \right)^{1-\alpha}, \tag{13}$$

$$\rho_r = (1-\alpha) p \theta_r \left(\frac{L_r}{S_r} \right)^{\alpha}, \tag{14}$$

where ρ_r is the rental price of land anywhere in the rural sector.

Housing Supply. Profits per unit of land of the developers are

$$\pi(\ell) = q(\ell)H(\ell) - \frac{H(\ell)^{1+1/\epsilon}}{1+1/\epsilon} - \rho(\ell),$$

where $\rho(\ell)$ is the rental price of a unit of land in location ℓ (henceforth the land price). Maximizing profits gives the following supply of housing $H(\ell)$ in a given location ℓ,

$$H(l) = q(\ell)^{\epsilon}, \tag{15}$$

where the parameter ϵ is the price elasticity of housing supply. More convex costs to build intensively on a given plot of land reduces the supply response of housing to prices.

Residential Land Prices. Lastly, free entry implies zero profits of land developers. This pins down land prices in a given location,

$$\rho(\ell) = \frac{q(\ell)H(\ell)}{1+\epsilon} = \frac{q(\ell)^{1+\epsilon}}{1+\epsilon}. \tag{16}$$

Equation (16), together with Equation (11), implies that land prices are also higher in locations closer to the city center, more so if land developers can build more intensively (higher ϵ). And, for locations beyond the fringe ϕ, the land price is constant, $\rho_r = \rho(\ell \geq \phi)$, as for the housing price q_r.

Arbitrage across land use implies that the land price in the urban sector, $\rho(\ell)$, must in equilibrium be above the marginal productivity of land for production of the rural good (Equation (14)), where the condition holds with equality in the rural part of the economy, for $\ell \geq \phi$,

$$\rho_r = \frac{q_r^{1+\epsilon}}{1+\epsilon} = (1-\alpha)p\theta_r \left(\frac{L_r}{S_r}\right)^{\alpha}. \tag{17}$$

Importantly, this equation shows that a fall in the relative price of rural goods and/or a reallocation of workers away from the rural sector lowers the price of urban land at the city fringe.

3.4 Market Clearing Conditions

Housing Market Equilibrium. Using Equations (8) and (11), the demand for housing space per worker in each location $h(\ell)$ is increasing with ℓ for $\ell \leq \phi$,

$$h(\ell) = \gamma\left(\frac{w(\ell)+r+\underline{s}-p\underline{c}}{q(\ell)}\right) = \left(\frac{\gamma}{q_r}\right)(w(\phi)+r+\underline{s}-p\underline{c})^{1/\gamma}(w(\ell)+r+\underline{s}-p\underline{c})^{1-1/\gamma}. \tag{18}$$

Facing higher housing prices, household closer to the CBD demand less housing space. Importantly, a lower fringe price q_r and lower spending for subsistence $p\underline{c}$ increase the demand for housing space in the city. In the rural area, housing demand per rural worker is constant, $h(\ell \geq \phi) = \gamma\left(\frac{w_r+r+\underline{s}-p\underline{c}}{q_r}\right)$.

Consider first locations within the city, $\ell \leq \phi$. Market clearing for housing in each location implies $H(\ell) = D(\ell)h(\ell)$, where $D(\ell)$ denotes the density (number of urban workers) in location ℓ. Within the city, the density $D(\ell)$ follows from Equations (15) and (18), hence

$$D(\ell) = \frac{H(\ell)}{h(\ell)} = \frac{q(\ell)^{1+\epsilon}}{\gamma(w(\ell)+r+\underline{s}-p\underline{c})}. \tag{19}$$

Density for $\ell \leq \phi$ can be rewritten using Equation (11) and Equation (16) as

$$D(\ell) = \rho_r\frac{1+\epsilon}{\gamma}(w(\phi)+r+\underline{s}-p\underline{c})^{-\frac{1+\epsilon}{\gamma}}(w(\ell)+r+\underline{s}-p\underline{c})^{\frac{1+\epsilon}{\gamma}-1}. \tag{20}$$

Importantly, a lower rural land price ρ_r at the urban fringe lowers density across all urban locations.

Integrating density defined in Equation (20) across urban locations gives the total urban population,

$$L_u = \int_0^{\phi} D(\ell)d\ell = \rho_r \int_0^{\phi} \frac{1+\epsilon}{\gamma} (w(\phi) + r + \underline{s} - p\underline{c})^{-\frac{1+\epsilon}{\gamma}} (w(\ell) + r + \underline{s} - p\underline{c})^{\frac{1+\epsilon}{\gamma}-1} d\ell. \quad (21)$$

Equation (21) pins down the city size ϕ. It says that if more workers are willing to move in the urban sector, the city will have to be bigger in area to host them—ϕ is increasing with L_u.

In the rural area, $\ell \geq \phi$, market clearing for residential housing imposes

$$L_r \gamma \left(w_r + r + \underline{s} - p\underline{c}\right) = S_{hr} \left(q_r\right)^{1+\epsilon} = S_{hr}(1+\epsilon)\rho_r,$$

where S_{hr} is the amount of land demanded in the rural area for residential purposes.

Land and labor market clearing. Land is used for residential or productive purposes. With total land available in fixed supply S, the land market clearing condition is

$$S_r + S_{hr} + \phi = S \quad (22)$$

with the demand of land for housing in the rural area S_{hr} equal to $\frac{L_r\gamma(w_r+r+\underline{s}-p\underline{c})}{(1+\epsilon)\rho_r}$.

The labor market clearing is such that the total population L is located either in the city or in the rural area,

$$L_u + L_r = L. \quad (23)$$

Aggregate land rents, rL, include the land rents generated both in the city and in the rural area,

$$rL = \int_0^{\phi} \rho(\ell)d\ell + \rho_r \times (S - \phi), \quad (24)$$

where it is useful to notice that the rental income in the city exceeds the rental income of farmland for the same area due to spatial frictions.

Good markets clearing. A last step consists in clearing the goods market for rural and urban goods to pin down the allocation of labor across sectors for a given equilibrium city size ϕ.

Let us introduce y as the aggregate per capita income in the economy net of spatial frictions,

$$y = r + \frac{L_r}{L} w_r + \frac{1}{L} \int_0^{\phi} w(\ell)D(\ell)d\ell.$$

Aggregating Equations (6)-(7) across locations, we get that aggregate per capita consumption of rural good and urban good satisfy

$$\begin{aligned} pc_r &= \nu(1-\gamma)(y + \underline{s} - p\underline{c}) + p\underline{c} \\ c_u &= (1-\nu)(1-\gamma)(y + \underline{s} - p\underline{c}) - \underline{s} \end{aligned}$$

The rural good is only used for consumption. The rural good market clearing condition is,

$$\nu(1-\gamma)y + \nu(1-\gamma)(\underline{s} - p\underline{c}) + p\underline{c} = py_r, \tag{25}$$

where $y_r = \frac{Y_r}{L}$ denotes the production per worker of the rural good.

The urban good market clearing is more involved as urban goods are either consumed, used as intermediary inputs to build residential housing (in all locations) or used to pay for commuting costs. The sum of these three uses equals the supply of the urban good, expressed per capita,

$$c_u + \frac{1}{L}\int_0^{\phi} \tau(\ell)D(\ell)d\ell + \frac{1}{L}\frac{\epsilon}{1+\epsilon}\int_0^{S} q(\ell)H(\ell)d\ell = y_u, \tag{26}$$

where $y_u = \frac{Y_u}{L}$ denotes the production per worker of the urban good.

3.5 Equilibrium Definition

For a given set of exogenous parameters, technological parameters $(\theta_u, \theta_r, \alpha)$, commuting cost parameters (a, ξ) and resulting spatial frictions $\tau(\ell)$ at each location $\ell \in \mathcal{L}$, housing supply conditions ϵ, and preference parameters, $(\nu, \gamma, \underline{c}, \underline{s})$, the equilibrium is defined as follows:

Definition 1. *An equilibrium is a sectoral labor allocation (L_u, L_r), a city fringe (ϕ) and rural land used for production (S_r), sectoral wages (w_u, w_r), a rental price of farmland (ρ_r), a relative price of rural goods (p) and land rents (r), such that:*

- *Workers are indifferent in their location decisions, Equation (10).*
- *Factors are paid the marginal productivity, Equations (12)-(14).*
- *The demand for urban residential land (or the city fringe ϕ) satisfies Equation (21).*
- *Land and labor markets clear, Equations (22) and (23).*
- *Land rents satisfy Equation (24).*
- *Rural and urban goods markets clear, Equations (25) and (26).*

The main intuition for the equilibrium allocation goes as follows: if the urban sector hosts more workers, the area of the city has to be larger (ϕ tends to increase with L_u). However, if the city is larger in area, the worker in the further away urban location commutes more, making the urban sector less attractive for workers: a higher ϕ reduces the incentives of workers to move from the rural to the urban sector (L_u tends to decrease with an increasing ϕ). Given technology, the combination of these two forces pins down the allocation of workers across sectors together with the land used for urban residential housing. Since the equilibrium cannot be described analytically, we use numerical illustrations to explain the main mechanisms through which increasing productivity, in the rural and urban sectors, change the population, area and density of cities. The numerical simulations are not aiming at being a measurement tool but at elucidating the main channels at play to understand urban expansion when economies go through the process of structural change. A quantitative evaluation in the context of France is provided in Section 4.

3.6 Numerical illustrations

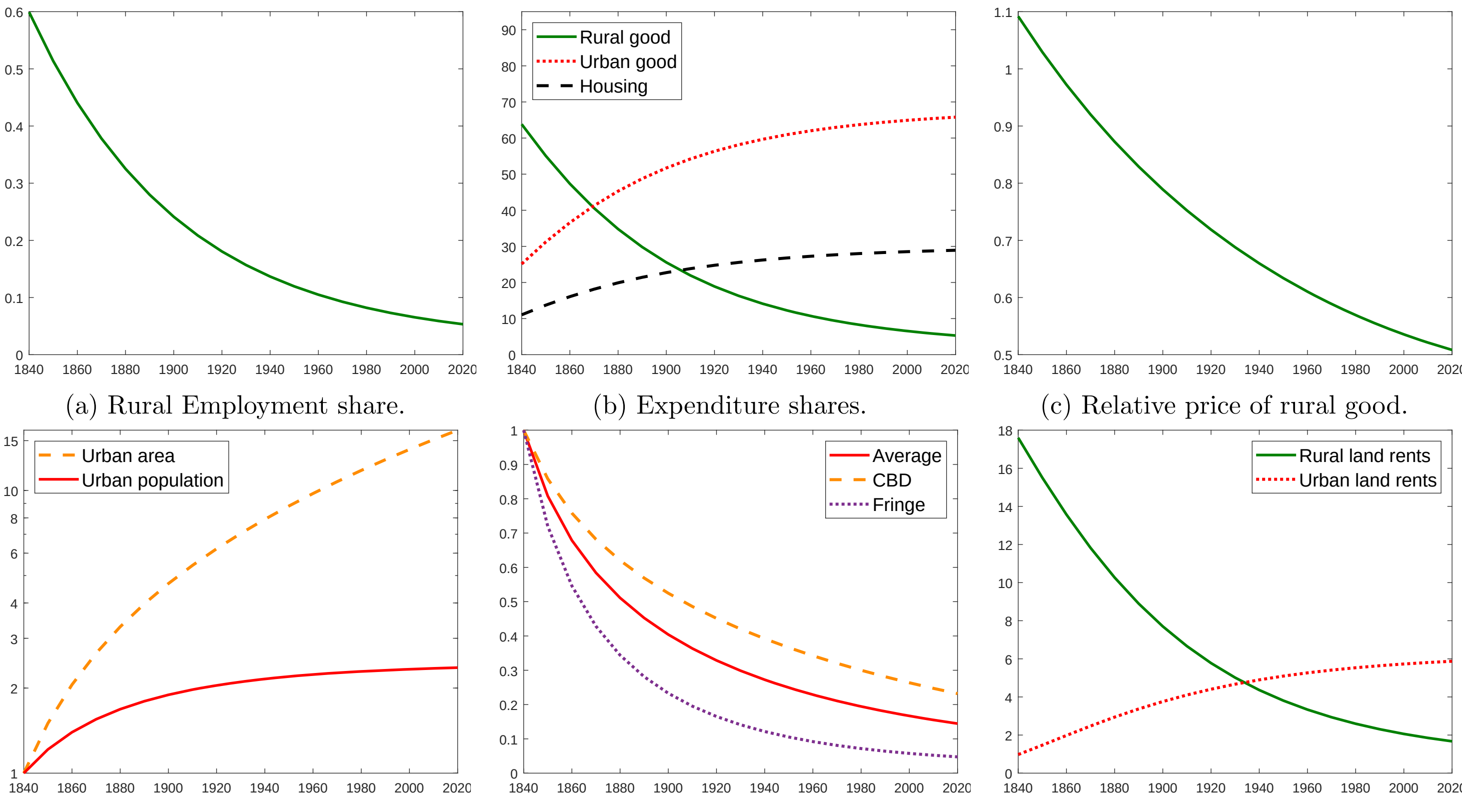
Parameter values. We consider an economy as described above endowed with land and labor, both normalized to 1. While the exercise is not quantitative, we nevertheless set parameters values in a reasonable range with respect to the data. The land intensity in rural production is set to 25% ($\alpha = 0.75$). We set the elasticity of housing supply ϵ to 4 in the range of empirical estimates. Preferences towards the different goods are set to roughly match the employment share in agriculture and the housing spending share in the recent period in France—$\nu = 2.5\%$ and $\gamma = 30\%$. At each date t, the productivity is assumed to be the same in both sectors, $\theta_{u,t} = \theta_{r,t}$, and the initial productivity is normalized to unity. Both sectors are growing at the same constant rate of productivity growth of 1.25% per annum. Most importantly, together with rising productivity, structural change emerges due to the presence of subsistence needs for rural goods, $\underline{c} = 2/3$. As we focus on subsistence needs, we set $\underline{s}$ to zero. With such preferences, the share of employment is the rural sector is about 60% at start. For comparison, we explore at a later stage the model dynamics when structural change is driven by increasing demand for urban goods rather than subsistence needs ($\underline{s} >> \underline{c}$). The values for the commuting costs parameters are set such that the urban area remains small relative to land used in agriculture, $a = 2$. The parameter determining the elasticity of commuting costs to urban income and commuting distance, ξ, is set to 2/3 to generate an increase in the average urban commuting speed comparable to the data (see Miles and Sefton (2020)).[13]

Baseline. Figure 6 summarizes the model dynamics following rising productivity in both sectors—starting at an initial period labeled 1840 for illustration purposes. The top panel shows the evolution of employment, spending shares and relative prices. As is well known in the literature, due to low initial productivity, the share of workers needed to produce rural goods is high at start to satisfy subsistence needs. The demand for rural goods for subsistence makes them initially relatively expensive and households spend a disproportionate share of income on rural goods. With rising productivity solving the 'food problem', workers move away from the rural to the urban sector, the relative price of rural goods falls, as well as the spending share towards rural goods.

The bottom panel of Figure 6 shows outcomes that are more specific to our theory with endogenous land use: urban area (compared to urban population), urban densities (average, central and fringe) and land rents (as a share of income). With structural change, urban area grows faster than urban population, leading to a fall in the average urban density (plots (d) and (e) of Figure 6). This is the outcome of two different forces. On the one hand, this is the natural consequence of *rural* productivity growth: higher rural productivity frees up farmland for cities to expand, lowering farmland rents relative to income. Moreover, as workers spend less on rural goods, they can afford

[13] The parameter a is a transformation of the commuting costs parameters but one can always set the commuting efficiency c_τ to target a given a. Regarding the parametrization of ξ, the average commuting speed in England (Miles and Sefton (2020)) or Paris (Appendix A.5.1) has been multiplied by almost 5 since 1840—in line with our experiment.

larger homes and spend relatively more on housing. The city expands outwards at a fast rate. With land at the city fringe getting cheaper (relative to income), the city expands by adding a less and less dense suburban fringe over time, contributing to the fall in average urban density (plot (e) of Figure 6). On the other hand, rising *urban* productivity leads to a reallocation of workers away from the dense center towards the fringe—contributing further to the fall in average urban density. With rising urban income, workers move towards the suburbs to enjoy larger homes despite rising opportunity cost of commuting time. This is so because they optimally choose faster commuting modes when moving towards the suburbs. Thus, although the mechanisms are entirely different, both rural and urban productivity growth contribute to urban sprawl and falling urban density.



(a) Rural Employment share. (b) Expenditure shares. (c) Relative price of rural good.

(d) City size (Index, 1840=1). (e) Urban densities (Index, 1840=1). (f) Land rents over income (%).

Figure 6: Baseline numerical illustration.

Notes: Simulation with 1.25% constant productivity growth in both sectors, $\underline{c} > 0$, and $\underline{s} = 0$.

Regarding land rents, the reallocation of workers away from agriculture and the fall in the relative price of rural goods exerts downward pressure of the price of farmland. Thus, land rents are reallocated away from the rural part towards the urban part (plot (f) of Figure 6)).

To sum up, beyond the well-known predictions regarding employment shares across sectors, our theory is able to qualitatively reproduce the salient facts described in Section 2 for France regarding the expansion of the urban area, the evolution of urban density and land values.

Rural versus urban productivity growth. To disentangle further the mechanisms at play, it is useful to investigate the model's implications when only rural or urban productivity growth occurs.

Figure 7 shows selected model outcomes with only rural productivity growth—θ_r growing at 1.25% per year, while θ_u is set to unity throughout. The qualitative implications are similar to the baseline illustration. Workers move away from the rural sector, the rural good and farmland are getting less expensive and urban density falls despite rising urban population. However, the city sprawls less: without urban productivity growth, there is less reallocation away from central locations towards the fringe. Average urban density falls mostly due to the addition of lower density habitat at the urban fringe where land gets cheaper—central density falling significantly less.

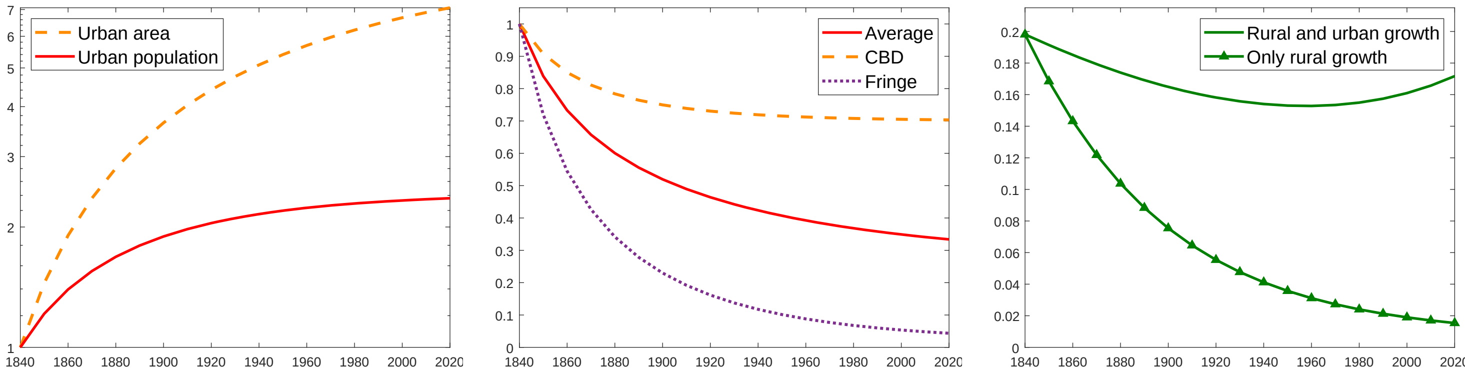
Figure 8 shows model outcomes with only urban productivity growth—θ_u growing at 1.25% per year, while θ_r is set to unity throughout (resp. a high value for comparison). Here, the qualitative differences to the baseline are more pronounced. Urban productivity growth leads to urban expansion in area but not in population: the rural workforce needs to remain large in order to satisfy subsistence needs and feed the population (plot (a) of Figure 8).[14] The city expands in area as higher urban productivity reallocates urban workers away from the center towards the urban fringe. As the demand for land at the fringe rises, so does the price: farmland is getting more expensive. This increases suburban density, mitigating the overall fall in urban density. Therefore, central density is falling more than the average one (plot (b) of Figure 8). With only urban productivity growth, rural land rents (as a share of income) do not fall and there is no reallocation of land values towards the urban areas (plot (c) of Figure 8). Thus, rising urban productivity and faster commutes are not sufficient to account for the evolution of urban densities and land rents across space.

Lastly, it is important to note that the reallocation of urban residents away from the center towards the suburbs is significantly stronger at a higher level of rural productivity. In other words, the interaction between rural and urban productivity matters for the area expansion of cities (plot (a) of Figure 8). If rural productivity is low, people spend most of their resources on rural necessity goods, limiting their ability to expand their housing space when urban productivity increases. As a consequence, rising urban productivity reallocates significantly less people towards the suburbs and cities stay dense despite higher urban wages. To the contrary, when rural productivity is high enough, rising urban productivity expands the urban area much more as urban residents afford larger housing space. In this sense, beyond the direct effect of rural productivity on urban expansion, rural productivity is also crucial as it provides the necessary incentive for people to relocate towards the city fringe and use faster commutes when urban productivity increases.

To sum up, our numerical illustrations show how, in the presence of subsistence needs, agricultural productivity growth not only matters for urbanization and the reallocation of workers away from the rural sector, but it is also essential to replicate the large historical decline in urban density, the fall in farmland prices (relative to income) and the reallocation of land rents towards urban areas.

Labor push versus labor pull. In the baseline illustration, the driver of structural change is rural productivity growth combined with subsistence needs for rural goods—a model where rising productivity frees up resources for the urban sector to expand ('rural labor push'). An alternative

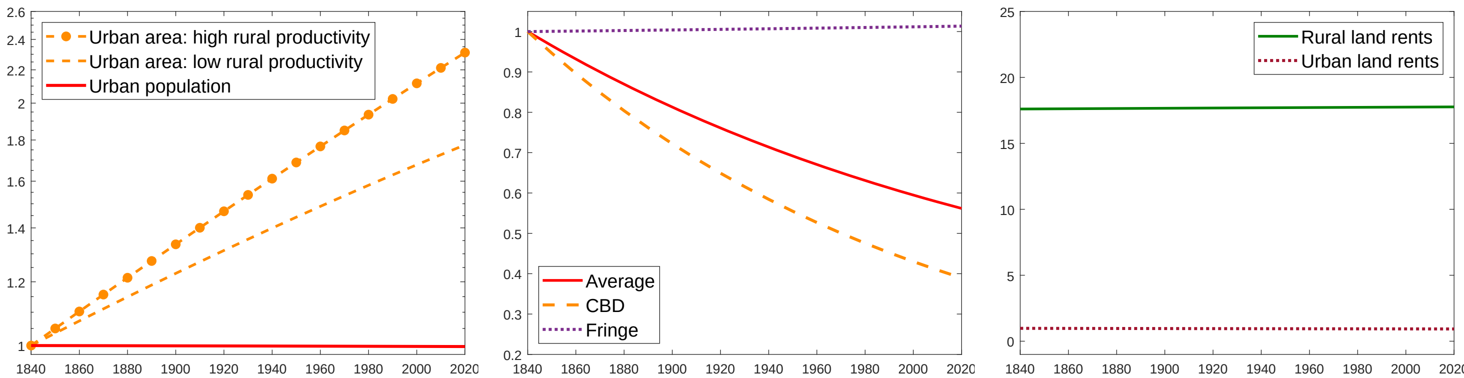
[14] Urban population may even slightly fall—producing subsistence needs with less land requiring more workers.



(a) City size (Index, 1840=1). (b) Urban densities (Index, 1840=1). (c) Farmland rental price.

Figure 7: Numerical illustration with only rural growth.

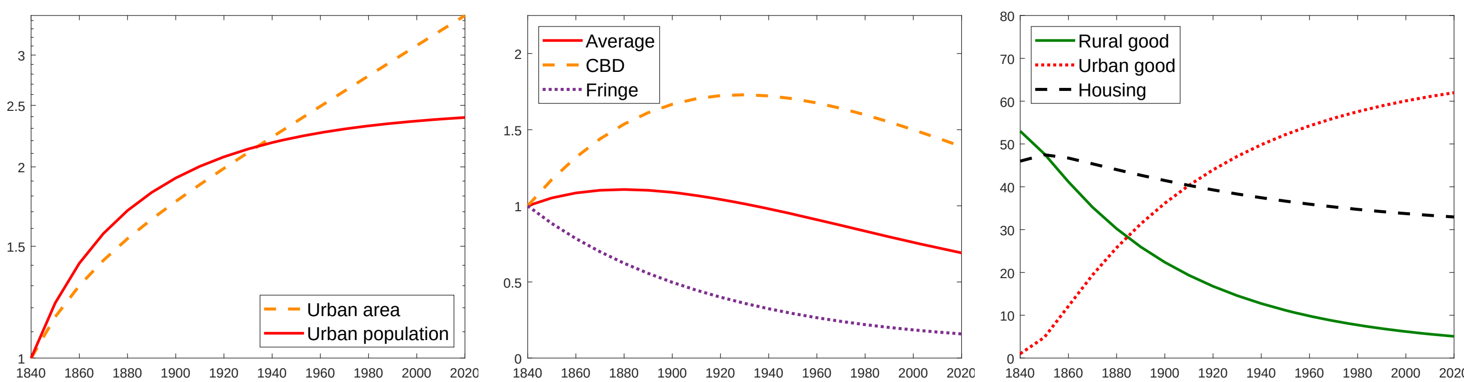
Notes: Simulation with 1.25% constant rural productivity growth and constant urban productivity; $\underline{c} > 0$ and $\underline{s} = 0$.



(a) City size (Index, 1840=1). (b) Urban densities (Index, 1840=1). (c) Land rents over income (%).

Figure 8: Numerical illustration with only urban growth.

Notes: Simulation with 1.25% constant urban productivity growth and constant rural productivity; $\underline{c} > 0$ and $\underline{s} = 0$. The line with circles corresponds to the simulation with rural productivity being equal to the last period value, while the others correspond to the simulation with rural productivity being equal to the initial period value.



(a) City size (Index, 1840=1). (b) Urban densities. (c) Expenditure shares.

Figure 9: Numerical illustration with $\underline{s} > \underline{c} > 0$.

Notes: Simulation with 1.25% constant productivity growth in both sectors. The preference parameters are such that $\underline{s} = 2\underline{c} > 0$, while keeping the initial rural employment share close to 60%.

view would emphasize a rising demand for (luxury) urban goods as income rises ('urban labor pull'). In our set-up, this would correspond to a high $\underline{s}$ relative to $\underline{c}$. For comparison, we simulate the economy with a value for $\underline{s}$ twice as large as $\underline{c}$ ($\underline{s} = 2\underline{c} = 1.2$), such that, keeping all other parameters to their baseline values, the initial share of employment in the rural sector remains close to 60%. Under such preferences, Figure 9 shows the model dynamics following rising productivity in both sectors. While such a calibration can generate employment shares broadly in line with the evidence, it cannot generate the observed fall in urban density. As income increases, the spending share on housing falls as the income elasticity of housing demand is low: workers are willing to reduce their housing size to consume more of the urban good. Thus, the city does not expand much in area to host more numerous urban workers and urban density does not fall. Urban density tends to increase due to the reallocation of workers towards the urban center (plot (b) of Figure 9): as they shrink their housing size, urban workers relocate towards central locations, increasing central density—the opposite of the data.[15] A high enough subsistence need is thus important for urban density to decline as it leads to an increase in the housing spending share following structural change. Note also that the evolution of the spending share on housing is informative regarding the relative magnitude of $\underline{c}$ and $\underline{s}$ (plot (b) of Figure 6 and plot (c) of Figure 9). An increasing share of housing spending, as in the data points towards a calibration where $\underline{c}$ is significantly larger than $\underline{s}$.

3.7 Discussion

In the baseline theory, average urban density falls with rising productivity and structural change. This effect comes from two channels, the fall in the rental price of farmland at the urban fringe and the increase in the housing expenditure share. It is amplified by a third channel, the use of faster commutes. Some assumptions important for these mechanisms deserve some discussion.

Preferences. As discussed above, with a lower income elasticity of housing demand ($\underline{s} > \underline{c}$), the housing spending share would fall with rising productivity, implying a lower rise in housing demand and possibly an increase in urban density (Figure 9). Note that more general preferences (e.g., CES Stone-Geary as in Herrendorf et al. (2013) or PIGL preferences as in Boppart (2014)) would allow for substitution effects on top of income effects. However, one could argue that income effects are of primary importance for agricultural goods, while substitution effects are more relevant for the reallocation between manufacturing and services, bundled into one urban sector in our analysis.

Rural Technology. The difference in land intensity between sectors and the substitutability between land and labor in rural production are important for the results. With a rural land intensity closer to the urban one, the farmland price would decrease less with structural change, limiting the fall in urban density. Similarly, with an elasticity of substitution between land and labor in the rural sector above (resp. below) unity, the farmland price would decrease less (resp. more) with the reallocation of labor to the urban sector as investigated in Section 4.6.[16]

[15] Suburban (fringe) density does fall in this experiment (plot (b) of Figure 9). The same mechanisms as in the baseline illustration play a role: structural change makes farmland cheaper at the city fringe.

[16] The rural production technology remains simple to focus on the core mechanisms. A more sophisticated pro-

Urban Technology and Commuting Costs. Urban production does not use land and is concentrated in the center. Relaxing only the first assumption is unlikely to change the results for a land intensity significantly smaller in the urban sector. However, with urban production using land, some activities could be reallocated in the suburbs since central land becomes more expensive as the city grows. With further away residents commuting less, urban density would decline even more. While endogenizing firms and workers location remains a difficult task, we partly capture these mechanisms in a later extension where we relax the monocentric assumption—assuming that commuting distance does not map one for one with residential distance (Section 4.6). In this latter Section, we also consider congestion and agglomeration forces absent from the baseline theory. A last important assumption implied by the commuting choice model is the concavity of commuting costs with respect to distance and the urban wage, $\xi < 1$. While not necessary, this assumption appears sufficient to guarantee a drop in urban density in the baseline experiment, but less concave commuting costs (a higher ξ) would limit the increase in urban area and the fall in density.[17]

Land use and housing regulations. Our baseline theory abstracts from land use and housing regulations, which would distort equilibrium prices and the equilibrium allocation. Stricter land use regulations aimed at preserving the rural area would limit the expansion of urban areas. This would imply higher urban housing prices together with a higher urban density. While such regulations are currently in place in France, they became effective only in the most recent decades. To the contrary, stricter housing regulations limiting the housing supply in some locations would make cities expand more in area and, consequently, decrease urban density. Such regulations are investigated in a reduced-form way in the quantitative model of Section 4, where the housing supply elasticities are assumed to be lower in the central parts of cities.

The baseline model described in this Section has only one city, which enlightens the aggregate spatial implications of structural change for a representative city. However, it does not allow to explore spatial variations across cities. The quantitative model of Section 4 will preserve the ingredients crucial for the aggregate results over time while allowing for multiple regions/cities.

4 Quantitative Model

This Section develops a quantitative version of the model to account for the process of structural change and urban expansion in France since 1840. We implement an economy with multiple regions with one city per region. Each region is similar to the one-city model of Section 3 with some extensions for quantitative purposes described below.

duction (with capital and/or factor biased technical change) could weaken or reinforce the results depending on the substitutability between factors and on the impact of technical change on land per worker. However, it is worth noting that, with commuting frictions, efficiency requires to reallocate labor more than land away from agriculture with structural change—leading to an rise in S_r/L_r and a drop in ρ_r (relative to income). Hence, our theory provides a complementary mechanism to technological explanations of the increase in land per worker in agriculture.

[17] Our approach implicitly assumes that commuting time is taken out of working time entirely. Results would be similar in a framework where commuting time also partly reduces leisure time if leisure is valued at the wage rate.

4.1 Set-up

For sake of space, we briefly describe the main additional elements of the quantitative model compared to the baseline model of Section 3. Details of the set-up are relegated to Appendix B.1.

Spatial structure and commuting costs. The economy is made of K different regions of area S. Each region $k \in \{1, ..., K\}$ is made of urban and rural land, with only one city k per region.[18] We consider a surface instead of a line segment as given land endowment. The city in each region k is circular with endogenous radius ϕ_k and area $\pi\phi_k^2$. Due to symmetry, the location $\ell_k \in (0, \phi_k)$ in city k also denotes the commuting distance.

For quantitative purposes, we expand the commuting choice model by introducing a more general spending cost on commuting f, which still depends on the mode choice m but also on the commuting distance ℓ_k and the labor costs $w_{u,k}$ in city k (see details in Appendix B.1). Intuitively, beyond its speed, the pecuniary cost of a commuting mode depends on the distance traveled (e.g. cost of gasoline) as well as the level of wages (e.g. wage of the bus driver). Under parametric assumptions, commuting costs under an optimal mode choice are of the following form (similar to Equation (4)),

$$\tau_k(\ell_k) = a \cdot w_{u,k}^{\xi_w} \cdot \ell_k^{\xi_\ell},$$

where the elasticities of commuting costs to income, ξ_w, and to distance, ξ_ℓ, are both positive, below unity and common across cities. The parameter a is inversely related to the efficiency of the commuting technology and homogenous across cities.

Preferences. Preferences over urban and rural goods are non-homothetic as in the baseline model of Section 3, and the composite consumption good is defined by Equation 1 at a given date t.

As described in Appendix B.1, instantaneous utility at date t is logarithmic and we consider a dynamic version of the model where households maximize their lifetime utility with borrowing and lending in a risk-free asset in net-zero supply. Given a discount factor β, this pins down the path of the equilibrium real interest rate and allows the computation of land values beyond rents.

Technology. Regions are heterogeneous in their urban and rural productivities. $\theta_{u,k}$ is the urban productivity in region/city k and $\theta_{r,k}$ the rural productivity. Given regional productivity parameters $\{\theta_{u,k}, \theta_{r,k}\}$, regional production in each sector is defined similarly to Section 3,

$$\begin{aligned} Y_{u,k} &= \theta_{u,k} L_{u,k} \\ Y_{r,k} &= \theta_{r,k} \left(\alpha (L_{r,k})^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(S_{r,k})^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \end{aligned}$$

where $L_{u,k}$ (resp. $L_{r,k}$) denotes the urban (resp. rural) workers and $S_{r,k}$ the land used for rural production in region k. σ is the elasticity of substitution between land and labor.

[18] For each region, the city center is centrally located within the region and regions are assumed large enough in area such that cities do not expand in neighboring regions.

The supply of housing space in each location ℓ of a given city (Equation (15)) holds up to a more flexible parametrization of the construction costs faced by land developers. The latter are such that the housing supply elasticities, $\epsilon_k(\ell)$, depend on the location within city k (as in Baum-Snow and Han (2019)), with $\partial\epsilon_k(\ell)/\partial\ell \geq 0$ and common elasticity in the rural area, $\epsilon(\phi_k) = \epsilon_r$. This is meant to capture that it might be costlier for developers to build closer to the center than in the suburbs or the rural part of the economy. Together with the mobility condition within a city, the housing market equilibrium at given at distance ℓ in city k leads to a density $D_k(\ell)$ similar to Equation (19),

$$D_k(\ell) = \left(\frac{q_{r,k}^{1+\epsilon_k(\ell)}}{1+\epsilon_k(\ell)}\right)\frac{1}{\gamma_\ell}(w_k(\phi_k) + r + \underline{s} - p\underline{c})^{-1/\gamma_{\ell,k}}(w_k(\ell) + r + \underline{s} - p\underline{c})^{1/\gamma_{\ell,k}-1},$$

where $w_k(\ell) = w_{u,k} - \tau_k(\ell)$ is the wage net of commuting costs in location ℓ of city k, $\epsilon_k(\ell)$ the location-specific housing supply elasticity, $\gamma_{\ell,k} = \frac{\gamma}{1+\epsilon_k(\ell)}$ represents the spending share on housing adjusted for the supply elasticity in location ℓ of city k, and $q_{r,k}$ the housing rental price in the rural area, tied to the rural land rent in region k, $\rho_{r,k} = q_{r,k}^{1+\epsilon_r}/\left(1+\epsilon_r\right)$. Importantly, due to region-specific rural productivity, $\theta_{r,k}$, spatial variations of land prices at the urban fringe, $\rho_{r,k}$, generate variations of urban local densities across regions.

Equilibrium. Workers are freely mobile within and across regions and labor markets clear globally. Urban and rural goods are freely traded within and across regions and goods markets clear globally.[19] In each region, land is used for housing and rural production and the land market clears locally. Perfect worker mobility implies a static equilibrium solved sequentially. An equilibrium with multiple regions is defined as follows, where corresponding Equations are relegated to Appendix B.1:

Definition 2. *In an economy with K regions with heterogeneous sectoral productivities $\{\theta_{u,k}, \theta_{r,k}\}$, an equilibrium is, in each region $k \in \{1, ..., K\}$, a sectoral labor allocation, $(L_{u,k}, L_{r,k})$, a city fringe ϕ_k and rural land used for production $S_{r,k}$, sectoral wages $(w_{u,k}, w_{r,k})$, a rental price of farmland $(\rho_{r,k})$ together with a relative price of rural goods p and land rents (r), such that:*

- *Workers are indifferent in their location decisions, within and across regions.*
- *Factors are paid the marginal productivity in each region $k \in \{1, ..., K\}$.*
- *The demand for urban residential land (or the city fringe ϕ_k) satisfies in each region $k \in \{1, ..., K\}$, $L_{u,k} = \int_0^{\phi_k} D_k(\ell)2\pi\ell d\ell$.*
- *The land market clears in each region $k \in \{1, ..., K\}$.*
- *The labor market clears globally.*
- *Rural and urban goods markets clear globally.*
- *Land rents satisfy, $rL = \sum_{k=1}^{K}\left(\int_0^{\phi_k}\rho_k(\ell)2\pi\ell d\ell + \rho_{r,k}\times(S - \pi\phi_k^2)\right)$.*

[19] The set-up abstracts from trade costs for goods or mobility costs for labor (mobility costs across regions are studied in Eckert and Peters (2022), trade costs in Donaldson and Hornbeck (2016) among others).

4.2 Calibration

The quantitative model is simulated in 10-year steps and calibrated using French historical data since 1840. For computational purposes, we consider $K = 20$ regions/cities selected among the initial set of 100 cities measured in 1870. One region represents the Parisian area and the remaining 19 cities are randomly drawn from the sample of 100 cities to preserve the distribution of city sizes in terms of population.[20] Each region is initially endowed with the same land area S. Data used for the calibration are described in detail in Appendix B.2.2.

Besides a few parameters calibrated externally, most of the model parameters are set to match data outcomes. While parameters are jointly determined to minimize the distance between the model's outcomes and a set of specified moments in the data, we provide, for sake of space, the main intuitions behind the identification of the model's parameters. Details of the minimization procedure for the joint estimation of parameters $\{\nu, \gamma, \underline{c}, \underline{s}, a\}$ together with the distribution of sectoral productivities across regions at each date t, $\{\theta_{u,k,t}, \theta_{r,k,t}\}$, are provided in Appendix B.2.4. Parameter values for the baseline simulation of the quantitative model are summarized in Table 1.

Parameter	Description	Value
S	Total Space	1.0
L_0	Total Population in 1840	1.0
θ_0	Initial Productivity in 1840	1.0
α	Labor Weight in Rural Production	0.75
σ	Land-Labor Elasticity of Substitution	1.0
ν	Preference Weight for Rural Consumption Good	0.0202
γ	Utility Weight of Housing	0.301
$\underline{c}$	Rural Consumption Good Subsistence Level	0.704
$\underline{s}$	Initial Urban Good Endowment	0.191
β	Annual Discount Factor	0.96
ξ_l	Elasticity of commuting cost wrt location	0.55
ξ_w	Elasticity of commuting cost wrt urban wage	0.75
a	Commuting Costs Base Parameter	1.693
ϵ_r	Housing Supply Elasticity in rural area	5.0
$\epsilon(0)$	Housing Supply Elasticity at city center	2.0

Table 1: Parameter values

Rural production function. The land intensity in agriculture is set to 25%, $\alpha = 0.75$ as in Boppart et al. (2019). Boppart et al. (2019) provide an estimate very close to unity for the elasticity of substitution between land and labor in agriculture. Thus, as in our baseline model, rural production in the quantitative model is Cobb-Douglas but we perform sensitivity with respect to the elasticity of substitution in Appendix B.3.1.

[20] We use 1870 for population measures. After selecting Paris by default, we compute median population for the remaining cities, and split the sample at this value. Above the median, we use 10 quantiles of city population to create nine bins, where we draw one city from each bin randomly; below the median we sample from all concerned cities 10 times without replacement. This strategy is employed because below the median, cities are very similar in terms of population, hence choosing randomly amongst all (instead of by bins) ensures better mixing of city types.

Rural and urban productivity. The productivity path for each region k in sector $s \in \{u, r\}$, $\theta_{s,k,t}$, is the product of a common (aggregate) component, $\theta_{s,t}$ and a region-specific component, $\theta^k_{s,t}$,

$$\theta_{s,k,t} = \theta_{s,t} \cdot \theta^k_{s,t}, \tag{27}$$

where the region-specific components are normalized such that aggregate sectoral productivity is equal to $\theta_{s,t}$ at all dates.[21] The path for aggregate productivity in both sectors, $\theta_{r,t}$ and $\theta_{u,t}$, is calibrated to match its data counterpart using aggregate French sectoral data on production, employment and agricultural land use since 1840.[22] The estimated path for $\theta_{r,t}$ and $\theta_{u,t}$ (displayed in Figure 10) is in line with the evolution of the standards of living in France since 1840. It is consistent with the conventional view that the nineteenth century is characterized by faster productivity growth in non-agricultural sectors, manufacturing in particular, while agricultural productivity grew significantly faster post-1950. More specifically, starting the agricultural crisis in the late nineteenth century, technological progress in French agriculture was slow and delayed relative to other countries, before catching up at a fast rate post-World War II (Bairoch (1989)).

Region-specific sectoral productivities, $\theta^k_{s,t}$, are estimated jointly with the parameters $\{\nu, \gamma, \underline{c}, \underline{s}, a\}$ in the minimization procedure described in Appendix B.2.4. However, their estimation relies on some targeted cross-sectional moments, namely the relative population of cities and local farmland values. The targeted population of each city is the population of the delineated urban areas measured using Census data in 1876 and 1950 and satellite data in 1975, 1990, 2000 and 2015 (see Appendix A.2). The targeted local farmland values are prices of arable land at the département level in 1892 from the Agricultural Census, and at the level of a département subdivision 'Petite Région Agricole (PRA)' from the Ministry of Agriculture in 1950, 1975, 1990, 2000 and 2015 (see Appendix A.3). For the estimation procedure, the distribution of city populations and local farmland values is kept fixed from 1840 until a first observation date set to 1870, and data are linearly interpolated in between observation dates.[23] Region-specific urban productivities, $\theta^k_{u,t}$, are identified to match the distribution of population of the 20 different cities. Region-specific rural productivities, $\theta_{r,k,t}$ are estimated to match the distribution of arable land values around each city—where the model-implied price of farmland, $\bar{\rho}_{r,k,t}$, is the appropriately discounted value of farmland rents located beyond the urban fringe $\phi_{k,t}$ in region k (see definition in Appendix B.2.3).[24]

Demographics. Aggregate population, L_t, is normalized to K in the first period and set at each

[21] The weighted mean of $\theta^k_{s,t}$ is normalized to 1, weighting by population in sector s and region k (Appendix B.2.4).

[22] 1840 is the first date of observation for agricultural land use necessary to compute the path of rural productivity. Due to the normalization of price indices, $\theta_{r,0}$ and $\theta_{u,0}$ are set equal to unity in 1840. The yearly path of θs in the data is smoothed to remove business cycles fluctuations. See Appendix B.2.2.1 for details.

[23] We have three potential dates for the first cross-sectional data point (1866 for the historical map delivering urban areas, 1876 for the population Census, and 1892 for farmland prices). For estimation, we target these initial observations at the unique initial date of 1870.

[24] An alternative to estimate $\theta_{r,k,t}$ could rely on local agricultural yields. However, this would require comparing yields for different crops given spatial differences in crop specialization. Data on local farmland values circumvent these issues. See Fiszbein (2022) for the modeling of crop choice across U.S counties.

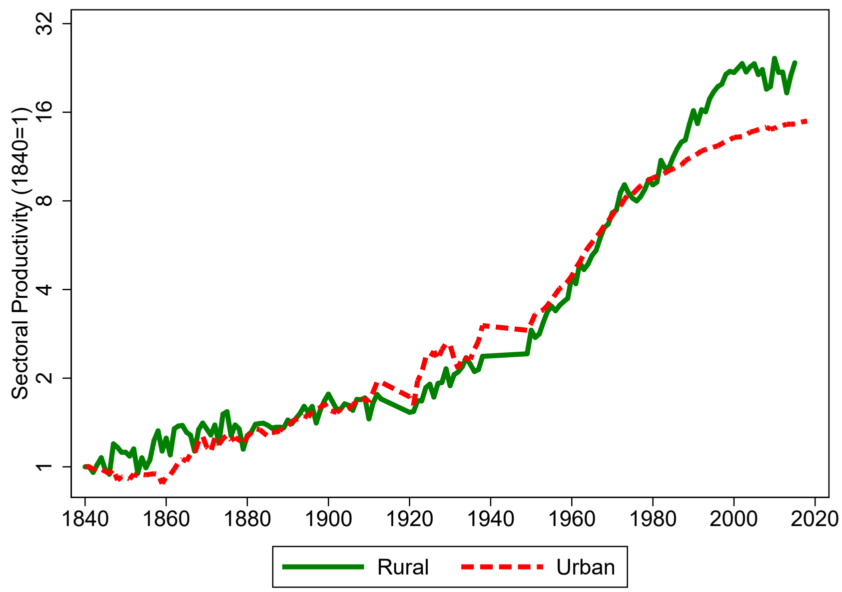


Figure 10: Estimated Aggregate Productivity Series, Rural ($\theta_{r,t}$) and Urban ($\theta_{u,t}$), 1840=1 (1840-2019). Estimation details in Appendix A.1.4.

date to match the increase of the French population since 1840 according to Census data.[25] Over the period considered, the French population roughly doubled and the increase in the labor force is of the same magnitude. Going forward, we use the projections for the French population by INSEE until 2050 and set a constant growth rate of 0.4% thereafter (see Appendix B.2.2.1).

Preferences. Given technology, demographics, and the commuting cost elasticities $\{\xi_l, \xi_w\}$, the preference parameters $\{\nu, \gamma, \underline{c}, \underline{s}\}$ are jointly set such that the agricultural employment share and the housing spending share are in line with the data. More precisely, the subsistence needs in agriculture parameter, $\underline{c}$, determines the initial agricultural employment share in 1840, while the preferences parameter towards the rural good, ν, determines the long-run employment of share in agriculture. Similarly, the endowment of urban good, $\underline{s}$, determines the housing spending share for the year 1900 (24% with a 5-year average around 1900)—our initial period of observation regarding consumption expenditures, while the preference parameter towards housing services, γ, determines the housing spending share in recent years (31% in 2010).

The last preference parameter, the discount factor β, is irrelevant for the equilibrium allocation given other parameters but pins down the rate of interest and thus matters for the value of land at each date. It is set externally to a standard value of 0.96 on an annual basis, but, within the range of admissible values, results do not depend on the value of β.[26]

[25] The normalization of the 1840 population together with homogeneous land area S across regions make sure that the land area per person in 1840 is independent of K, equal to $1/S$. Thus, with homogeneous productivities across space, the quantitative model behaves like a one-city model of population normalized to unity in each region.

[26] The minimization procedure detailed in B.2.4 implies computing rural land values around each city but estimates of region-specific productivities aiming at matching relative arable land values barely depend on the value of β.

Housing supply conditions. Existing estimates of the housing supply elasticities, ϵ, typically vary between 2 and 5, depending on the location as well as on the estimation technique (see, among others, Albouy et al. (2018), Combes et al. (2017) and Baum-Snow and Han (2019)). Baum-Snow and Han (2019) provides evidence of the *within-city* variation of the housing supply elasticities, ranging from about 2.5 at the CBD to about 5 at the fringe of cities. In all regions, we set an elasticity of 2 at the CBD and 5 at the fringe and the rural area.[27] For comparison purposes, we perform sensitivity analysis with a constant elasticity of housing supply, $\epsilon = 3$ (see Appendix B.3.2).

Commuting costs. The elasticities of commuting costs to income, ξ_w, and to distance, ξ_ℓ, are calibrated using individual level commuting data detailed in Appendix A.5.1. In the model, the elasticity of speed to commuting distance is equal to $1 - \xi_\ell$. We find in Appendix A.5.1 that this elasticity is precisely estimated within a narrow range around 0.45—depending on the sample used and the controls. Thus, ξ_ℓ is set externally to 0.55.[28]

The elasticity of commuting costs to income ξ_w is tied to the evolution of urban speed when average income increases. More precisely, $(1 - \xi_w)$ is the elasticity of speed to wage income at a given commuting distance. Using the individual commuting data detailed in Appendix A.5.1, one can estimate the percentage change in speed over 30 years for a given commuting distance. Over the period 1984-2013, this increase is equal to 11% for an increase in measured aggregate urban productivity of 44%—yielding an estimate for $\xi_w = 1 - \frac{11}{44}$. Thus, ξ_w is set externally to 0.75.

The remaining parameter a is estimated to make the total urban area, $\sum_k \pi\phi_k^2$, represent 17% of rural land in the recent period—the measured artificial land is 17% of the agricultural land in 2010. Results are not very sensitive to a as long as urban land remains a small fraction of available land.

4.3 Results: aggregate outcomes

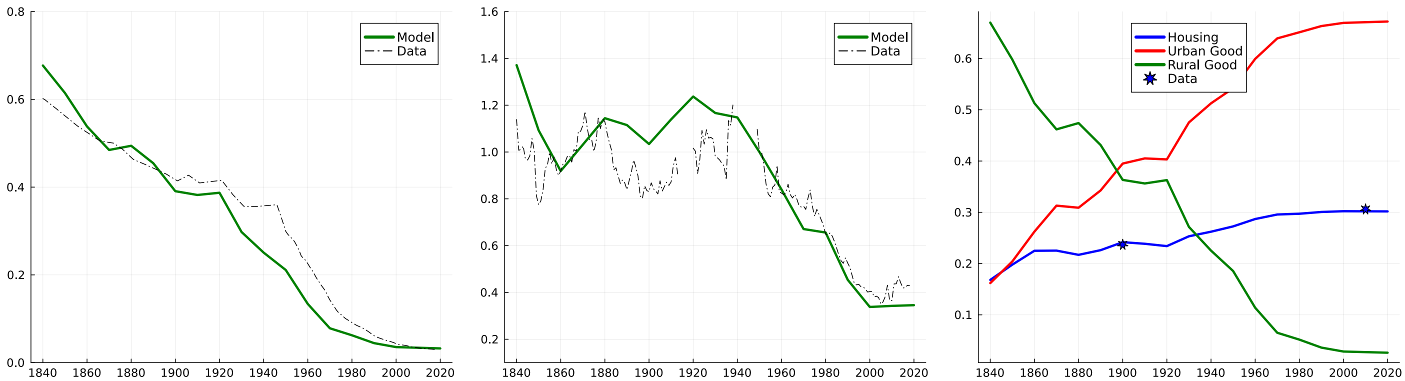
We first focus on aggregate outcomes over the period 1840-2020 to investigate the ability of the model to reproduce quantitatively the salient facts of Section 2. Model predictions across regions/cities are investigated in a second step. Outcomes are aggregated across regions and compared to aggregate data when available. For urban outcomes, one can interpret the following results as model predictions for the 'average' representative French city.[29] The mapping between model output and data counterparts is described in Appendices B.2.2 and B.2.5.

Structural change. Figure 11 shows that our model is able to account for the patterns of structural change observed in France. Rising rural productivity reallocates labor away from the rural sector and makes rural necessity goods less valuable. The relative price of rural goods falls as productivity increases. Our model fits the data on the historical evolution of the relative price remarkably well,

[27] With Cobb-Douglas production of housing using land and structure, there is a mapping between ϵ and the land share in production. Typical estimates of the land share are between 0.2 and 0.3, corresponding to ϵ between 2 and 4. We assume that $\epsilon(\ell)$ evolve linearly from the central value to the fringe value. Results do not depend on this choice.

[28] Commuting data also shows that the relationship between speed and commuting distance is very close to log-linear.

[29] Alternatively, these are approximately the outcomes of a city in a region with regional sectoral productivities corresponding to the aggregate ones.



(a) Rural employment share. (b) Relative price of rural good. (c) Spending shares.

Figure 11: Structural change.

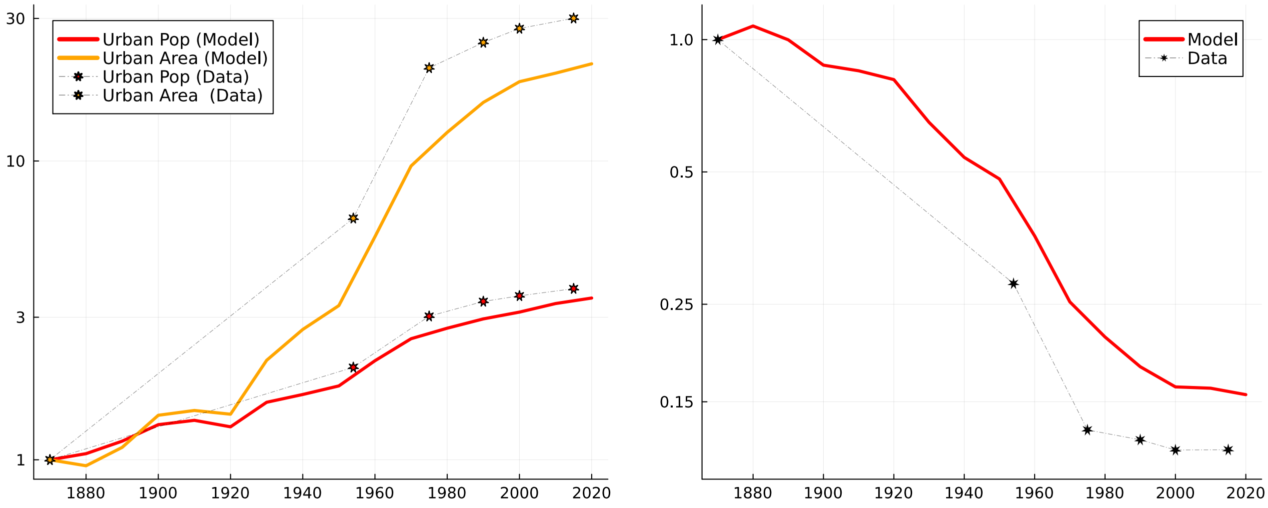
Notes: Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1. Corresponding data for the employment share, the relative price of rural goods and spending shares are described in Appendices A.1.2, A.1.3 and A.1.5. The relative price is normalized to 1 in 1950.

despite not being targeted (Figure 11b). Moreover, rising income leads to a reallocation of spending away from rural goods towards the urban good and housing services: the spending share on the rural good gradually falls, the share spent on the urban good continuously increases, and so does the spending share on housing services, although at a slower speed (Figure 11c). Overall, the spending share patterns are broadly in line with aggregate data if one abstracts from fluctuations in the interwar period (see Figure A.6 in Appendix A.1.5).

Urban expansion. Figure 12 shows the model's outcomes regarding the evolution of city size (area versus population) and the average urban density. For comparison with data on urban expansion, the plots start in 1870—normalizing the value in 1870 to unity. In line with the data, cities expand much faster in area than in population (Figure 12a). While our model does not account for the full observed expansion of the urban area, particularly so until 1950, it explains a very large fraction. As a consequence, the model predicts a large fall in average urban density—density is divided by more than 6 since 1870, slightly less than in the data (Figure 12b). As structural change slows down, so does the fall in urban density. Note that urban density falls throughout despite rising aggregate population, which tends to increase density in all locations.

Density within cities. Figure 13 shows the model predictions for density in different locations of the 'average' French city. Figure 13a depicts the evolution of the central density and the density at the fringe of the city (relative to the average), where densities are normalized to 1 in 1840 for readability.[30] The fall in average density is driven both by a fall in central density and a fall in density at the urban fringe. The fall in density at the suburban fringe is the natural consequence of structural change: the reallocation of workers away from agriculture combined with less valuable

[30]Densities of the 'average' French city are population-weighted average across cities. The fringe of the city center is at 15% of the radius of each city in 1840. Central density is the population-weighted average across cities of the density within this radius. See Appendix B.2.5 for details.

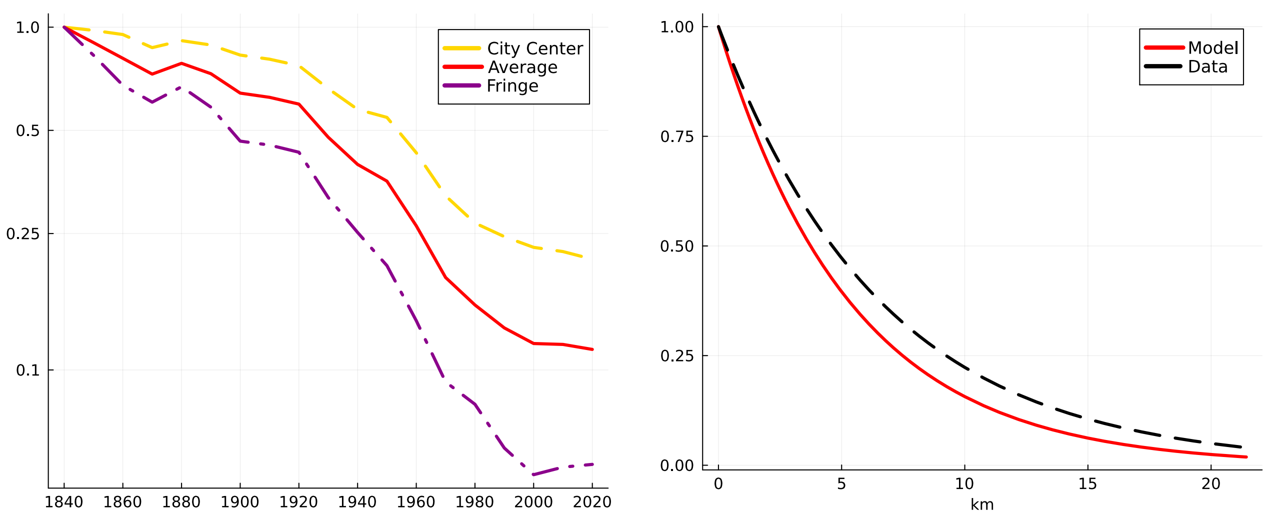


(a) Urban Area and Population (1870=1)

(b) Average urban density (1870=1)

Figure 12: Urban expansion.

Notes: Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1. Plots start in 1870 for comparison with data. Corresponding data for urban population, area and average density are described in Appendix A.2. Data and model outcomes are normalized to 1 in 1870 and shown on a log-scale.



(a) Urban density (1840=1).

(b) Density gradient (2020).

Figure 13: Density across space.

Notes: Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1. Density in different urban locations (left plot) is normalized to 1 in 1840 for readability. Densities are population-weighted averages across cities. Density of the city center is computed on a circle ending at 15% of the initial city radius in 1840. The right panel shows the model implied average exponential decay of urban density in model (year 2000) and data (year 2015). Estimation of model decay is described in detail in Appendix B.2.5.1, while for data in Appendix A.2.4. Both normalized to 1 at distance 0.

rural goods puts downward pressure on the price of farmland. Households can afford larger homes in the suburban parts of the city. Central density also falls because households find it worth to use faster commuting modes and to move towards the suburbs as their income rises. The former mechanism, more specific to our theory, is crucial to generate a fall in average density that is larger than the fall in the central one—in line with the Parisian data discussed in Section 2. Our model predicts that the overall fall in the central density is about 60% of the fall in the average density—in the ballpark of the estimates for Paris. Lastly, one can measure the density gradient by distance within urban areas, both in the data and in the model in the recent period (see Appendix A.2.4 and Appendix B.2.5). The model predictions are shown in Figure 13b for the 'average' city. The shape of the curve is very close to an exponential (fitted curve) as in the data, and the value of the coefficient of the fitting curve is in the ballpark of the data although slightly higher. Thus, our quantitative model provides a reasonable fit of the data regarding the density of urban settlements within a city and across time.

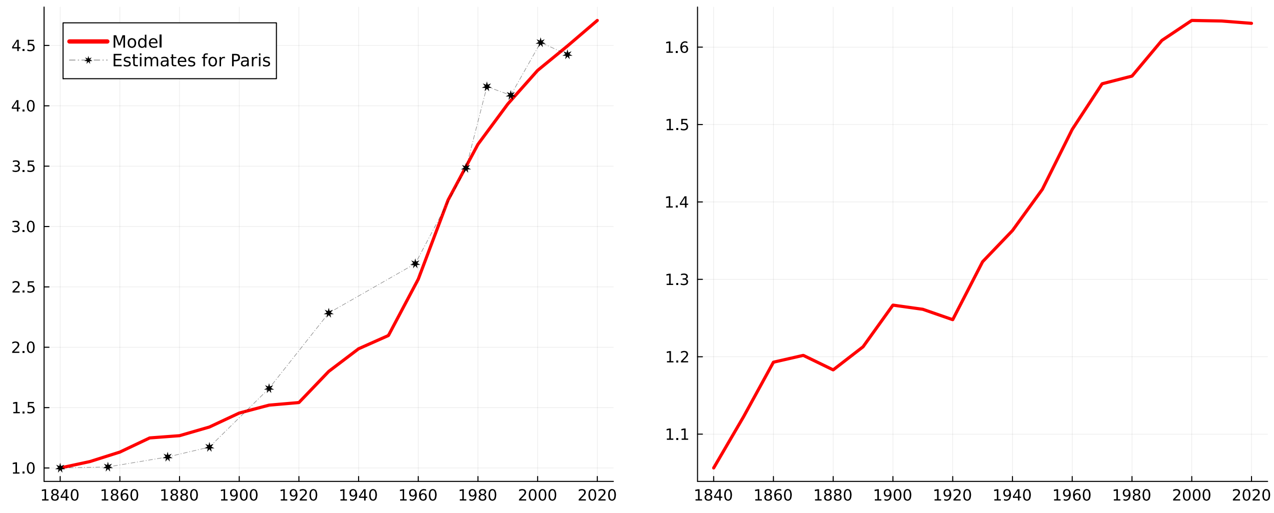
Commuting speed and the 'agricultural productivity gap'. Our model with endogenous commuting costs generates predictions regarding the evolution of commuting speed across time. Moreover, the marginal urban worker, who has the longest commute, needs to be compensated relative to the rural worker in each region. Our model thus predicts an endogenous urban-rural wage gap, which depends in each region on the city fringe (ϕ_k) and the commuting costs in this furthest away location. These predictions, averaged across regions, are shown in Figure 14. Over time, our model generates almost a five-fold rise in the average commuting speed (Figure 14a). We collected historical data on the use of different commuting modes for Paris to provide an estimate of the evolution of the average commuting speed in the Parisian urban area (see Appendix A.6 for details). The overall increase in average speed since 1840 predicted by the model is of a similar magnitude than in the Parisian data.[31] Beyond the overall increase, the predictions about the timing line up relatively well with the evolution of commuting speed in the Parisian area. The increase by a factor of about 2 until 1930 reflects the more intensive usage of public transport and their increase in speed over this period (from the initial horse-drawn omnibus to the metro). The later increase, more specifically post-World War II, reflects the increasing car usage.

Following Gollin et al. (2014), Figure 14b shows the 'agricultural productivity gap', averaged across regions. For each region k, the 'agricultural productivity gap' is a monotonic transformation of commuting costs at the fringe of the city—proportional to the urban-rural wage gap, $w_{u,k}/w_{r,k}$. We compute the average raw 'agricultural productivity gap' at a given date as,

$$\text{Raw-APG} = \sum_{k=1}^{K} \left(\frac{L_k}{L}\right) \left(\frac{L_{r,k}/L_{u,k}}{VA_{r,k}/VA_{u,k}}\right),$$

where $\frac{L_k}{L}$ is the population-weight of region k, $L_{s,k}$ and $VA_{s,k}$ denotes the employment and value

[31] Miles and Sefton (2020) find a similar increase for the U.K. Historical data are unfortunately not available for the rest of France. The model implied speed in Paris is also very close to the data counterpart.

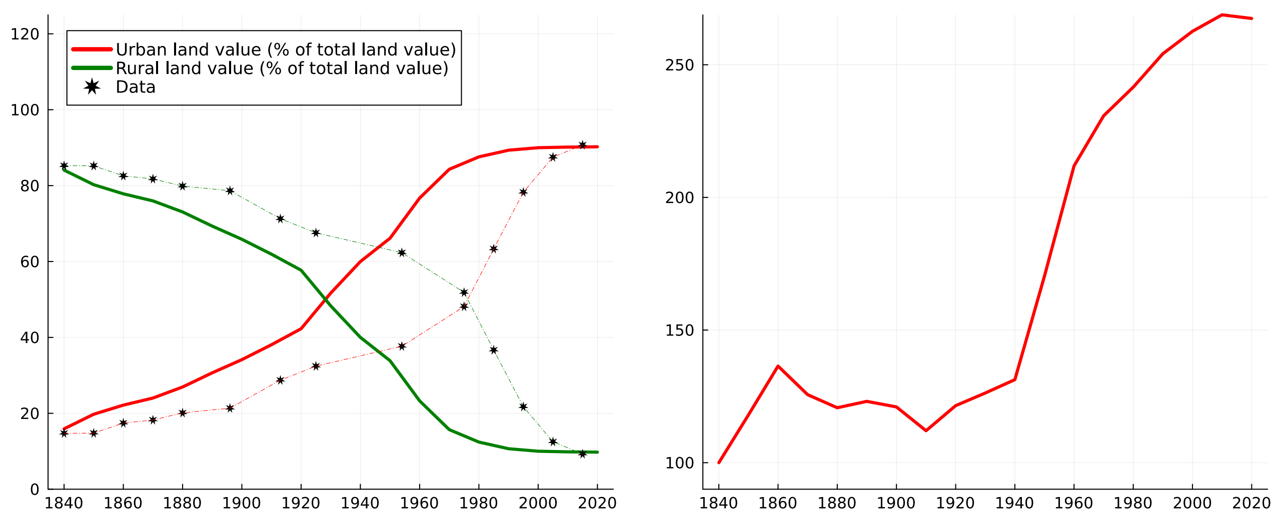


(a) Average urban commuting speed (1840=1).

(b) Agricultural productivity gap.

Figure 14: Commuting speed and the 'agricultural productivity gap'.

Notes: Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1. The average urban commuting speed (left plot) is the density-weighted average of speeds across urban locations (see Appendix B.2.5 for definition, normalization to 1 in 1840). Estimates for Paris are detailed in Appendix A.6. The agricultural productivity gap (right plot) is defined as the population-weighted average across regions of $\frac{L_{r,k}/L_{u,k}}{VA_{r,k}/VA_{u,k}}$.



(a) Urban versus rural land wealth.

(b) Real Housing Price Index (1840=100).

Figure 15: Land values and housing price.

Notes: Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1. Land and housing values are computed as the discounted sum of future land rents in each location. Corresponding data (dashed) are based on Piketty and Zucman (2014) and described in more detail in Appendix A.1.6. The real housing price index averages the purchasing housing prices across locations (deflated using a model implied GDP-deflator). Details on the computation are provided in Appendix B.2.5.

added in sector s of region k. The value predicted by the model for the recent period, around 1.6, is in line with the values computed by Gollin et al. (2014) for France—lying in between their Raw-APG and Adjusted-APG. Computing the Raw-APG for the entire sample period directly from historical national accounts data, we find that our model falls short of the entire gap, especially for the initial years, but explains a large fraction since 1960.[32] Our quantitative model suggests that spatial frictions combined with location-specific housing can generate urban-rural wage gaps of a significant economic magnitude. It also provides insights on the persistence of fairly large gaps even in developed countries, where labor misallocation is arguably less relevant.

Land values and housing prices. Figure 15 shows the model predictions for land values and housing prices. Figure 15a shows the reallocation of land value across rural and urban use.[33] Due to structural change, the value of rural land relative to urban land fell dramatically. In the model, while the value of agricultural land constituted more than 80% of the total land value, it is less than 10% nowadays. This is broadly in line with data from Piketty and Zucman (2014) even though our model misses the timing of the reallocation around the time of World War II—arguably due to war destructions.[34] Importantly, the value of urban land (per unit of land) increased faster in the recent decades. This mirrors the evolution of the housing price index since 1840 (Figure 15b), whose shape reminds of the hockey-stick shown in Figure 5b. The model generates about half of the increase in housing prices described in Knoll et al. (2017) post-World War II. Quantitatively, the model misses the very steep increase in the 2000s, most likely due to factors outside the model such as the large decline in interest rates and/or a tightening of land use restrictions.[35]

4.4 Results: outcomes across regions

While the main purpose of the quantitative model is to reproduce the aggregate facts developed in Section 2, the model with multiple regions/cities provides additional predictions across space. The dispersion across regions of urban and rural productivities, $\{\theta_{u,k,t}, \theta_{r,k,t}\}$, generates dispersion across regions of sectoral employment and wages, of land use and urban density, of urban and rural land values. We focus on the dispersion of urban density and land values, more central in our contribution. We also focus on the implications of the dispersion of rural productivity since a crucial aspect of our story is the role of rural productivity for the expansion and density of cities.

Region-specific productivity changes. Before investigating the model predictions across space, it is important to clarify the response of a given region facing regional productivity changes in sector

[32] Using wage data, Sicsic (1992) provides estimates of the urban-rural wage gap in France over the period 1852-1911. Like in the U.K., he finds a significant increase of the gap over the period, in line with our predictions.

[33] To compute the urban land value in the data, we multiply the housing wealth by the share of land in housing, whose average is 0.32 in the data for the period 1979-2019.

[34] War destructions arguably delayed the increase in housing wealth (to the post-reconstruction period). This delay has been possibly reinforced by a drop in housing values following the Great Depression and by the rent control imposed in France in between the wars (see discussion in Appendix A.1.5).

[35] France has a planned allocation of land use (agricultural, housing, protected area such as forests) decided at the municipality level. These restrictions are likely to play a larger role at the end of the sample as the law regarding the 'Plans Locaux d'Urbanisme (PLU)' initiated in 2000 becomes stricter and more broadly enforced.

s, changes in $\theta^k_{s,t}$, as opposed to common (aggregate) productivity changes, changes in $\theta_{s,t}$.

In response to a local increase in rural productivity, $\theta^k_{r,t}$, region k sees its rural sector expand in terms of employment and value added, while city k shrinks in area. Intuitively, a rise in region k's rural productivity leads to higher rural wages and land values in region k. Region k, then, attracts rural workers from other regions, which further increases rural land values there. With higher prices at the urban fringe, urban land and housing prices increase, making city k less attractive. As a consequence, urban area in city k falls and urban density increases.[36] This latter prediction is at the heart of our story: higher land prices at the fringe of cities increase urban density.

It is important to note that the predictions for region k are drastically different when the increase in rural productivity is common across regions (an increase in $\theta_{r,t}$). In this case, the rural sector shrinks and rural land prices drop in all regions, since structural change forces operate. As workers move to the urban sector, all cities expand both in area and population, but faster in area: urban density decreases as illustrated in Section 4.3. In other words, for a given change in rural productivity $\theta_{r,k,t}$ in region k, the response is drastically different whether the productivity change is local or common. General equilibrium effects through the relative price of rural goods following a common (aggregate) increase in rural productivity are crucial for the result—a reminiscence of the role of rural productivity for structural change in open versus closed economies (Matsuyama (1992), Gollin (2010), Uy et al. (2013), Bustos et al. (2016a), Teignier (2018) among others).[37]

Similarly, a higher region-specific urban productivity, $\theta^k_{u,t}$, significantly increases the size of city k, both in population and area—workers from other cities move towards the relatively more productive city. Due to higher housing prices, city k gets then relatively denser. To the opposite, a common increase in urban productivity, $\theta_{u,t}$, barely increases the population of city k—the same amount of rural workers are needed to feed the urban population. The rise in $\theta_{u,t}$ does, however, lead to a fall in the density of all cities, as urban area increases due to faster commuting modes.

Thus, again, depending on their local or global nature, productivity changes in a given city k have entirely different implications for urban population and density. While variations in the time-series are arguably dominated by aggregate productivity changes (Section 4.3), region-specific productivity changes might generate very different cross-sectional implications. We now investigate further some of these implications across regions.[38]

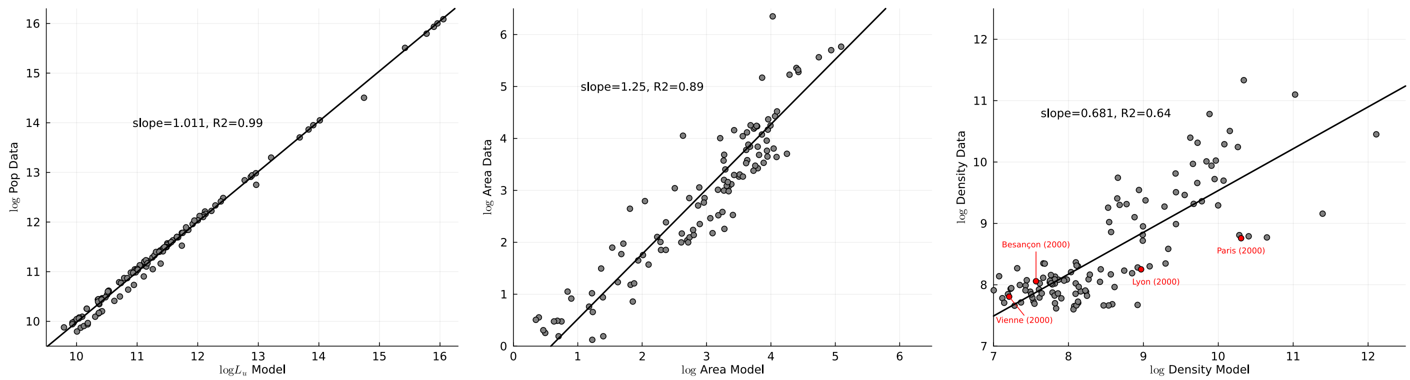
City size and urban density. Beyond the targeted distribution of population across cities, the model does a fairly good job at reproducing the distribution of urban area and average urban density across time and space (see Figure 16). In particular, Figure 16c plots the log of average urban density in a given city against its data counterpart for the dates where it is observed in the data (1870, 1950, 1975, 1990, 2000 and 2015).[39] The model predicts that, over time, for a given

[36] To the opposite, the rural sector in other regions shrinks while their respective cities expand—the effects might be relatively small though if region k accounts for a small share of total employment.

[37] See also Donaldson and Hornbeck (2016) for the role of falling trade costs for regional agricultural specialization.

[38] See Figure B.1 (App. B.2.1) for cross-sectional predictions and a visual guide to the identification of the $\theta_{s,k,t}$.

[39] We interpolate model outcomes for 1975 and 2015. Model outcomes are defined up to a constant of normalization



(a) Urban Population. (b) Urban Area. (c) Urban Density.

Figure 16: Regional Urban Moments.

Notes: We plot the log of model population/areas/density vs the log of population/areas/density in the data for all observed dates. Variables are centered such that the mean in the data across observations matches the model's counterpart. Data and model outcomes are for the dates $t \in \{1870, 1950, 1975, 1990, 2000, 2015\}$, with model outcomes interpolated to obtain 1975 and 2015 values. Sample of 20 cities. Outcomes of the baseline simulation of the quantitative model where parameters are set to the values of Table 1.

city, urban density falls as urban population increases following common (aggregate) productivity changes—in line with the aggregate results. In the cross-section, due to higher housing prices, more populated cities are however denser (as illustrated by selected cities in 2000 in Figure 16c). Both predictions, over time and in the cross-section, are qualitatively in line with the data discussed in Section 2. Quantitatively, the model does notably better in the time-series than in the cross-section. At a given date, more populated cities are significantly denser in the model than in the data.

Urban density and rural land values. A second important implication, crucial for our mechanisms, goes as follows: a relatively higher rural productivity in region k, higher $\theta^k_{r,t}$, increases land prices at the fringe of city k, leading to higher density in city k. To test this prediction, we investigate the link between average urban density in a given city and its farmland price at the fringe using satellite measures of urban density and the corresponding local price of arable land of the 'Petite Région Agricole'. We perform the following regression in the model and in the data,

$$\log \text{density}_{k,t} = a_t + b \cdot \log \bar{\rho}_{r,k,t} + c \cdot Z_{k,t} + u_{k,t}, \tag{28}$$

where density$_{i,t}$ is the average urban density of city k, $\bar{\rho}_{r,k,t}$ the farmland price around city k, a_t a time-effect and $Z_{k,t}$ region/city-specific controls. Controlling for aggregate changes through a_t, the model unambiguously predicts $b > 0$, when controlling for region-specific urban productivity, $\theta^k_{u,t}$. In other words, a city in region k should be denser when the value of farmland is higher, holding everything else constant. When turning to the data, two important caveats extensively discussed in Appendix A.4 are in order: measurement issues and endogeneity concerns. For the latter, beyond possible reverse causality, unobservable local characteristics (e.g., land use regulations

defining the measurement unit; normalization such that the mean across all observations matches the data counterpart.

	log Urban Density		
	Model	Data (OLS)	Data (IV)
$\log \overline{\rho}_{r,k,t}$	0.370***	0.126***	0.346***
	(0.020)	(0.026)	(0.084)
Num.Obs.	80	766	314
R2	0.994	0.253	0.336
Controls	$w_{u,k,t}$	$w_{u,k,t}$	$w_{u,k,t}$
FE: year	X	X	X

Table 2: Urban density and rural land values.

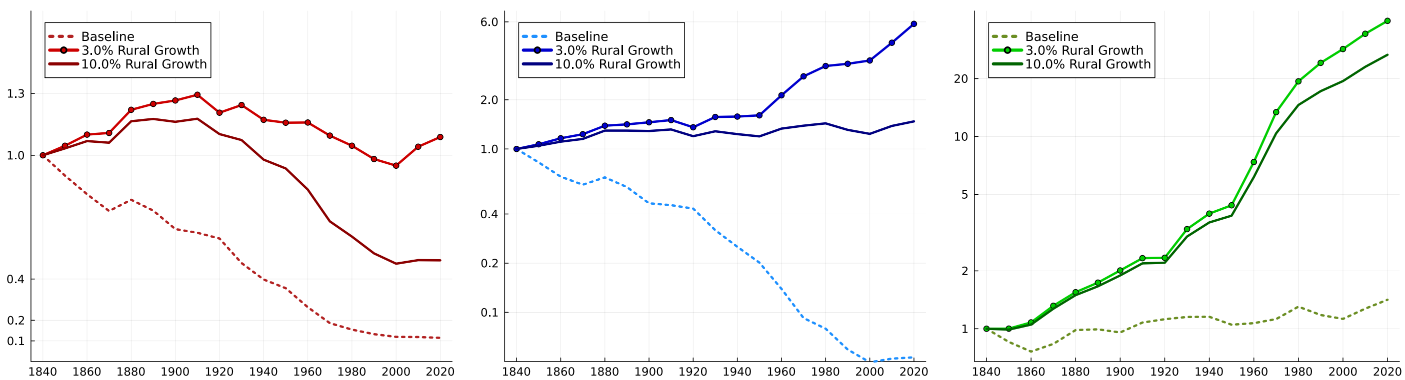
Notes: Results of Regression Eq. 28 in the model and in the data for years $t \in \{1975, 1990, 2000, 2015\}$. Model regressions are based on outcomes of the baseline simulation of the quantitative model with a set of $K = 20$ cities. Farmland values in region k, $\bar{\rho}_{r,k,t}$, are computed as the discounted sum of future land rents beyond the urban fringe $\phi_{r,k,t}$ in region k. Details on the computation are provided in Appendix B.2.3. Average urban density, density$_{k,t}$, is the urban population $L_{u,k,t}$ of city k divided by its area $\pi\phi_{k,t}^2$. Data on local farmland value $\bar{\rho}_{r,k,t}$ is the price of arable land in the Petite Region Agricole (PRA) of city k. Average urban density is measured using GHSL data for a sample of 200 cities. For IV-regressions, local farmland values are instrumented by wheat yields on the restricted sample of cities in départements with wheat as one of the main crops in 2000. Controls are urban wages (in log), $w_{u,k,t}$, in city k in model and data. Standard errors clustered at the département level. See Appendix A.4 for details.

or local amenities) might simultaneously affect the local price of farmland and urban density. To address these issues, we instrument local farmland prices using département-level data on wheat yields focusing on a sub-sample of cities in départements where wheat is one of the main crops. Given the reduced sample, we use a larger sample of cities, the 200 largest French cities, to preserve statistical power. Details of the empirical strategy are relegated to Appendix A.4. Our baseline IV-estimates using this subsample of cities are shown in Table 2 together with the OLS estimate on the whole sample of 200 cities measured in years 1975, 1990, 2000 and 2015. Results are striking: cities in locations with higher farmland values are denser. Quantitatively, the IV-estimated elasticity is relatively close to its model's counterpart—a 10% increase in the local farmland value increasing urban density by about 3.5%. Beyond validating the cross-sectional prediction, these results provide more convincing evidence of our mechanisms over time, whereby lower rural land values at the fringe of cities lowers urban density along the process of structural change.

4.5 Counterfactual Experiments

In order to shed further light on the mechanisms at play and discuss the sensitivity of our results to the different elements of the model, we perform alternative experiments. These experiments aim at showing how structural change and the use of faster commutes interact in driving urban expansion.

The role of rural productivity growth. To emphasize further the crucial role of technological progress in agriculture and structural change for our results, it is useful to perform sensitivity analysis with lower aggregate rural productivity growth. We perform simulations with a stagnating (resp. slowly growing) rural productivity, where the growth rate of θ_r is 3% (resp. 10%) of the baseline at each date. While reducing the aggregate component of rural productivity growth, the urban region-specific components, $\theta^k_{u,t}$, are re-estimated to preserve the distribution of city populations and urban aggregate productivity growth.[40] All other parameters are kept to their baseline values. Results of these simulations are shown in Figure 17 for some variables of interest (aggregated across cities) together with the baseline simulation for comparison. With low improvements of the rural technology, the urban density falls significantly less and might even increase if rural productivity stays sufficiently low (Figure 17a). The growth of population and urban productivity puts pressure on land in the rural area to feed an increasingly numerous and richer population. This increases the relative price of rural goods and the price of farmland at the urban fringe (Figure 17c)—preventing the city to expand.[41] Furthermore, facing higher price of rural goods, households reduce their housing spending share to feed themselves, reducing the demand for urban land. These forces tend to make the city much denser than our baseline—more so at the urban fringe due to rising farmland values (Figure 17b). Thus, urban density might increase despite the relocation of urban workers towards the less dense part of the city as they commute faster due to rising urban productivity. It is worth emphasizing that population growth, by putting pressure on land, makes improvements in agricultural productivity even more crucial to generate a sizable expansion in urban area.



(a) Average urban density (1840=1). (b) Density at the fringe (1840=1). (c) Rental price of farmland.

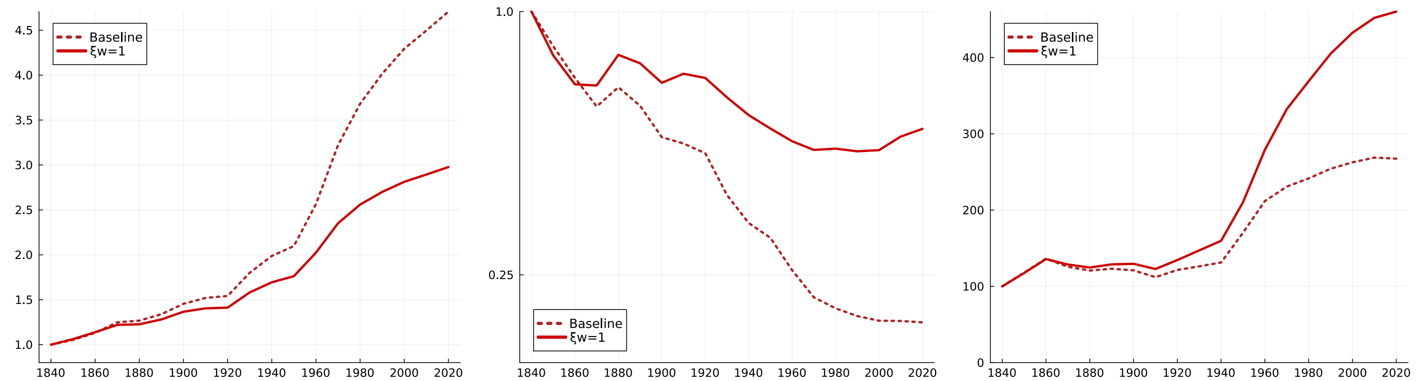
Figure 17: Sensitivity to rural productivity growth.

Notes: Productivity growth in the rural sector is set to 3% of the baseline rural productivity growth (solid line), resp. 10% of the baseline (solid line with circles). Region-specific urban productivity parameters are re-estimated to preserve the distribution of city populations. Other parameters are kept to their baseline value of Table 1. Simulation for the baseline rural productivity growth is shown in dotted for comparison.

This simulation does not say that improvements in commuting technologies do not matter for the expansion in area of cities. However, it makes clear that they matter only when combined with rural productivity growth and structural change. The next experiment provides further insights on the quantitative role of commuting costs for our results.

[40] Although not crucial for the results, re-estimating the region-specific urban productivities preserves aggregate urban productivity and facilitates the numerical solution: otherwise workers are moving massively to Paris due to its faster (baseline) urban productivity growth. With a low rural growth, workers must come from small cities (instead of the rural area), which increases aggregate urban productivity, empties some cities and leads to corner solutions.

[41] In the simulation with stagnating rural productivity, cities might even shrink in size. Workers move away from cities despite urban productivity growth as more rural workers are needed to feed the increasing population.



(a) Average commuting speed (1840=1). (b) Average urban density (1840=1). (c) Real Housing Price Index (1840=1).

Figure 18: Sensitivity to the elasticity of commuting costs to income.

Notes: The elasticity of commuting cost to income, ξ_w, is set to 1. All other parameters are kept to their baseline value of Table 1. Simulation for the baseline calibration shown in dotted for comparison.

The elasticity of commuting costs to income. To shed further light on the quantitative importance of falling commuting costs and rising commuting speed, we set the elasticity of commuting costs to income, ξ_w, to unity, $\tau_k(\ell_k) = a.w_{u,k}.\ell_k^{\xi_\ell}$.[42] All other parameters are set to their baseline values. With such a calibration, the fraction of wages devoted to commuting in given location does not fall with rising urban productivity, contrary to our baseline. This is so because the speed of commuting does not increase with a rising opportunity cost of time (urban wage). When compared to the baseline, this illustrates the quantitative role of the use of faster commutes when urban productivity increases. Figure 18 shows the results aggregated across cities in this alternative calibration together with the baseline for comparison. Figure 18a makes clear that increasing the elasticity of commuting costs to income limits the increase in the average commuting speed over the period.[43] As the cost of faster commutes increases more than in the baseline, urban workers do not relocate away from central locations towards the suburbs of the city as much. This severely limits the expansion in area of the city and the average urban density falls significantly less than in the baseline (Figure 18b).

Thus, when combined with rural productivity growth, the use of faster commutes and the corresponding decline in commuting costs (as a share of the urban wage) is quantitatively important to account for the overall decline in urban density—particularly so in central locations. In this alternative experiment, as the urban area expands much less but urban population grows essentially as much due to structural change, urban land values and housing prices increase much more than in the baseline (Figure 18c). This mirrors the role of improvements in commuting modes to limit the increase in urban land values emphasized in Heblich et al. (2018) and Miles and Sefton (2020).[44]

[42]This is the limit value. In this knife-edge case, workers do not switch to faster modes at a given location with rising wages: the higher operating cost of faster commutes offsets the benefits due to a rising opportunity cost of time.

[43]The average speed still increases. First, due to structural change, some workers locate in new suburban locations, where they are willing to use faster commuting modes. Second, relative to the baseline simulation, urban workers may relocate from a slow to a fast commuting city, which affects commuting speed positively.

[44]Higher urban housing prices generate an agricultural productivity gap about twice as large as in the baseline in

4.6 Sensitivity and Extensions

We investigate the robustness of the findings to the production side in the rural and housing sector, to the presence of agglomeration/congestion forces and to more general commuting costs.

Sensitivity to technological parameters.. We perform sensitivity with respect to the elasticity of substitution between land and labor in the rural sector, σ. For sake of space, results are relegated to Appendix B.3.1. The baseline assumes a unitary elasticity, $\sigma = 1$. Values used in the literature typically range between 0 and 1 (Bustos et al. (2016b) and Leukhina and Turnovsky (2016)) and we perform sensitivity analysis with alternative values, keeping all other parameters to the baseline. With a lower σ, the farmland rental price (relative to income) falls more over time as land and labor are more complement in the rural sector. With a lower opportunity cost of expanding the city, the urban area increases more and the average urban density falls more—getting closer to the data.

Appendix B.3.2 shows sensitivity with respect to the housing supply elasticity—assuming a constant value in the mid-range of empirical estimates, $\epsilon(\ell) = \epsilon_r = 3$ in all locations. Keeping all parameters constant but changing the housing supply elasticity barely affects the aggregate implications. However, compared to our baseline simulation, a more elastic housing supply at the center leads to a larger provision of housing in these locations. The center is significantly denser than in the data—the within-city density gradient becomes significantly steeper than in the data.

Congestion and Agglomeration. We extend the model to account for possible urban congestion/agglomeration forces. For sake of space, these extensions are further developed in Appendix B.3.3. We consider additional urban congestion costs by assuming that commuting costs are increasing with urban population, $a(L_{u,k}) = a \cdot L_{u,k}^{\mu}$. This summarizes the potential channels through which larger cities might involve longer and slower commutes. We set externally $\mu = 0.05$ and re-estimate the model using the same strategy described in Appendix B.2.4. Congestion forces reduce the expansion in area and the extent of suburbanization. By rising commuting costs, they also increase urban housing prices relative to the baseline.

We also introduce urban agglomeration forces by assuming that the urban productivity increases externally with urban employment in city k, $\theta_{u,k}(L_{u,k}) = \theta_{u,k} \cdot L_{u,k}^{\lambda}$. We set $\lambda = 0.05$, in the range of empirical estimates for France (Combes et al. (2010)). We show in Appendix B.3.3 that if one re-estimates the model's parameters in presence of agglomeration—outcomes are virtually identical. Given that the estimation targets the urban population distribution and aggregate productivity, our results remain robust to any reasonable magnitude of agglomeration forces. In the same Appendix, we also discuss the equilibrium effects of agglomeration forces. While agglomeration effects are important for the allocation of urban employment across cities, these effects remain small in the aggregate for the allocation across sectors—despite the very large urban expansion over time driven by structural change. Agglomeration forces make all cities more productive over time as workers reallocate in the urban sector. However, higher urban incomes make also rural goods more valuable

the recent period. Equivalently, the urban resident at the fringe faces much higher commuting costs.

increasing rural workers' wage almost one for one. General equilibrium forces thus prevent stronger worker reallocation towards the urban sector despite agglomeration benefits.

Commuting distance and residential location. Guided by the structure of French cities, our baseline results hinge on the assumption of a monocentric model where urban individuals commute to the city center to work. While endogenizing firms' location across space is beyond the scope of the paper, one can still partly relax the monocentric assumption by assuming that commuting distance at location ℓ_k in city k, $d_k(\ell_k)$, does not map one for one with residential distance ℓ_k from the central location. Using data available for the recent period to investigate the link between commuting distance and residential location (see Appendix A.5.2 for details), we find that households residing further away do commute longer distances on average. However, commuting distance increases less than one for one with the distance of residence from the city center. Moreover, individuals residing close to the center commute longer distances than the distance of their home from the central location. Lastly, data show that commuting distance increases less with the distance of residence from the center in larger cities.[45] Based on these observations, we model commuting distance, in location ℓ_k of city k, $d_{k,t}(\ell_k)$ in a reduced-form way as follows,

$$d_{k,t}(\ell_k) = d_0(\phi_{k,t}) + d_1(\phi_{k,t}) \cdot \ell_k, \tag{29}$$

with $d_0(\phi)$ being a positive and increasing function of ϕ satisfying $\lim_{\phi\to 0} d_0(\phi) = 0$, and $d_1(\phi)$ being a decreasing function belonging to $(0,1)$ with $\lim_{\phi\to 0} d_1(\phi) = 1$. d_0 represents the (minimum) commuting distance traveled by an individual living in the center, while d_1 is the slope between commuting distance and residential distance from the center. The functional forms of d_0 and d_1 are described in Appendix B.3.4 under a specification that fits recent commuting data. For sake of space, details of the results are relegated to Appendix B.3.4. Quantitatively, cities expand more in area in the last decades in this extension, bringing the model closer to the data. As a consequence of a larger sprawling, the average urban density falls more. This is driven by a larger fall of central density: with urban expansion, residents close to the center end up commuting larger distances—implicitly due to the reallocation of jobs away from the center—, making central locations less attractive relative to the suburbs. As a result, this extension provides a better fit of cross-sectional data. Relative to the baseline, commuting distances in the center (resp. at the fringe) are larger (resp. lower) in larger cities. This, in turn, increases the area of more populated cities, reducing their average density and bringing the model closer to the data. Larger cities are still noticeably denser than in the data, but less so compared to the baseline monocentric model.

5 Conclusion

This paper develops a spatial general equilibrium model of structural change with endogenous land use and studies its implications for urbanization. We document a persistent fall of urban density in

[45] This suggests a larger dispersion of employment away from the center in larger cities. See Appendix A.5.2.

French cities since 1870 and show that the theoretical and quantitative predictions of the model are broadly consistent with the data. The quantitative version of the theory calibrated to French data explains (at least) three fourths of the urban area expansion and of the decline in average urban density, about half of the rise in housing prices, and most of the land value reallocation from rural to urban since the mid-nineteenth century. Novel predictions regarding urban density across space line up relatively well with available data.

Agricultural productivity growth is shown to be crucial for the results, since it reduces the price of land at the urban fringe and frees up resources to be spent on housing. As a consequence, while workers reallocate away from agriculture, cities grow faster in area than in population and land prices do not rise very rapidly. Faster commuting modes also play an important and complementary role but only when combined with rural growth and structural change. When rural productivity is high, they allow households to live further away from their workplace and enjoy larger homes, contributing significantly to the decline in urban density, particularly at the city center.

Our baseline theory relies on a monocentric urban structure where all workers commute from their residential location to the center. While French cities exhibit the qualitative features of monocentric cities, such an urban structure certainly remains an approximation. Data show that commuting distance increases with residential distance to the center but less than one for one. This suggests that workers sort into jobs and residential locations that are closer to each other. Relaxing further the monocentric structure remains an important step to better account for the expansion of cities and the evolution of density across urban locations. We leave for future research a theory that jointly determines firms and workers location decisions across the urban space.

Relatedly, we focus on the reallocation of economic activity from the rural to the urban sector, abstracting from the reallocation within the urban sector. Admittedly, we could extend our framework to consider the transition from manufactures to services in the later period. While aggregate results might not be much affected, we believe it would matter for the cross-section of cities in recent times. Some services are provided locally, especially in large cities, implying that not all workers have to commute to the center. We also leave this extension for future research.

We also believe that our approach can be used to study the aggregate implications of policies regulating land use and urban planning. Such policies are likely to play a role in explaining the evolution of housing prices in recent years, which our current setup cannot fully replicate. To the extent that land-use policies reduce city growth on the extensive margin, they lead to greater demand for available housing units and to faster rise in their prices. The general equilibrium structure of our quantitative spatial model is well suited to conduct such policy counterfactuals.

References

Ahlfeldt, Gabriel M, Stephen J Redding, Daniel M Sturm, and Nikolaus Wolf, "The economics of density: Evidence from the Berlin Wall," *Econometrica*, 2015, *83* (6), 2127–2189.

Albouy, David, "What are cities worth? Land rents, local productivity, and the total value of amenities," *Review of Economics and Statistics*, 2016, *98* (3), 477–487.

_ , Gabriel Ehrlich, and Minchul Shin, "Metropolitan land values," *Review of Economics and Statistics*, 2018, *100* (3), 454–466.

Alder, Simon, Timo Boppart, and Andreas Müller, "A theory of structural change that can fit the data," *American Economic Journal: Macroeconomics*, 2021, *forthcoming.*

Alonso, William et al., "Location and land use. Toward a general theory of land rent.," *Location and land use. Toward a general theory of land rent.*, 1964.

Angel, Shlomo, Jason Parent, Daniel L Civco, and Alejandro M Blei, *Persistent Decline in Urban Densities: Global and Historical Evidence of 'Sprawl'*, Lincoln Institute of Land Policy., 2010.

Bairoch, Paul, "Les trois révolutions agricoles du monde développé: rendements et productivité de 1800 à 1985," *Annales*, 1989, pp. 317–353.

Baum-Snow, Nathaniel and Lu Han, "The microgeography of housing supply," *Work in progress, University of Toronto*, 2019.

Bonnet, Odran, Guillaume Chapelle, Alain Trannoy, Etienne Wasmer et al., "Secular trends in Wealth and Heterogeneous Capital: Land is back... and should be taxed," Technical Report, Sciences Po 2019.

Boppart, Timo, "Structural change and the Kaldor facts in a growth model with relative price effects and non-Gorman preferences," *Econometrica*, 2014, *82* (6), 2167–2196.

_ , Patrick Kiernan, Per Krusell, and Hannes Malmberg, "The macroeconomics of intensive agriculture," Technical Report, Mimeo, Stockholm University 2019.

Brueckner, Jan K, "Analyzing third world urbanization: A model with empirical evidence," *Economic Development and Cultural Change*, 1990, *38* (3), 587–610.

_ and Somik V Lall, "Cities in developing countries: fueled by rural–urban migration, lacking in tenure security, and short of affordable housing," in "Handbook of regional and urban economics," Vol. 5, Elsevier, 2015, pp. 1399–1455.

Budí-Ors, Tomás and Josep Pijoan-Mas, "Macroeconomic Development, Rural Exodus, and Uneven Industrialization," *CEPR DP17086*, 2022.

Bustos, Paula, Bruno Caprettini, and Jacopo Ponticelli, "Agricultural productivity and structural transformation: Evidence from Brazil," *American Economic Review*, 2016, *106* (6), 1320–65.

_ , _ , and _ , "Agricultural productivity and structural transformation: Evidence from Brazil," *American Economic Review*, 2016, *106* (6), 1320–65.

Combes, Pierre-Philippe, Gilles Duranton, and Laurent Gobillon, "The production function for housing: Evidence from France," 2017.

_ , _ , and _ , "The costs of agglomeration: House and land prices in French cities," *The Review of Economic Studies*, 2018, *86* (4), 1556–1589.

_ , _ , _ , and Sébastien Roux, "Estimating agglomeration economies with history, geology, and worker effects," in "Agglomeration economics," University of Chicago Press, 2010, pp. 15–66.

_ , Laurent Gobillon, Gilles Duranton, and Clement Gorin, "Extracting Land Use from Historical Maps Using Machine Learning: The Emergence and Disappearance of Cities in France Extracting Land Use from Historical Maps Using Machine Learning: The Emergence and Disappearance of Cities in France," *mimeo*, 2021.

Comin, Diego A, Danial Lashkari, and Martí Mestieri, "Structural change with long-run income and price effects," *Econometrica*, 2021, *89* (1), 311–374.

Davis, Morris A and Jonathan Heathcote, "The price and quantity of residential land in the United States," *Journal of Monetary Economics*, 2007, *54* (8), 2595–2620.

DeSalvo, Joseph S and Mobinul Huq, "Income, residential location, and mode choice," *Journal of Urban Economics*, 1996, *40* (1), 84–99.

Donaldson, Dave and Richard Hornbeck, "Railroads and American economic growth: A "market access" approach," *The Quarterly Journal of Economics*, 2016, *131* (2), 799–858.

Duranton, Gilles and Diego Puga, "The growth of cities," in "Handbook of economic growth," Vol. 2, Elsevier, 2014, pp. 781–853.

_ and _ , "Urban land use," in "Handbook of regional and urban economics," Vol. 5, Elsevier, 2015, pp. 467–560.

Eckert, Fabian and Michael Peters, "Spatial structural change," 2022.

Fiszbein, Martin, "Agricultural Diversity, Structural Change, and Long-Run Development: Evidence from the United States," *American Economic Journal: Macroeconomics*, 2022, *14* (2), 1–43.

Glaeser, Edward L and Matthew E Kahn, "Sprawl and urban growth," in "Handbook of regional and urban economics," Vol. 4, Elsevier, 2004, pp. 2481–2527.

— , **Joseph Gyourko, and Raven Saks**, "Why is Manhattan so expensive? Regulation and the rise in housing prices," *The Journal of Law and Economics*, 2005, *48* (2), 331–369.

Gollin, Douglas, "Agricultural productivity and economic growth," *Handbook of agricultural economics*, 2010, *4*, 3825–3866.

— , **David Lagakos, and Michael E Waugh**, "Agricultural productivity differences across countries," *American Economic Review*, 2014, *104* (5), 165–70.

— , **Remi Jedwab, and Dietrich Vollrath**, "Urbanization with and without industrialization," *Journal of Economic Growth*, 2016, *21* (1), 35–70.

— , **Stephen L Parente, and Richard Rogerson**, "The food problem and the evolution of international income levels," *Journal of Monetary Economics*, 2007, *54* (4), 1230–1255.

Grossman, Volker and Thomas Steger, *Das House-Kapital: A Long Term Housing & Macro Model*, International Monetary Fund, 2017.

Heblich, Stephan, Stephen J Redding, and Daniel M Sturm, "The Making of the Modern Metropolis: Evidence from London," Working Paper 25047, National Bureau of Economic Research September 2018.

Herrendorf, Berthold, Richard Rogerson, and Ákos Valentinyi, "Two Perspectives on Preferences and Structural Transformation," *American Economic Review*, December 2013, *103* (7), 2752–89.

— , — , **and** — , "Growth and structural transformation," in "Handbook of economic growth," Vol. 2, Elsevier, 2014, pp. 855–941.

IPCC, "Sustainable development, poverty eradication and reducing inequalities," *Roy, Joyashree and Tschakert, Petra and Waisman, Henri and Halim, Sharina Abdul and Antwi-Agyei, Philip and Dasgupta, Purnamita and Hayward, Bronwyn and Kanninen, Markku and Liverman, Diana and Okereke, Chukwumerije and others*, 2018.

Knoll, Katharina, Moritz Schularick, and Thomas Steger, "No price like home: Global house prices, 1870-2012," *American Economic Review*, 2017, *107* (2), 331–53.

Kongsamut, Piyabha, Sergio Rebelo, and Danyang Xie, "Beyond balanced growth," *The Review of Economic Studies*, 2001, *68* (4), 869–882.

Lagakos, David and Michael E Waugh, "Selection, agriculture, and cross-country productivity differences," *American Economic Review*, 2013, *103* (2), 948–80.

LeRoy, Stephen F and Jon Sonstelie, "Paradise lost and regained: Transportation innovation, income, and residential location," *Journal of Urban Economics*, 1983, *13* (1), 67–89.

Leukhina, Oksana M. and Stephen J. Turnovsky, "Population Size Effects in the Structural Development of England," *American Economic Journal: Macroeconomics*, July 2016, *8* (3), 195–229.

Lewis, W Arthur, "Economic development with unlimited supplies of labour," *The manchester school*, 1954, *22* (2), 139–191.

Matsuyama, Kiminori, "Agricultural productivity, comparative advantage, and economic growth," *Journal of economic theory*, 1992, *58* (2), 317–334.

Mendras, Henri, *La fin des paysans: changement et innovations dans les sociétés rurales françises*, Vol. 110, Colin, 1970.

Michaels, Guy, Ferdinand Rauch, and Stephen J Redding, "Urbanization and structural transformation," *The Quarterly Journal of Economics*, 2012, *127* (2), 535–586.

Miles, David and James Sefton, "House prices and growth with fixed land supply," *The Economic Journal*, 2020.

Mills, Edwin S, "An aggregative model of resource allocation in a metropolitan area," *The American Economic Review*, 1967, *57* (2), 197–210.

Muth, Richard, "Cities and Housing," *Chicago: University of Chicago Press*, 1969.

Nichols, Donald A, "Land and economic growth," *The American Economic Review*, 1970, *60* (3), 332–340.

Piketty, Thomas and Gabriel Zucman, "Capital is back: Wealth-income ratios in rich countries 1700–2010," *The Quarterly Journal of Economics*, 2014, *129* (3), 1255–1310.

Redding, Stephen J, "Suburbanization in the United States 1970-2010," Technical Report, National Bureau of Economic Research 2021.

_ **and Esteban Rossi-Hansberg**, "Quantitative spatial economics," *Annual Review of Economics*, 2017, *9*, 21–58.

Restuccia, Diego, Dennis Tao Yang, and Xiaodong Zhu, "Agriculture and aggregate productivity: A quantitative cross-country analysis," *Journal of monetary economics*, 2008, *55* (2), 234–250.

Ricardo, David, *The Works and Correspondence of David Ricardo, Vol. 1: Principles of Political Economy and Taxation*, Online Library of Liberty, 1817.

Schultz, Theodore William, *The economic organisation of agriculture*, McGraw-Hill, 1953.

Sicsic, Pierre, "City-farm wage gaps in late nineteenth-century France," *Journal of Economic History*, September 1992, *52* (3), 675–695.

Teignier, Marc, "The role of trade in structural transformation," *Journal of Development Economics*, 2018, *130*, 45–65.

Toutain, Jean-Claude, *La production agricole de la France de 1810 à 1990: départements et régions: croissance, productivité, structures* number 17, Presses universitaires de Grenoble, 1993.

Uy, Timothy, Kei-Mu Yi, and Jing Zhang, "Structural change in an open economy," *Journal of Monetary Economics*, 2013, *60* (6), 667–682.

Young, Alwyn, "Inequality, the urban-rural gap, and migration," *The Quarterly Journal of Economics*, 2013, *128* (4), 1727–1785.