Structural Transformation of Land and the Carbon Balance

Nicolas Coeurdacier (Sciences Po and CEPR)
Cecile Gaubert (UC Berkeley, NBER and CEPR)
Emeric Henry (Sciences Po and CEPR)

June 28, 2026

Abstract

Structural transformation reallocates not only labor but also land—across agriculture, cities, and forests—, reshaping the carbon balance of the economy. We develop a quantitative spatial model in which agriculture, cities, and forestry compete for land, and calibrate it to newly assembled data for France covering 1950–2020 and some 1,500 regions. In the model, higher agricultural productivity raises a location's farmland in the cross-section, but lowers it economy-wide once prices adjust. As agricultural productivity increases in the aggregate, land leaves farming, forests expand in rural areas, and cities sprawl. The quantification reveals that on its own, this structural change would have reallocated even more land out of agriculture, but agricultural subsidies, tilted toward less productive regions, hold some of it back. The carbon implications that run through land use are ambiguous—forests store carbon while sprawling cities emit more—and in our empirical setting the latter dominates, making the reallocation of land that followed structural change a net source of emissions.

1 Introduction

Economic development is characterized by a gradual reallocation of resources across sectors. The shift of labor out of agriculture and into manufacturing and services that accompanies structural transformation is well documented. Less attention has been paid to a parallel transformation of land use. Yet structural transformation not only reallocates workers and production across sectors, it also reallocates land across agriculture, forests, and urban uses. These shifts are also shadowed by policy: as agriculture contracts, governments have steadily expanded support to the sector, so that subsidies are almost a mechanical companion of structural change. Understanding how economic development reshapes the allocation of land—and how far agricultural policy has reshaped it in turn—is a central objective of this paper.

The long-run evolution of land use in France illustrates these forces very clearly. Since 1950, agricultural land has declined by almost 20 percent, while urban land has more than tripled and forest cover has expanded by roughly 50 percent. These patterns hold qualitatively across much of the developed world. At the same time, governments have implemented large agricultural support programs, most notably through the European Common Agricultural Policy (CAP), transferring resources toward rural areas and influencing land reallocation.

These changes matter not only because they reshape where people live and work, a central concern in spatial and urban economics, but also because they fundamentally alter the carbon balance of the economy. Land use is a major determinant of greenhouse gas emissions. Forests absorb carbon, and urban sprawl influences emissions: as cities sprawl, energy used for housing increases and commuting distances lengthen. These channels are first-order: in France, housing and commuting account for about 40 percent of emissions, while forests offset roughly a quarter as a carbon sink. As structural transformation reallocates land across these competing uses, it can generate large shifts in emissions. Yet this environmental dimension of structural transformation remains largely unexplored.

This paper asks two related questions. How does economic development, through structural transformation, reshape land use and carbon emissions? And to what extent have agricultural policies altered this process? To answer these questions, we develop a quantitative spatial model in which agriculture, forestry, and cities compete for land. Technological progress and demographic change drive structural transformation and resulting emissions, while heterogeneous local productivities determine where land is reallocated. We estimate the model using newly assembled spatial data for France covering the period 1950-2020 and use it to quantify the effects of technological change and agricultural subsidies on land use and emissions.

The spatial dimension is central to these questions. Structural transformation is driven by aggregate forces, but land reallocation occurs locally. Productivity, agricultural subsidies, and land suitability vary substantially across locations, implying that identical aggregate shocks can generate very different local outcomes. In remote rural areas, land released from agriculture is more likely to be converted into forests, whereas in urban and peri-urban areas it tends to accommodate housing and urban expansion. Because carbon sequestration and emissions associated with housing and commuting also vary across space, the carbon consequences of structural transformation depend critically on where land is reallocated. Understanding these consequences therefore requires a spatial framework linking aggregate economic change to local land-use decisions.

The paper proceeds as follows. First, we build a quantitative spatial model of land use and carbon emissions. In a closed economy partitioned into small units, several production sectors compete for land in each location: rural sectors– agriculture and forestry–, an urban and a housing sector. Housing is local, other goods freely traded. On the supply-side, sectors are heterogeneous in their land intensity and productivity, which also varies across regions. Subsidies, heterogeneous across space and sectors, distort production decisions. On the demand-side, non-homothetic (Stone-Geary) preferences drive the consumption of goods from each sector with agricultural goods as necessities. Workers sort across regions and sectors depending on wages, housing costs, amenities and commuting costs between residence and workplace. Equilibrium conditions determine goods and factor prices, the spatial distribution of land use, labor and population. This translates into emissions as a by-product of the allocation—emissions due to housing, commuting and the production of each sector, but also storage in forests.

This framework accounts for the main drivers of land use across space and time. *Across space*, land use is driven by local technological differences, adjusted for subsidies, and amenities. Regions that are more populated, more productive in the labor-intensive urban sector, or richer in amenities have more built-up land; this expansion is checked by the value of land in rural uses– the opportunity cost of enlarging the urban footprint. For the forest-agriculture split, comparative advantage logic applies: regions relatively more productive in agriculture use land for farming—more so if subsidized. *Across time*, across equilibria in general equilibrium, cross-sectional predictions are reversed when productivity evolves in all regions: higher aggregate agricultural productivity *reduces* agricultural land use. Rising agricultural productivity makes the necessity good less valuable, reallocating factors away from agriculture, increasing forest cover and urban sprawl. Compensating agricultural policies mitigate this agricultural decline. Importantly, the incidence across regions of aggregate changes depend on their specialisation: in rural regions less specialized in agriculture, farmland declines more to the benefit of forests; in very urban regions, urban footprint expands the most. These stark predictions, across space and time, are derived in a tractable version of the model. They are reminiscent of two competing views regarding agricultural expansion: Jevons' Paradox, locally, versus Borlaug Hypothesis, globally (see also Matsuyama (1992)).

Second, we assemble coherent data on land use for France over 1950–2020 at a granular level (about 1,500 regions). Qualitatively, the stylized facts line up with the theory. Over the period, agricultural land recedes especially where it is least productive, forests expand in rural areas, and built-up land spreads around cities. Using multiple sources, we also put together data over 1950-2020 on sectoral employment, wages, prices, agricultural revenues and subsidies—digitizing historical records to get back in time. This large data effort provides the necessary sectoral spatial inputs for a quantitative evaluation since 1950. They are combined with sectoral emissions used for the carbon accounting of France since 1970.

Third, we map theory to data, calibrating the quantitative model of land use and emissions over 1950–2020. The calibrated model is used, first, as a laboratory to disentangle the drivers of land use change and emissions over space and time, specifically the role of technology and agricultural subsidies. A uniform rise in sectoral productivities to their 2020 levels already reproduces the broad reallocation—agriculture retreats, forests expand in rural areas, and cities sprawl—and on its own fits the data quite well. However, that fit is deceptive: the productivity gains were in fact higher in initially more productive regions, and these heterogeneous changes alone would have pushed far more land out of agriculture and into forest than is observed. What holds back this overshoot is agricultural policy.

On net, structural change has two distinct carbon effects. By shifting production from emission-intensive agriculture toward cleaner urban sectors, it lowers emissions per unit of GDP by more than half. Its effect through land use has an ambiguous sign—forests store carbon while sprawling cities emit more—. The latter quantitatively dominates in our empirical context, making the land reallocation that followed structural change a net source of emissions. We find that subsidies have preserved agricultural land, in more deprived regions but also in the aggregate, increasing carbon emissions by about 10%. Importantly, the geography of subsidies, tilted towards less productive regions, is crucial to understand their aggregate effects: a uniform subsidy of the same budget barely moves the allocation. In a last step, we perform policy counterfactuals for possible reforms of the CAP in line with the environmental objectives of the European Union.

Related literature This paper relates to several strands of research in spatial economics, in the macroeconomics of structural transformation and in environmental and land change sciences. It contributes to the field of economic geography and quantitative spatial economics (QSE) surveyed in Redding and Rossi-Hansberg (2017) by developing a quantitative theory of land use where several heterogeneous sectors compete for land across the entire territory. Emphasizing the drivers of urban sprawl and urban density, including commuting technology (see, among others, Glaeser and Kahn (2004), Baum-Snow (2007, 2020), Ahlfeldt et al. (2015), Combes et al. (2019) and Heblich et al. (2020); see also survey by Duranton and Puga (2015)), previous literature focuses on the allocation of factors within urban boundaries, while we also study land use beyond urban landscapes. Using similar quantitative tools, our setting also relates to the spatial modelling of land use in rural sectors, within agriculture (Costinot et al. (2016), Sotelo (2020), Domínguez-Iino (2026)) or between forestry and agriculture, often with a specific focus on tropical deforestation (see, among others, Souza-Rodrigues (2019), Delacote et al. (2021), Assunção et al. (2023), Salazar Restrepo and Leite Mariante (2024), Araujo et al. (2023), Araujo (2024), Farrokhi et al. (2025), Prakash (2026), Szerman et al. (2026), Imbert et al. (2026)). Our approach incorporates in general equilibrium interactions with urban sectors (manufacturing and services) on the consumption and production side—a relevant aspect for aggregate productivity and carbon emissions since agriculture and forestry also compete with urban sectors on product and factor markets. Importantly, at the margin of cities, the value of land used for agriculture or forestry determines the opportunity cost of expanding cities and matters for urban sprawl and related emissions from housing, commuting and land use change. We also contribute to the related literature in spatial environmental economics (surveyed Balboni and Shapiro (2025)). Recent work investigates the role of the spatial distribution of economic activity for climate change adaptation (Conte et al. (2021), Conte et al. (2025), Bilal and Rossi-Hansberg (2023), Cruz and Rossi-Hansberg (2024)) and the impact of environmental policies and the climate on land use dynamics (Grosset-Touba et al. (2024), Hsiao (2026), Du Puy (2026), Hsiao et al. (2026)). This paper focuses on the effects of structural transformation and compensating agricultural policies on land use and carbon emissions. Covering the different sectors of the economy and the entire territory, the framework provides an integrated quantitative assessment of the reallocation of factors across space and sectors on the carbon balance.

Our approach investigating the sectoral reallocation of production factors over a long-period is also linked to the macro literature on structural transformation (surveyed in Herrendorf et al. (2014)). Related papers also investigates the spatial dimension of structural change (Caselli and Coleman (2001), Michaels et al. (2012), Desmet and Rossi-Hansberg (2014), Fajgelbaum and Redding (2022), Eckert and Peters (2025), Budí-Ors and Pijoan-Mas (2025), Coeurdacier et al. (2025)). Compared to these papers, we incorporate land use reallocation across heterogeneous sectors along the process of development and urbanization. This allows us to disentangle the environmental impact of structural transformation.

More broadly, this paper relates to the measurement and analysis of land use dynamics in geography and land change science (Turner et al. (2007)), where we deepen the modelling of equilibrium economic forces and interactions across diverse sectors using methodological tools from QSE for theories of land use. From an empirical perspective, the paper relates to studies investigating the importance of the structure and density of cities for environmental concerns (see, among others, Ribeiro et al. (2019), Glaeser and Kahn (2010), Eeckhout and Christoph (2021) and the meta-analysis in Ahlfeldt and Pietrostefani (2019)), the measurement of carbon footprints across space (e.g. Jones and Kammen (2014) for the US), the historical measurement of land use dynamics (Ellis et al. (2013), Winkler et al. (2021), Gorin et al. (2025) for France) and the role of land use changes in agriculture/forestry for climate change mitigation (IPCC (2022)).

The paper is organized as follows. Section 2 develops a quantitative theory of land use. Section 3 describes the French data over the period 1950-2020. Data are used in Section 4 to describe the evolution of land use, agricultural policies and carbon emissions in France over the period. Section 5 estimates the model using the same data. Section 6 provides counterfactuals to isolate the role of structural transformation and agricultural policies on land use and carbon emissions and sheds light on the effect of policy reforms on welfare and emissions.

2 A Quantitative Theory of Land Use

2.1 Model Setup

At a given date, we consider an economy populated by N workers and comprised of many small regions $i \in \{1, ..., J\}$ endowed with land $\bar{Q}_i$. The distance to commute from i to j is defined by d_{ij}. Within each region $i \in \{1, ..., J\}$, different sectors employ workers and compete for land: two rural sectors (agriculture and forestry), an urban sector meant to capture manufacturing and services, and a housing sector. Sectors are heterogeneous in their land intensity and their productivity, the latter also varies across regions. Workers choose where to live and where to work, accounting for heterogeneous costs of living, wages, commuting costs and local amenities. Time subscripts are omitted for convenience.

Technology Production of output $Y_{i,s}$ in sector s and region i combines land with other inputs with different land-use intensities, namely:

$$Y_{i,s} = T_{i,s} \left(\frac{L_{i,s}}{\alpha_s}\right)^{\alpha_s} \left(\frac{Q_{i,s}}{\beta_s}\right)^{\beta_s} \quad \text{for s} \in \{a, f, u\}, \tag{1}$$

$$Y_{i,s} = T_{i,s} \left(\frac{I_{i,s}}{\alpha_s}\right)^{\alpha_s} \left(\frac{Q_{i,s}}{\beta_s}\right)^{\beta_s} \quad \text{for s} \in \{h\}, \tag{2}$$

where s indexes sectors ($a$griculture, $f$orestry, $u$rban or $h$ousing), $T_{i,s}$ is productivity and inputs are labor $L_{i,s}$, land $Q_{i,s}$ and intermediate urban inputs $I_{i,s}$. We allow for decreasing returns to scale (DRS)[1] in rural sectors $r \in \{a, f\}$, $\nu_r = \alpha_r + \beta_r \leq 1$. Constant returns to scale (CRS) are assumed in sectors $s \in \{u, h\}$, $\nu_s = \alpha_s + \beta_s = 1$,

---

[1] Decreasing returns embody the notion that expanding regional production requires cultivating less fertile land and strains fixed rural resources, such as water.

and for simplicity, the urban sector uses only labor, $\alpha_u = 1$. Rural and urban goods are freely traded at price p_s for $s \in \{a, f, u\}$, while housing is a non-traded good with price $p_{i,h}$ that is region-specific. The urban good is the numeraire.

Preferences and budget constraint We follow the literature on structural transformation surveyed in Herrendorf et al. (2014) in assuming that preferences are non-homothetic in agricultural vs non-agricultural good. Specifically, the utility of worker ω when living in i and working in j in sector s is Stone-Geary:

$$u_{i,j,s} = A_{i,j,s} \cdot c_h^{\gamma} c_u^{\gamma_u(1-\gamma)} c_f^{\gamma_f(1-\gamma)} \left(c_a - \underline{a}\right)^{\gamma_a(1-\gamma)} \varepsilon_{i,j,s}\left(\omega\right), \tag{3}$$

where c_s is the consumption of good s, $\underline{a}$ is the subsistence need in agricultural goods, and $\varepsilon_{i,j,s}\left(\omega\right)$ is the idiosyncratic preference of worker ω for choice i, j, s. The composite amenity adjusted for commuting costs between i and j,

$$A_{i,j,s} = \frac{A_i \cdot A_{j,s}}{d_{i,j}^{\xi}},$$

combines a residential amenity A_i and a sector-specific work amenity $A_{j,s}$ and is discounted by commuting costs. These costs increase in distance $d_{i,j}$ with a constant elasticity ξ. Households' budget constraint is

$$p_{i,h} c_h + \sum_{s=a,f,u} p_s c_s = w_{j,s} + \pi, \tag{4}$$

where $w_{j,s}$ denotes the wage rate in region j and sector s, and π is a claim to aggregate land rents and profits in the country net of lump-sum taxes (described below), equal for all workers.

Subsidies and taxes Producers receive a subsidy per unit of output in rural sectors $r \in \{a, f\}$ in region i, denoted $s_{i,r}$, so that rural revenues in region i are $p_r(1+s_{i,r})Y_{i,r}$. Subsidies are financed lump-sum equally across all workers and $\mathbb{S}_r = \sum_i p_r s_{i,r} Y_{i,r}$ denotes the aggregate amount of subsidies to sector r.

Urban land premium In all regions i, land is freely allocated across rural uses, implying that land rents are equalized between agriculture and forestry, $\rho_i = \rho_{i,a} =$

$\rho_{i,f}$. Land used for housing, however, commands a region-specific premium $m_i \geq 1$, such that:

$$\rho_{i,h} = m_i \rho_i. \tag{5}$$

The premium m_i captures the heterogeneity of land value within a given built-up area.[2] The premium m_i can also incorporate the servicing costs of equipped land (e.g. sewage, electricity, ...) and/or the presence of regulations limiting the conversion of rural land into built-up.

2.2 Equilibrium Allocation

Household choices We assume that the preference shocks $\varepsilon_{i,j,s}(\omega)$ for the triplet i, j, s are distributed Frechet, with shape parameter κ. Given the properties of the Frechet distribution, the number of workers living in i and working in j in sector s is a simple function of the indirect utility of choice i, j, s:

$$N_{i,j,s} = N \frac{\left(V_{i,j,s}\right)^{\kappa}}{\sum_{i'j's'} \left(V_{i',j',s'}\right)^{\kappa}}, \tag{6}$$

with, given expenditures under Stone-Geary utility (3) and the budget constraint (4):

$$V_{i,j,s} = \chi A_{i,j,s} \cdot \frac{w_{j,s} - p_a \underline{a} + \pi}{p_{i,h}^{\gamma}}. \tag{7}$$

Workers' choices are driven by sectoral wages $w_{j,s}$ at workplace j, residential housing costs $p_{i,h}$ and amenities adjusted for commuting costs, $A_{i,j,s}$.

Firms' optimization Firms in all sectors are perfectly competitive. Profit maximization implies that their marginal cost equates output price, so that for all traded sectors $s \in \{a, f, u\}$, given (1):

$$p_s = \left(\frac{w_{j,s}^{\alpha_s} {\rho_j}^{1-\alpha_s}}{(1 + s_{j,s}) T_{j,s}} \right) \left(\frac{Q_{j,s,t}}{\beta_s} \right)^{1-\nu_s} \tag{8}$$

---

[2] More centrally located neighborhoods provide better access to amenities, which is capitalized in the housing land rental price. A wedge emerges between the rental price of rural land at the urban fringe ρ_i and the average price within the built-up area, $\rho_{i,h}$.

where the second term in bracket adjusts for the possibility of DRS in rural sectors, $s \in \{a, f\}$. In addition, in each rural sector, relative input demand is

$$L_{j,s} = \frac{\alpha_s}{\beta_s} \frac{\rho_j}{w_{j,s}} Q_{j,s}. \tag{9}$$

For the urban sector, Eq. (8) boils down to $w_{j,u} = T_{j,u}$ while in the non-traded housing sector:

$$p_{j,h} = (m_j \rho_j)^{1-\alpha_h}. \tag{10}$$

Profits and land rents With decreasing returns, profits in each region-sector are equal to $(1 - \nu_r) p_r (1 + s_{j,r}) Y_{j,r}$. Therefore, net claims to profits π satisfy:

$$\pi N = \sum_{j,s} \left(\rho_{j,s} Q_{j,s} + (1 - \nu_s) p_s (1 + s_{j,s}) Y_{j,s} - p_s s_{j,s} Y_{j,s} \right). \tag{11}$$

Equilibrium definition An equilibrium of the model is output prices p_s for $s \in \{a, f\}$, land prices $\{\rho_j\}_j$, housing prices $\{p_{j,h}\}_j$ and wages $\{w_{j,s}\}_{j,s}$ for each region such that:

1. Land markets clear locally: $\forall j \in [1, ..., J]$, $\sum_s Q_{j,s} = \bar{Q}_j$.
2. Labor markets clear locally: $\forall j \in [1, ..., J], \sum_{i,s} N_{i,j,s} = L_{j,s}$.
3. Housing markets clear locally: $\forall i \in [1, ..., J]$, $m_i \rho_i Q_{i,h} = (1 - \alpha_h) \gamma \sum_{j,s} N_{i,j,s} \cdot (w_{j,s} - p_a \underline{a} + \pi)$.
4. Rural markets clear nationally: $p_s \sum_i Y_{i,s} = \sum_{i,j,s'} N_{i,j,s'} \left(p_s \underline{s} + (1 - \gamma) \gamma_s \cdot (w_{j,s'} - p_a \underline{a} + \pi) \right)$ for $s \in \{a, f\}$

The market for urban goods clears by Walras' law.

2.3 Emissions and Welfare

Emissions as a by-product Greenhouse gas emissions arise as a by-product of the equilibrium allocation of production, land and people across space. We distinguish five sources—production in each of the three sectors (a, f, u), residential energy use (housing), and commuting—and express all of them in CO_2 equivalent. Total emissions are the sum of these components, $E = \sum_{s \in \{a,f,u,h,c\}} E_s$.

For the three traded sectors $s \in \{a, f, u\}$, emissions combine a production and a land-cover component,

$$E_s = \mu_s \left(\sum_i Y_{i,s} \right) + \sum_i \lambda_{i,s} Q_{i,s},$$

The first term is proportional to output, with μ_s the emission intensity of production in sector s. The second is proportional to land cover, where $\lambda_{i,s}$ is the net carbon released ($\lambda_{i,s} > 0$) or stored ($\lambda_{i,s} < 0$) per unit of land used by sector s in region i: forests are carbon sinks ($\lambda_{i,f} < 0$), whereas cultivated land tends to release soil carbon ($\lambda_{i,a} > 0$). We let this intensity vary across regions, as the carbon-storage capacity of forests is itself spatial.[3]

Housing generates emissions both through energy use—heating, in particular—and through the land it covers. Summing across regions,

$$E_h = \mu_h \left(\sum_i N_i \left(\frac{Y_{i,h}}{N_i} \right)^{\epsilon_h} \left(\frac{N_i}{Q_{i,h}} \right)^{\epsilon_{h,r}} \right) + \lambda_h \left(\sum_i Q_{i,h} \right), \tag{12}$$

where N_i is the residential population of region i and $Y_{i,h}/N_i$ is housing consumption per resident, our measure of dwelling size. Energy-use emissions (first term) increase with dwelling size ($\epsilon_h \geq 0$) but fall with residential density ($\epsilon_{h,r} \leq 0$), as denser housing is cheaper to heat per unit; the second term is the carbon released by built-up land cover.

Commuting emissions rise with distance but may fall with density, since denser areas rely more on public transport and smaller cars,

$$E_c = \mu_c \sum_{i,j,s} N_{i,j,s} \left(d_{i,j}\right)^{\epsilon_d} \left(\frac{N_i}{Q_{i,h}} \right)^{\epsilon_{c,r}} \left(\frac{N_j}{Q_{j,h}} \right)^{\epsilon_{c,w}}, \tag{13}$$

where $\epsilon_d \geq 0$ is the elasticity with respect to commuting distance and $\epsilon_{c,r}, \epsilon_{c,w} \leq 0$ those with respect to residential and workplace density. We estimate both the housing and commuting elasticities on granular 2020 data, justifying these functional forms empirically (Section 4.3).

---

[3] Forests in regions with a milder climate are better carbon sinks per unit of land, being less exposed to heatwaves, fires and parasites, as detailed in the appendix.

Welfare Welfare is the sum of utilities across all locations and choices, net of the social cost of aggregate emissions,

$$W = U - \lambda E, \tag{14}$$

where λ is a parameter measuring how a planner weights emissions, and $U = \Gamma \left(\sum_{i,j,s} V_{i,j,s}^{\kappa} \right)^{1/\kappa}$. The constant $\Gamma \equiv \Gamma_f \big(1 - \frac{1}{\kappa}\big)$, where $\Gamma_f(\cdot)$ denotes the Gamma function, arises from aggregating the Fréchet-distributed idiosyncratic preferences and is well-defined for $\kappa > 1$.

2.4 Land Allocation in the Model

To gain intuition on how land is allocated across uses in the theory, we proceed in two steps. First, we describe the cross-sectional distribution of land use across regions, in a given equilibrium of the model - that is, taking general equilibrium prices p_a and p_f as given. This sheds light on how technological differences across regions and sectors map into cross-sectional differences in land use specialization. Second, we derive comparative statics of the model with respect to aggregate shocks, such as changes in agricultural TFP. We illustrate how land use allocation, in the aggregate and across regions, evolve due to the general equilibrium response of prices p_a and p_f to aggregate shocks.

2.4.1 Land use across regions (within an equilibrium)

In this section, we help build intuition by focusing on a special case of the model that is solvable with pencil and paper. Proofs are relegated to the appendix.

We focus on the empirically relevant case where agriculture is less land intensive than forest, $\beta_a/\alpha_a < \beta_f/\alpha_f$ (equivalently $\beta_a < \beta_f$ if $\nu_a = \nu_f$). We consider the special case with no cross-region commute ($d_{ij} = \infty$ for $i \neq j$), no subsidies ($s_{i,r} = 0$), no urban land premium ($m_i = 1$), residential amenity only ($A_{j,s} = 1$), housing uses only land ($\alpha_h = 0$) and firms and land are owned by absentee landlords. We also consider for now the case of homothetic demand ($\underline{a} = 0$). This assumption is intuitively innocuous when studying cross-sectional allocation of land: the value of $\underline{a}$ matters for how equilibrium rural prices p_a, p_f are determined, not for the cross-sectional allocation of resources conditional on prices.

In what follows we show that the equilibrium allocation of land between housing, agriculture and forestry, given total land supply in a region, satisfies two equations. The first one can be thought of as the supply of rural land, where we define rural land as $Q_{i,r} = Q_{i,a} + Q_{i,f}$. Specifically, the supply of rural land is total land supply net of land used for housing. The second one is demand for rural land.

Lemma 1. *The supply of rural land* $Q^S_{i,r}$ *and the demand for rural land* $Q^D_{i,r}$ *are respectively:*

$$Q^S_{i,r} = \frac{\beta_f}{\beta_f + \gamma\alpha_f}\bar{Q}_i - \frac{\gamma\beta_f}{\beta_f + \gamma\alpha_f} \cdot \mathbb{H}(Q_{i,a}), \tag{15}$$

$$\textit{and } Q^D_{i,r} = \mathbb{R}(Q_{i,a}) \cdot Q_{i,a}, \tag{16}$$

where $\mathbb{H}'(Q_{i,a}) > 0$ *and* $\mathbb{R}(Q_{i,a}) > 1,\ \mathbb{R}'(Q_{i,a}) > 0$*; the two curves cross once.*[4]

Equation (15) is the supply of rural land, total land net of housing. It falls as $Q_{i,a}$ rises: more agricultural land lowers the marginal product of land and hence land prices, all else equal, cheapening housing and crowding out rural land.[5] This operates through the housing-demand term $\mathbb{H}(Q_{i,a})$, which is increasing. The curve shifts intuitively with local fundamentals: housing demand is stronger, and rural land correspondingly scarcer, where a location is more attractive to residents or urban workers ($\partial\mathbb{H}/\partial T_{i,u}$, $\partial\mathbb{H}/\partial A_i > 0$), and weaker where agricultural productivity is higher ($\partial\mathbb{H}/\partial T_{i,a} < 0$)—more productive farmland limiting built-up.

Equation (16) is the demand for rural land: within the rural area, land is split between agriculture and forest to equalise the return to land across usage. The property $\mathbb{R}' > 0$ means the forest share of rural land rises as the rural area expands — $Q_{i,r}$ grows faster than $Q_{i,a}$. The intuition runs through the land price: a more abundant rural area carries a lower land price, which favours forest, the more land-intensive use. Together, the two curves pin down $(Q_{i,a}, Q_{i,f}, Q_{i,h})$ in each region (Figure 1).

---

[4] The functions $\mathbb{R}(.)$ and and $\mathbb{H}(.)$ can be fully solved as a function of model parameters and general equilibrium quantities. Namely, $\mathbb{H}(Q_{i,a}) = \frac{T_{i,u}L_{i,u}}{\rho_i} + \left(\frac{\alpha_a}{\beta_a} - \frac{\alpha_f}{\beta_f}\right) Q_{i,a}$ where $\frac{L_{i,u}}{\rho_i} = \xi \cdot T^{\kappa}_{i,u} \cdot (p_a T_{i,a})^{-\frac{(1+\kappa)(1+\gamma\kappa)}{1+\kappa(1-\alpha_a+\gamma\alpha_a)}} \cdot A_i^{\frac{(1+\kappa)\kappa(1-\alpha_a)}{1+\kappa(1-\alpha_a+\gamma\alpha_a)}} \cdot Q_{i,a}^{\frac{(1+\gamma\kappa)\alpha_a}{1+\kappa(1-\alpha_a+\gamma\alpha_a)}}$ and $\mathbb{R}(Q_{i,a}) = 1 + \Omega \cdot Q^{\zeta}_{i,a} \, (p_a A_i T_{i,a})^{-\omega(1+\kappa)/(\alpha_f(1-\gamma))} \cdot \left(\frac{p_a}{p_f}\right)^{-(1+\kappa)/\alpha_f} \cdot \left(\frac{T_{i,a}}{T_{i,f}}\right)^{-(1+\kappa)/\alpha_f}$, where we have used $(1 + \omega)\alpha_a/\alpha_f = 1 + \zeta$, and $1 + \omega = (1 + \kappa\mu_f)/(1 + \kappa\mu_a)$, and $\mu_r = ((1 - \alpha_r) + \gamma\alpha_r)$.

[5] A second, smaller channel is at play: higher agricultural production hires more rural workers, who also demand housing.

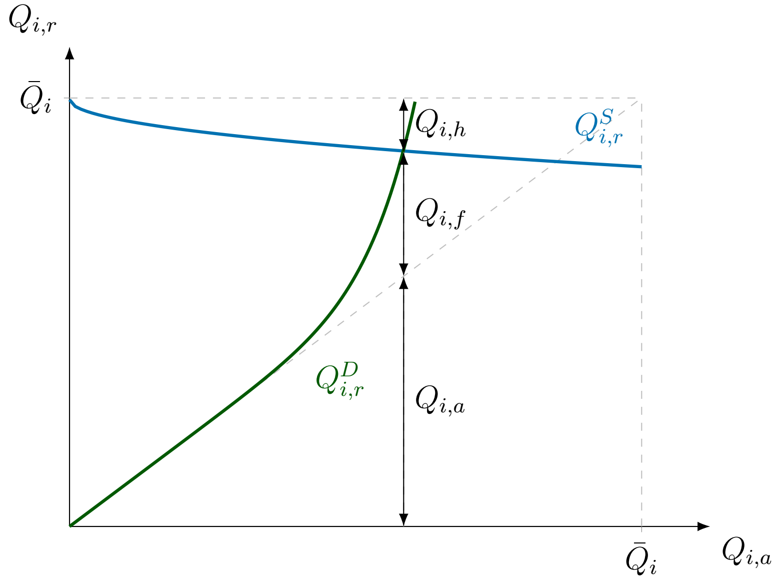


Figure 1: Equilibrium allocation of land in a region. The supply $Q^S_{i,r}$ and demand $Q^D_{i,r}$ for rural land cross at a unique point, fixing agricultural land $Q_{i,a}$; total land $\bar{Q}_i$ then splits into agriculture, forest $Q_{i,f}$, and housing $Q_{i,h}$.

Proposition 1. *The following comparative statics describe the allocation of land uses across regions, in a given equilibrium:*

- *Urban TFP:* $\frac{\partial Q_{i,h}}{\partial T_{i,u}} > 0$, $\frac{\partial Q_{i,a}}{\partial T_{i,u}} < 0$, $\frac{\partial Q_{i,f}}{\partial T_{i,u}} < 0$, $\frac{\partial}{\partial T_{i,u}}\left(\frac{Q_{i,a}}{Q_{i,a}+Q_{i,f}}\right) > 0$,[6] *and* $\frac{\partial \rho_i}{\partial T_{i,u}} > 0$;
- *Agricultural TFP:* $\frac{\partial Q_{i,a}}{\partial T_{i,a}} > 0$, $\frac{\partial Q_{i,f}}{\partial T_{i,a}} < 0$, $\frac{\partial}{\partial T_{i,a}}\left(\frac{Q_{i,a}}{Q_{i,a}+Q_{i,f}}\right) > 0$, *and* $\frac{\partial \rho_i}{\partial T_{i,a}} > 0$ *(the effect on* $Q_{i,h}$ *is ambiguous);*
- *Forest TFP:* $\frac{\partial Q_{i,h}}{\partial T_{i,f}} < 0$, $\frac{\partial Q_{i,a}}{\partial T_{i,f}} < 0$, $\frac{\partial Q_{i,f}}{\partial T_{i,f}} > 0$, $\frac{\partial}{\partial T_{i,f}}\left(\frac{Q_{i,a}}{Q_{i,a}+Q_{i,f}}\right) < 0$, *and* $\frac{\partial \rho_i}{\partial T_{i,f}} > 0$.

The model predicts, quite intuitively, that zones productive in the urban sector specialise their land use in cities. The rural land they retain, moreover, leans towards agriculture rather than forest: urban productivity raises land rents, and expensive land favours the less land-intensive use. At the other end of the spectrum, low urban productivity regions where land is cheap specialise in forest, the most land-intensive use. Note that the same logic applies when the residential amenity rises in place of

---

[6] The rural-share sign under $T_{i,u}$ additionally requires forest land to be more rent-elastic, $B_f > B_a$; this follows from the land-intensity condition under common returns $\nu_a = \nu_f$. The other comparative statics need only $\beta_a/\alpha_a < \beta_f/\alpha_f$.

urban productivity.[7]

Naturally, forest (resp. agricultural) land use is higher where forest (resp. agricultural) productivity is higher. Higher forest productivity also lowers agricultural and housing land use: as the most land-intensive sector, forestry bids up land rents and makes land scarce for every other use. Higher agricultural productivity also raises land rents, squeezing forests, the most land-intensive sector. However, the effect on residual housing, $Q_{i,h} = \bar{Q}_i - Q_{i,a} - Q_{i,f}$, is ambiguous, increasing if forest contraction outweighs agricultural expansion and falling otherwise. Equivalently, $Q_{i,h} = \gamma I_i/\rho_i$ combines two forces that both rise with $T_{i,a}$, resident income I_i and the rent ρ_i.

2.5 Land use response to aggregate shocks (GE)

We now ask: how does land use respond to a shock to aggregate sectoral productivity or aggregate population? To that end, we crucially restore the non-homothetic preferences channel ($\underline{a} \geq 0$), as it is the channel driving the land use response to an aggregate shock.

Homogeneous regions For tractability, we start by shutting down heterogeneity across regions. Subscripts i are temporarily removed.

Proposition 2. *With homogeneous regions, CRS in rural sectors ($\nu_a = \nu_f = 1$) and land-only housing ($\alpha_h = 0$), the share of land allocated to each sector $s \in \{a, f, h\}$ is*

$$\frac{Q_s}{\bar{Q}} = \frac{\theta_s + \beta_a \frac{p_a \underline{a}}{I} \mathbf{1}_{s=a}}{\sum_s \theta_s + \beta_a \frac{p_a \underline{a}}{I}},$$

where $\theta_h = \gamma$ and $\theta_s = \beta_s(1-\gamma)\gamma_s$ for $s \in \{a, f\}$ combine each sector's land intensity and expenditure share, and I is per-capita income net of subsistence.[8]

As $\kappa \to \infty$ (perfect sectoral mobility), and provided agricultural output satisfies subsistence ($T_a(\bar{Q}/L)^{\beta_a} > \underline{a}$), the subsistence burden $x \equiv p_a\underline{a}/I$ satisfies:

$$\frac{dx}{dT_a} < 0, \qquad \frac{dx}{dL} > 0, \qquad \frac{dx}{dT_u} = \frac{dx}{dT_f} = 0,$$

---

[7] High residential amenity attracts workers from all sectors, increasing land use for housing. This pressure on land prices hurts the most land-intensive sector (forestry) more than agriculture, tilting rural land use further towards agriculture. In rural (low $T_{i,u}$) regions, a higher residential amenity can even raise Q_a at the expense of a larger drop in Q_f.

[8] $I = \left(\sum_s w_s L_s\right)/L + r - p_a\underline{a}$, with $r = \rho\bar{Q}/L$ the per-capita land-rent rebate.

and $\partial p_a/\partial T_a < 0$*,* $\partial p_a/\partial L > 0$*. Moreover,* $\partial(p_aT_a)/\partial T_a < 0$ *if agriculture is more land intensive than the economy's expenditure-weighted average, a mild condition since urban production uses no land.*

All aggregate land-use changes operate through a single object, the subsistence burden $x = p_a\underline{a}/I$. Under homothetic preferences ($\underline{a} = 0$) it is zero, and land shares are fixed by expenditure shares and land intensities alone. With $\underline{a} > 0$, an increase in agricultural productivity raises agricultural output faster than income-inelastic (subsistence) demand, lowering the agricultural price p_a in general equilibrium and the subsistence burden: factors — land included — reallocate away from agriculture. Urban and forest productivity, which leave the burden untouched, leave every land share unchanged.

A larger population works the other way. With land in fixed supply, more people bid up land rents, raise the cost of agricultural output, and so raise the burden, pulling factors back into agriculture while housing and forest land contract. The pull is stronger the poorer the economy.[9] Aggregate land use is thus a race: agricultural land contracts, freeing land for forest and cities, only when agricultural productivity outpaces population.

Implications across heterogeneous regions We now consider an economy of regions heterogeneous in their productivity and residential amenity hit by a common proportional rise in agricultural productivity. Each small region takes as given relative prices, p_a and p_f, determined in general equilibrium. We investigate how the resulting common shift across regions of $p_aT_{i,a}$ impacts land use heterogeneously across regions depending on their specialization. Under the mild condition of Proposition 2, this common shift, $\Delta\ln(p_aT_{i,a}) = \Delta\ln p_a + \Delta\ln T_a$, is *downward*, p_a falling by more than T_a rises.[10] A proposition in the appendix formalizes the land use response depending on the specialization region i described graphically in Figure 2. The common drop of

---

[9] The semi-elasticity $\partial(Q_a/\bar{Q})/\partial\ln x = (1-\alpha_a)(\theta_f+\theta_h)\,x/(\Theta+(1-\alpha_a)x)^2$ (with $\Theta = \sum_s\theta_s$) is hump-shaped in the burden, peaking at $x = \Theta/(1-\alpha_a)$, where $Q_a/\bar{Q} = (\theta_a+\Theta)/2\Theta$; it weakens beyond the peak.

[10] This holds if and only if $1-\alpha_a > \Theta$, when regions are homogeneous, and by continuity for small heterogeneity across regions. Θ is built from the land shares α_s and preference parameters γ_s, which are common to all regions, so the threshold does not vary with the cross-regional distribution of productivities and amenities; since the equilibrium varies continuously with that distribution and the inequality is strict at homogeneity, the common move stays downward in a neighbourhood of homogeneity.

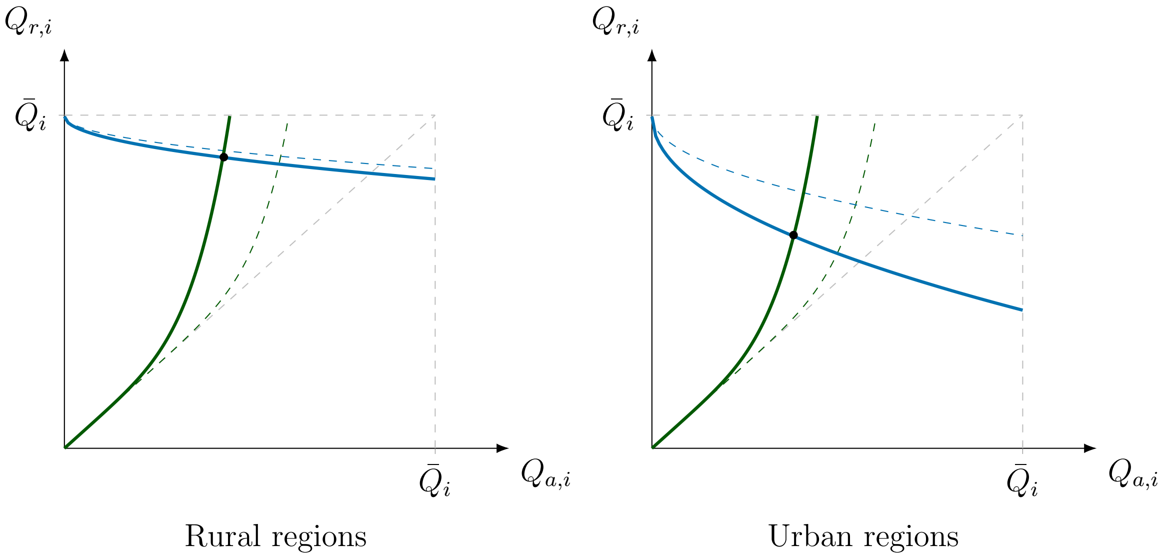


Figure 2: Heterogeneous land use response across regions to a common shift in T_a

$p_a T_{i,a}$ moves downwards the supply of the rural land, $Q^S_{i,r}$, and to the left the demand for rural land, $Q^D_{i,r}$. Intuitively, a drop in $p_a T_{i,a}$ lowers the farmland price, leading to more demand for housing ($Q^S_{i,r}$ shift), and less demand for agricultural land ($Q^D_{i,r}$ shift). In more rural regions (left panel), low $T_{i,u}$ (or low A_i), the downward shift is $Q^S_{i,r}$ is limited as few people live there (at the extreme of $T_{i,u} \to 0$, $\Delta Q^S_{r,i} = 0$). Therefore, the land use reallocation is mostly driven by the shift in $Q^D_{i,r}$, which increases forest cover at the expense of agricultural land. We show that this reallocation is larger in regions with more rural mixed land-use (at the extreme, $\Delta Q_{i,f} \to 0$ in fully specialized regions in either a or f). Urban land, $Q_{i,h}$, is also more likely to contract in regions less specialized in agriculture. In more urbanized regions (right-panel), high $T_{i,u}$ (or high A_i), the downward shift in $Q^S_{i,r}$ is larger, limiting forest expansion, even more so if the region is specialized in forestry (high $T_{i,f}/T_{i,a}$). In other words, while agricultural land always contract, the freed land mostly goes to forestry in rural regions and mostly to urban in more productive and more populated regions.

3 Data

This section provides an overview of the data used to establish stylized facts and calibrate the model. Additional details are provided in the appendix.

Geography and Period We equate the J zones of our model to a granular partition of mainland France. The starting point is the 2,054 French cantons, a granular administrative partition of France. In urban areas, a zone aggregates cantons that are in the same urban area ("aire urbaine").[11] More rural cantons are kept as separate zones. This procedure yields a partition of France into $1,549$ regions. We focus our attention on four cross-sections: $t \in \{1950, 1975, 2000, 2020\}$.

3.1 Land Use

At the heart of our study is a novel dataset describing land use in France since 1950. We start with the *HILDA+* dataset produced by Winkler et al. (2021), which reports the main use of land at a 1 km spatial resolution across Europe on an annual basis. HILDA+ combines satellite imagery for recent decades with a probabilistic reconstruction of historical land use based on auxiliary data sources. We aggregate these data into three categories for each zone: agriculture, forest and built-up (our "urban" category)—leaving aside a small residual share of the territory (e.g. waterbodies, moors, mountains' summits,...).

We assess the accuracy of HILDA+ by comparing it with a range of alternative data sources at different levels of granularity (land use surveys from *Teruti*, alternative satellite data from *Corine*, agricultural Census measures of farmland). Agricultural and forest land are measured very accurately. Urban land, however, exhibits two biases. The build-up in rural areas has a small footprint that the 1km resolution of HILDA+ cannot detect (a downward aggregation bias). Moreover, the extrapolation backwards of HILDA+ assumes that extremely urban locations today were also very urban in the past, which is quite inaccurate for the suburbs of large cities.

From 1975 onward, we redress the data using higher-resolutionsatellite measures of urban built-up (*GHSL*, 250m resolution). We validate the corrected land-use data against independent sources not used in the correction procedure and find that it closely matches alternative measures of urban land use. For 1950, we adjust land-use data backwards using a parametric relationship between built-up growth and residential population growth, estimated on granular land use data available for Ile-de-France at this date.

---

[11] In INSEE's 2010 definition, an "aire urbaine" is a contiguous group of municipalities ("communes", about 36,000 in France) made up of an employment pole with more than 10,000 jobs and its commuting crown.

3.2 Emissions

To quantify the carbon consequences of land reallocation, we construct disaggregated carbon-emissions accounts. Our starting point is the annual greenhouse gas inventories produced by CITEPA, which report emissions in CO_2 equivalents by sector since 1970. We aggregate these data into the production sectors represented in our model—urban production, agriculture, forestry, and housing—as well as emissions from commuting and land cover. For land cover, we use *regional* emissions available from 1990 onward. CITEPA reports emissions from energy production separately; we reallocate these emissions to the sectors using the energy based on official data sources. Our accounting departs from CITEPA's treatment of harvested wood. CITEPA nets wood removals from forest carbon absorption. Instead, we treat wood harvesting as a production activity and allocate the associated carbon emissions to the sectors using wood products. Land cover absorption is entirely driven by carbon sequestration resulting from forest growth.

We also use more granular data on emissions from commuting and housing to calibrate the model. Local commuting emissions are constructed using INSEE's mobility data. Local residential energy consumption is obtained from the Ministry of Environmental Transition, while housing characteristics, including the number of rooms and the construction period, come from the 2022 Population Census.

3.3 Employment, Production and Subsidies

We combine a rich variety of data sources to construct a consistent dataset on production and employment across sectors, years and locations. Table 1 summarizes the variables we construct, together with their sources and coverage. For 1950, the historical sources we digitize are available only at the département level. We allocate them across zones within each département using the earliest available granular within-département distribution.

The construction of agricultural value added and subsidies is more involved and is further detailed. Agricultural value added (including indirect subsidies, e.g. support to agricultural prices, subsidies to buy intermediate inputs, ...) is observed at the département-level and distributed within département in proportion to the value of production observed at a granular level. Direct subsidies (direct transfers to farmers) are observed at the farm-level for recent years and at the département level for earlier dates. Aggregating recent farm-level data and distributing earlier departement-level data proportionately to agricultural factor inputs provides direct subsidies for each zone at the different dates.[12] By definition, agricultural revenues of each zone is the sum of value-added and direct subsidies. Lastly, indirect subsidies are not directly observed in agricultural accounts and constitute, depending on the time period, a significant share of public subsidies. They are recovered in aggregate from the budgets produced by the Ministry of Agriculture.

Table 1: Main employment, population, and production data sources

Data	**Source and coverage**
Residential population	Since 1975: *Census*, employment by place of residence. 1950: digitized declarations '1024' from *Stat. Générale de la France.*
Commuting	2019: *INSEE-SDES* Census-based commuting data - residence-workplace flows, commuting distance and mode.
Employment and wages	Since 1975: *DADS* by workplace for urban wages and wages of salaried agricultural workers and *Census* for urban employment by workplace. 1950: digitized declarations '1024' (see above). Since 1970: *Agricultural Census* for agricultural employment (incl. self-employed). 1950: digitized 1954 *Agricultural Census.*
Agricultural VA and production over space	Digitized *agricultural accounts* (départemental from 1962), Production in value from *Agricultural Census* (farm level, from 1970).
Agricultural subsidies	Direct payments from *agricultural accounts* (départemental from 1962) and farm-level in 2022 (*Telepac*). Aggregate support from digitized public spending since 1950 (Boyer (1999) and *Concours Publics à l'Agriculture*).
Aggregate sectoral value added or production	From 1949: Rural VA (agriculture+forestry), Urban (residual), *INSEE* From 1959, production/VA in agriculture from *agricultural accounts.* Wood production from 1947, *Ministry of Agriculture.*
Sectoral prices	From 1949: Agricultural and urban prices from *INSEE & OECD.* From 1948: Digitized wood prices from *Revue Forestière Française.*

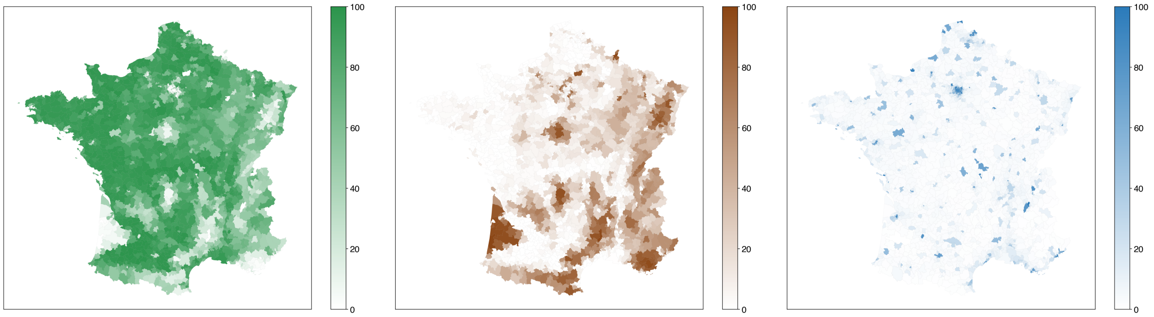
---

[12] Département-level direct subsidies are allocated proportionately to land and labor, with equal weight on both inputs, in line with recent data.

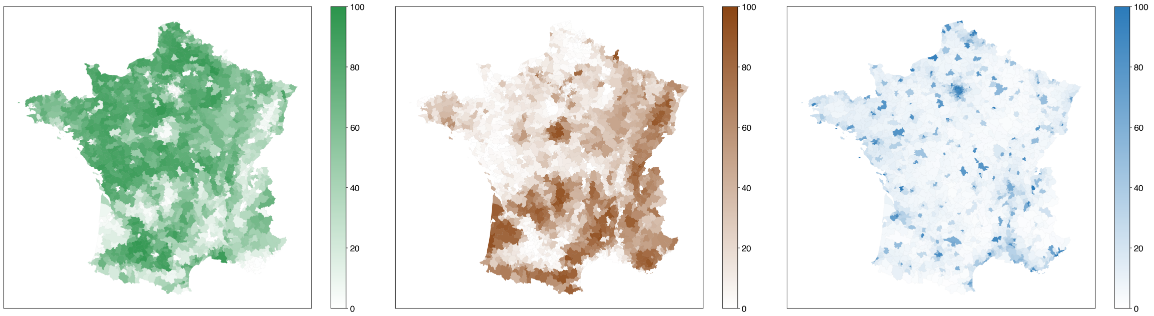
4 Stylized Facts

4.1 Land use across time and space

The distribution of land use is highly uneven over space. Each map in Figure 3 shows these specialization patterns by representing the share of land use in a given sector across zones in 1950 and 2020.



Agriculture 1950 (73%) Forest 1950 (23%) Urban 1950 (4%)



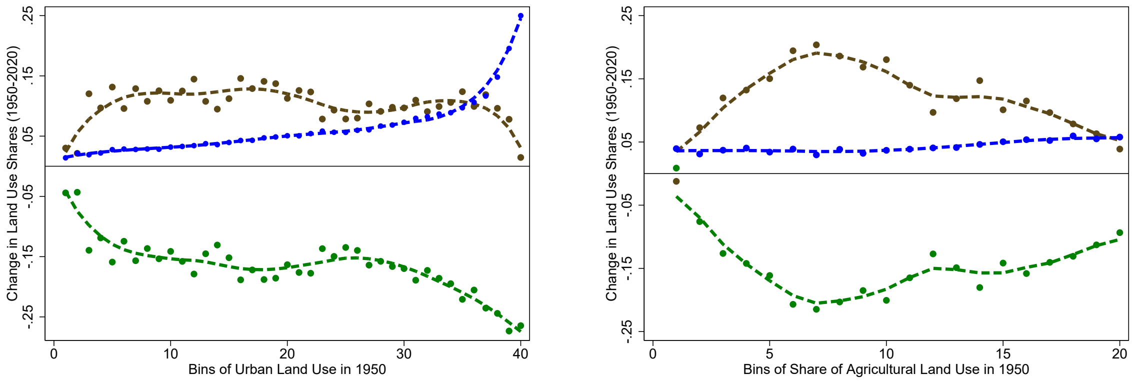
Agriculture 2020 (57%) Forest 2020 (33%) Urban 2020 (10%)

Figure 3: Land use shares in 1950 and 2020

Notes: Share of land use for each sector (agriculture, forest and urban built-up) across the 1,549 regions for 1950 (top panel) and 2020 (bottom panel). Aggregate land use shares in parenthesis. Other non-productive land use are not considered such that land use shares sum to 1 in each region j and in the aggregate. See the appendix for the construction of the land use data.

In 2020, agricultural land covers 57% of France, forests 33% and the urban built-up spans 10% of the territory in 2020. Land use has changed substantively since 1950. Three main facts emerge: a drop in agricultural land use ($\approx -20\%$ since 1950), a conversion into urban built-up with urbanization ($\approx 200\%$ increase since 1950) and an increase in forest cover ($\approx +50\%$ since 1950). This structural transformation of land qualitatively tracks the well-documented reallocation of employment away from agriculture towards the urban sector, although it is more muted: since 1950, employment in agriculture has collapsed from about 5 millions ($\approx 30\%$ of employment) to 0.7 million ($\approx 2\%$ of employment).

Land use reallocation has been quite heterogeneous across space. Figure 4 summarizes this heterogeneity by reporting changes in land-use shares, measured in percentage points. Guided by the logic of the model, regions are aggregated by bins of land use specialization in 1950. We adopt this way of representing land use changes throughout the paper. Panel (a) sorts the 1,549 regions by their 1950 urban land share and groups them into 40 bins, each representing the same total area. The leftmost bins correspond to the most rural regions, while the rightmost bins correspond to the most urbanized regions.



(a) All bins of urban land use

(b) Rural Areas (bottom 75%)

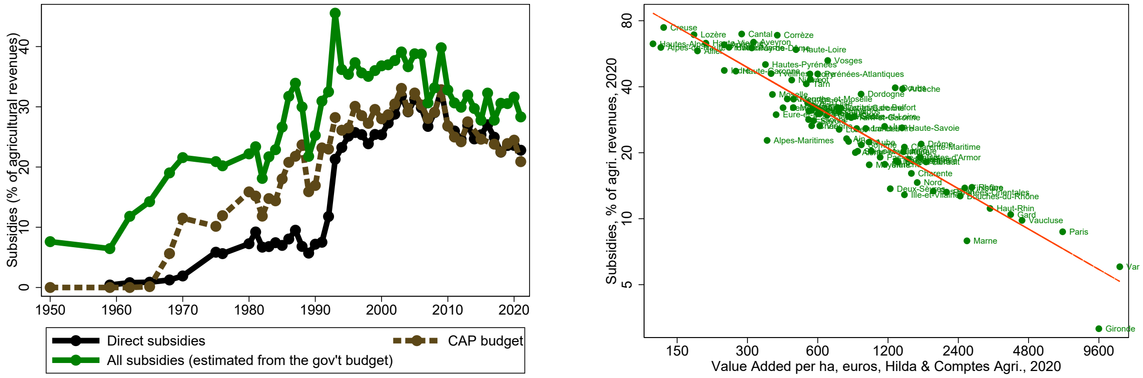
Figure 4: Land use reallocation by initial land use (1950-2020)

Notes: Percentage points change in the share of land use by sector by bins of land use specialization in 1950. The left panel bins regions by share of urban land use in 1950. The right panel bins regions by share of agricultural land use relative to total rural land use.

Panel (a) shows a pervasive drop in agricultural land (represented in green), systematic afforestation (brown) and increase in build up (blue). The development of urban land is skewed towards areas that were already urban in the 1950s—a phenomenon of sprawl around urban areas. Panel (b) zooms in on rural areas, corresponding to the bottom 75% in terms of initial built-up in 1950. It represents land-use change by bin of initial share of agricultural land use relative to rural land use. Again, each bin corresponds to the same total land area. Panel (b) shows that locations with mixed agricultural-forest land use see the largest reallocation. The U-shape evolution of agriculture combines two forces: the most productive agricultural land survived structural change more (to the right); the least productive zones were already near-fully forested in 1950 (to the left).

4.2 Agricultural subsidies

After WWII, French agriculture lagged behind other advanced economies (Bairoch (1989)). Early national agricultural policies targeted modernization, tilting subsidies toward investment and rural development. Later on, with rising productivity and falling prices, agricultural policy shifted toward compensating a declining sector — and was increasingly set at the European level under the Common Agricultural Policy (CAP). Figure 5a plots the evolution of agricultural subsidies as a share of agricultural revenues since 1950 (green line) and the progressive substitution of national schemes for European ones (dotted brown line). Agricultural subsidies have risen fourfold as a share of revenue, from roughly 8% in the 1950s to 32% today, notwithstanding a recent decline.



(a) Agricultural subsidies.

(b) Direct subsidies in 2020.

Figure 5: Agricultural subsidies

Notes: In Panel (a) subsidies are presented as a share of revenue. Panel (b) plots the share of direct subsidies in agricultural income in 2020 against land productivity. Agricultural revenues is the sum of VA and direct subsidies. Land productivity is the value added per ha of agricultural land.

Figure 5a also decomposes total support into direct subsidies (black line) and indirect subsidies (the residual). Before 1992, CAP support relied primarily on indirect subsidies, including guaranteed floor prices through public purchasing. The 1992 MacSharry reform marked the beginning of a gradual transition from price support to direct payments to farmers. Initially, these payments were largely designed to compensate farmers for reductions in price support and remained coupled to specific crops or production activities. The 2005 CAP reform completed this shift by largely decoupling payments from current production. Direct support became based primarily on eligible land, livestock holdings, and historical payment entitlements rather than on production decisions.

Importantly, the reliance on subsidies varies substantially across space in the recent period. Direct payments are strongly redistributive, partly reflecting the goal of preserving agriculture in rural regions. Figure 5b plots the share of direct subsidies in agricultural income against land productivity, measured as value added per hectare of agricultural land, across départements in 2020 on a log scale. Subsidies account for a much larger share of farmers' income in low-productivity areas: above 60% in the least productive départements, compared with below 15% in the most productive ones.[13]

4.3 Emissions

Sectoral emissions Land use and land-related activities account for a large share of national emissions and carbon absorption: on average over the period 1990-2020, commuting and housing represents 39% of gross emissions agriculture 18%, and forests offset 24% through carbon sequestration. These land-related emissions and sinks are the central object of our analysis. Figure 6 plots their evolution by sector from 1970 to 2022, together with other emissions.

Since the 70s, production-related emissions in the urban sector declined steadily, reflecting cleaner electricity generation (in particular the expansion of nuclear power) and improvements in manufacturing efficiency. Agricultural emissions, by contrast, remained broadly stable. Commuting emissions rose between 1970 and 1990 before stabilizing, as the growth in vehicle use was gradually offset by falling emissions per vehicle. Housing emissions fell sharply in the 1980s and continued to decline more gradually thereafter.

Forests increasingly acted as a carbon sink over most of the period, as forest

---

[13] Results are very similar for 2000. Before 1975, direct subsidies are much smaller in magnitude and support is indirect. Indirect subsidies are only observed in the aggregate but were arguably much less spatially tilted towards low-productivity regions, as they were implemented through price support.

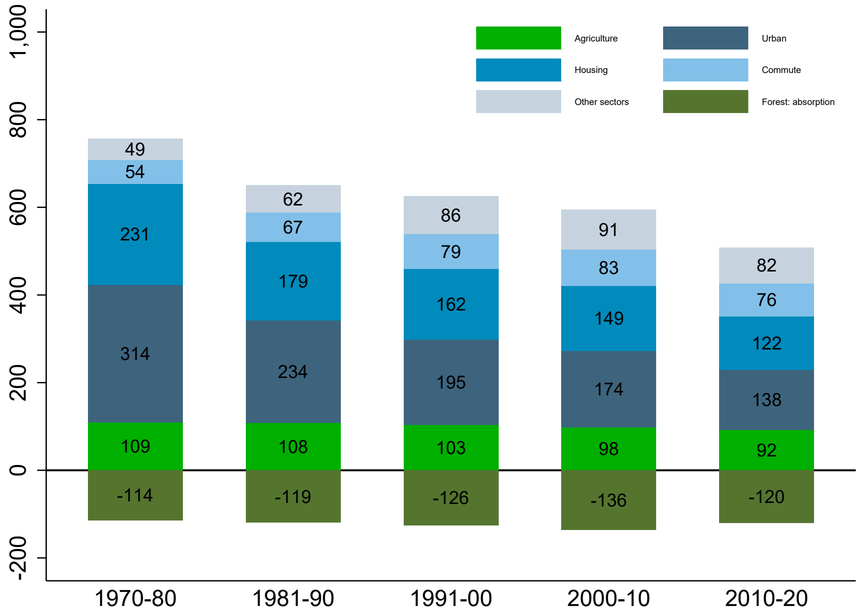


Figure 6: Emissions by sector and decade

Notes: Mton of CO_2 equivalent. Authors' computations based on CITEPA.

area expanded. This trend reversed in the 2010s, however, largely because repeated droughts reduced absorption capacity. We use regional data on forest absorption to allow sequestration rates to vary with local weather and soil conditions. Absorption per hectare varies substantially across regions, by a factor of six between the extremes, and lower absorption capacity is strongly associated with higher summer temperatures (see the appendix).

Commuting and housing emissions across space Granular 2020 data on commuting and residential energy use let us estimate how these emissions vary with distance and density. Commuting emissions rise with distance, with an elasticity of 0.91, and fall with density at both the residence and the workplace, with elasticities of -0.07 and -0.04 (Figure 7). Housing emissions rise with dwelling size, with an elasticity of 0.85, and fall with residential density, with an elasticity of -0.09. The appendix reports the underlying specifications.

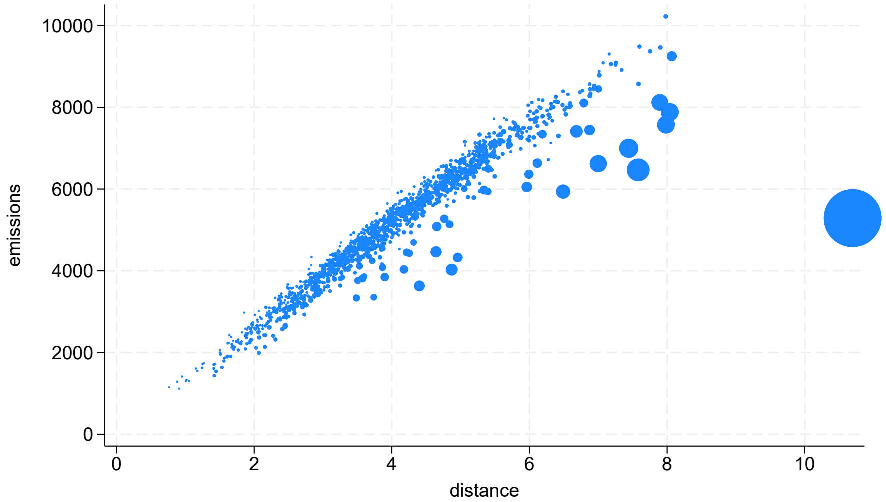


Figure 7: Commuting emissions as a function of within-zone distance.

Notes: Weekly emissions per capita due to commuting (in C02e grams). Distance in kms. Each dot is a zone and zones are weighted by the number of internal commuters in the zone. See the appendix for details.

5 Calibration and Model Fit

5.1 Calibration

We calibrate the model by inverting the equilibrium of Section 2: conditional on model elasticities and on the spatial data, we recover the location fundamentals and the aggregate preferences that make the model reproduce the data. Recovering location fundamentals by inversion is standard in quantitative spatial economics (Redding and Rossi-Hansberg, 2017). A distinctive feature of our approach is that we estimate non-homothetic preferences from the reallocation of labor and land across sectors between 1950 and 2020. The two cross-sections are therefore calibrated jointly.

Externally calibrated parameters A first set of parameters is calibrated outside the model (Table 2). Following Fuglie (2015), the labor and land income shares in agriculture are $\alpha_a = 0.51$ and $\beta_a = 0.17$, implying decreasing returns $\nu_a = 0.68$.[14] Imposing the same returns to scale in forestry and a labor share $\alpha_f = 0.23$, the stable average of digitized forestry accounts over 1977–2000, gives $\beta_f = 0.45$. The land share

---

[14] This is in line with the consensus evidence pointing to a labor income share around 0.5 and a land income share around 0.2 for developed countries, including the US (Boppart et al. (2026), Valentinyi and Herrendorf (2008)).

in housing is $1 - \alpha_h = 0.35$ (Combes et al., 2021), the housing expenditure share is $\gamma = 0.30$ (Coeurdacier et al., 2025), and the dispersion of idiosyncratic location tastes is $\kappa = 3.3$, the migration elasticity of Monte et al. (2018).

Table 2: Aggregate parameters calibrated externally

parameter	value	source
α_a	0.51	Fuglie (2015)
β_a	0.17	Fuglie (2015)
α_f	0.23	INSEE - comptes de la sylviculture
β_f	0.45	$\nu_a = \nu_f$
α_h	0.65	Combes, Duranton and Gobillon (2021)
γ	0.30	Coeurdacier, Oswald and Teignier (2025)
κ	3.3	Monte, Redding and Rossi-Hansberg (2018)

Parameterization and normalizations A few choices are made ex ante. We normalize the rural work amenities to one, $A_{j,a} = A_{j,f} = 1$, so that only the urban work amenity varies across space; allowing it to vary is natural, as it captures commuting patterns not easily explained by other forces, whereas there is less justification for such heterogeneity in the rural sectors. We normalize housing productivity to one, $T_{j,h} = 1$, as it is not separately identified from residential amenities. And we build the within-zone commuting distance d_{ii} from the data rather than leave it free: it is measured for 2020 from INSEE commuting data and scaled to earlier dates by the built-up area, to capture urban sprawl, $d_{i,i,t} = d_{i,i,2020}\,(Q^d_{i,h,t}/Q^d_{i,h,2020})^\zeta$ with $\zeta = 0.484$.[15]

Non-homotheticities The demand parameters are recovered jointly from the two cross-sections. The subsistence requirement $\underline{a}$ and the agricultural taste γ_a, both time-invariant, follow from agricultural goods-market clearing (4) at 1950 and 2020: given the measured productivity growth, the magnitude of the agricultural decline pins down the income elasticity of food demand, and hence these two parameters—which is why the dates must be calibrated jointly. We allow the preference weight towards forest goods, $\gamma_{f,t}$, to vary over time, accounting for a potential drop in the use of wood as an energy source; it is the only date-specific preference, pinned down by

---

[15] The proximity of ζ to 1/2 reflects that the average distance between two points in an area of size Q_h scales with its radius, $\sqrt{Q_h}$. The elasticity ζ is estimated on the INSEE commuting (mobility) data, with the specification reported in the appendix.

the afforestation through forest goods-market clearing at each date. The estimation conditions on the observed aggregate share of subsidies in agricultural revenue, $S^d_{a,t}$, equal to 7.6% in 1950 and 31.6% in 2020.

Inverting the spatial fundamentals Conditional on these parameters, we invert the equilibrium of Section 2, separately at each date and up to a normalization of units. The inversion recovers six spatial residuals from six spatial moments. The residuals are the three subsidy-augmented productivities $\widetilde{T}_{j,a}, \widetilde{T}_{j,f}, \widetilde{T}_{j,u}$, with $\widetilde{T}_{j,s} \equiv (1 + s_{j,s})T_{j,s}$ differing from true productivity only in agriculture; the residential and urban-work amenities $A_i, A_{j,u}$; and the urban land premium m_i. The matched moments are urban wages $w^d_{j,u}$, agricultural revenue $R^d_{j,a}$, forest cover $Q^d_{j,f}$, built-up land $Q^d_{j,h}$, residential population N^d_i, and the workplace distribution of urban employment $L^d_{j,u}$. Agricultural land is not a separate moment: it follows from the land endowment by market clearing, $Q_{j,a} = \bar{Q}_j - Q^d_{j,f} - Q^d_{j,h}$.

The residuals are jointly determined, but each is, in the main, identified by one moment. Land earns a fixed share β_a of agricultural revenue, so the agricultural first-order condition recovers the local land rent ρ_j from revenue and agricultural land. Given rents, each sector's productivity is the residual of its price equation: urban productivity from urban wages, forest productivity from forest cover, and agricultural productivity from agricultural revenue. The aggregate level of each matches the growth of aggregate sectoral output, a Solow residual.[16] The residential amenity A_i rationalizes the population living in each zone, and the urban work amenity $A_{j,u}$ the workplace distribution of urban employment. The urban land premium m_i rationalizes the built-up area through housing-market clearing. Two aggregate margins close the picture: the *level* of the urban work amenity is set by aggregate agricultural employment—a lower urban amenity draws workers into agriculture—while the agriculture–urban wage gap sets the aggregate level of agricultural wages. The spatial distribution of agricultural employment is itself left free: with no agricultural work amenity, canton-level $L_{j,a}$ is a sorting outcome, pinned down only once revenue identifies agricultural productivity. The full system of inversion equations is in

---

[16] We target the volume of wood production for forestry, the value added of manufacturing and services deflated by the urban price index for the urban sector, and agricultural value added at factor cost (inclusive of subsidies) deflated by the agricultural price index for agriculture. To avoid the 2020 COVID shock while preserving a 70-year change, we use 1949 and 2019 in place of 1950 and 2020 (see the appendix). The implied Solow-residual growth is about 2.3% per year for urban and agriculture, and 1.4% for forestry.

Appendix E.

Commuting Across zones, commuting distances d_{ij} are time-invariant distances between zone centroids. The commuting elasticity ξ is estimated from the average commuting distance in 2020, $\bar{d}^d_{2020} = 13.34$ km (over trips below 100 km), the only date for which commuting data are available.

Agricultural subsidies The calibration up to this stage relies only on the aggregate value of subsidies, the share of agricultural revenue documented in Section 4. Producer subsidies drive a wedge between productivity and revenue, and the inversion recovers the subsidy-inclusive residual $\widetilde{T}_{j,a}$ given only that aggregate share. Separating productivity $T_{j,a}$ from the subsidy requires the local rate $s_{j,a}$, which we construct after the calibration. We combine the locally-observed direct subsidies with a spatially uniform rate of indirect subsidies—price and market support, which are unobserved across space—set so that the implied total matches the observed aggregate.[17]

Emission intensities Emissions are a by-product of the allocation and are calibrated last, holding the equilibrium fixed. The production and land-cover intensities $\{\mu_s, \lambda_s\}$ are set to reproduce the 2020 sectoral carbon accounts (Section 3.2). The forest land intensity is allowed to vary across the 21 administrative regions, capturing that forests in warmer regions store less carbon per unit of land. The density elasticities of housing and commuting emissions enter these intensities and are estimated directly on the granular 2020 data (Section 4.3 and the appendix).

Estimation results The estimated agricultural preferences combine a strong non-homotheticity with a low long-run weight: the subsistence term accounts for almost a quarter of expenditure in 1950 ($p_a\underline{a} \approx 25\%$), while the long-run taste is small, $\gamma_a \approx 0.5\%$. While γ_a is on the low side relative to standard values (Duarte and Restuccia (2010), Herrendorf et al. (2013), Coeurdacier et al. (2025)), the implied long-run agricultural employment share lies in the range of the literature, owing to imperfect mobility across sectors. Less standard is the declining taste for forest goods: $\gamma_{f,t}$ falls markedly between 1950 and 2020, in line with the replacement of wood by

---

[17] This assumption is arguably innocuous quantitatively: indirect subsidies are a small share of subsidies in 2020, when subsidies are large, while in 1950 they are a high share but total subsidies are very low.

other materials. Although its 1950 level may appear high, non-homotheticity keeps the forest spending share low throughout (around 4% in 1950 and 1% in 2020): the decline in the expenditure share on agricultural necessities raises the urban share, not the forest one. The recovered spatial residuals also pass basic consistency checks: across regions and at both dates, the land and labor used in a sector are positively correlated with that sector's productivity residual, and the urban land premium is higher in denser regions.

5.2 Assessing Model Fit

By construction, the model matches in both periods land use, agricultural revenues, population, urban employment and wages across space.[18] We validate the model performance by investigating its ability to match untargeted moments at (in-sample) dates 1950 and 2020, and to fit the evolution of factor use at (out-of-sample) interim dates, 1975 and 2000.

Untargeted moments Starting with aggregate moments, we compare the change in the relative prices in agriculture, $p_{a,t}$, and in forestry, $p_{f,t}$, to their data counterpart. The fit is quite close for both prices. In the model, over 1950-2020, the log change of the relative price of agricultural goods is -101% compared to -95% in the data; the corresponding change for p_f is -42% in the model compared to -39% in the data.[19] In other words, while our model matches by construction the agricultural decline in terms of quantities (land use and employment), it also matches untargeted relative prices driving it.

In the cross-section, one can validate the model by looking at the dispersion of agricultural employment across space. The fit is also very good, the model accounts for more than 85% of the spatial variations in the data, even though the model overestimates agricultural employment in regions with fewer workers (see Figure 8).[20]

---

[18] These outcomes are matched in the aggregate with the exception of urban employment. Instead, the estimation matches the change in the average sectoral wage gap, $\bar{w}^d_{a,t}/\bar{w}^d_{u,t}$ together with aggregate agricultural employment. This implies a close fit for aggregate urban employment since the forestry sector has few workers.

[19] In line with the calibration, the data counterpart is taken over 1949-2019 to avoid the 2020 covid shock.

[20] When regressing $\log L_{j,a,t}$ in the data against the model counterpart, the elasticity is slightly above unity, around 1.15 at both dates.

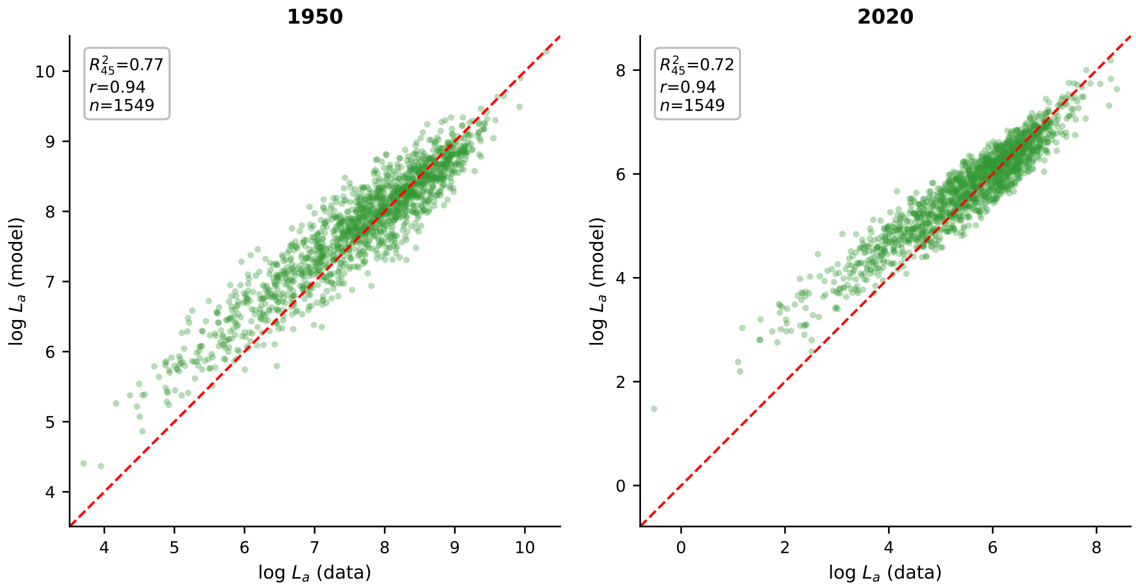
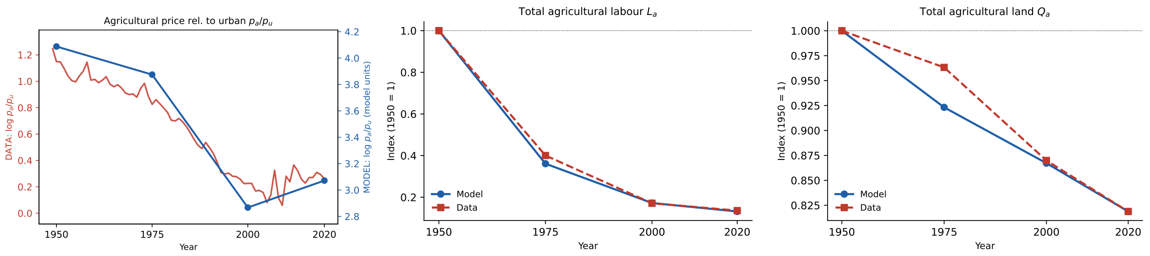


Figure 8: Agricultural labor across space: data vs. model.

Notes: Agricultural employment (log) across regions, $\log(L_{j,a,t})$, in the in-sample cross-sections 1950 and 2020. Data on the horizontal axis, model on the vertical; the dashed line is the 45-degree line.

Out-of-sample interim dates The model is calibrated in 1950 and 2020. As model validation, we confront the model's predictions to the data at interim dates, 1975 and 2000. To do so, we fix the distribution of spatial parameters, with the exception of subsidies, to their 1950 value and apply homogeneous shifts across space to the different drivers of factor reallocation (sectoral TFP, population, amenities, urban land premium). Heterogeneous agricultural subsidies, $s_{j,a,t}$, are set to their data counterpart. We also let the residual forest expenditure share parameter, $\gamma_{f,t}$, evolve between the estimated 1950 and 2020 values. While homogeneous shifts in sectoral TFP and population can be disciplined to match their aggregate data counterpart in 1975 and 2000, the homogeneous shift in urban work amenities, $A_{u,t}$, urban land premium, $m_{i,t}$ and the shift in the preference towards forest goods, $\gamma_{f,t}$, do not have immediate correspondence in the data. We proceed as follows: $\gamma_{f,t}$ is estimated in order to match the change in the relative price of wood, $p_{f,t}$ at both dates, where the data counterpart is smoothed—leaving aside the transitory spike following the oil shocks in the 1970s (see the appendix for details). The residual shifts in $A_{u,t}$ and $m_{i,t}$ are simply linearly interpolated in between 1950 and 2020. Equipped with a full set of predicted residuals in 1975 and 2000, we solve for the equilibrium at both dates and compare model's outcomes to the data. This exercise illustrates the out-of-sample predictive power of the model with aggregate shifters. Figure 9 displays the predicted evolution of aggregate outcomes compared to the data—for completeness, (in-sample) 2020 outcomes are also shown. It shows that aggregate shifts in the drivers of structural transformation predict relatively well the evolution of relative prices and the reallocation of factors away from agriculture. Figure 10 displays the predicted land use changes since 1950 across bins of urban land use in 1950.[21] The model predicted changes match relatively well the structural transformation of land across periods and across space, qualitatively and quantitatively. Beyond the fit of the model's predictions to the data suggestive of the reasonable out-of-sample performance of the model, it is worth insisting that variations in land use changes across space are obtained despite homogeneous shifts of the residuals.



(a) Relative price, $p_{a,t}$ (b) Labor share, $L_{a,t}/L_t$ (c) Land use share, $Q_{a,t}/\bar{Q}$

Figure 9: Model fit: relative price, aggregate labor and land use in agriculture, 1950-2020.

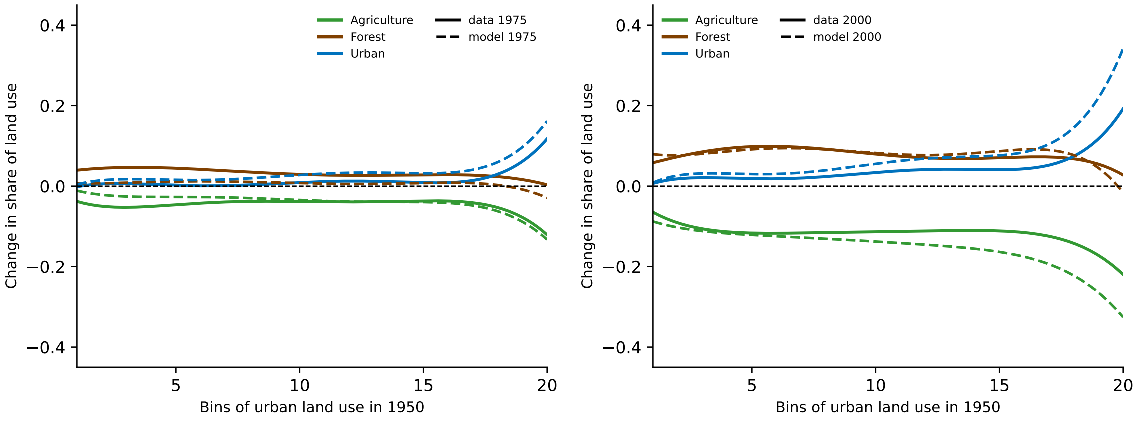
Notes: Agricultural relative price $p_{a,t}$, agricultural labor share $L_{a,t}/L_t$, and agricultural land share $Q_{a,t}/\bar{Q}$ over 1950–2020, model (solid) vs. data (dashed). 2020 is in-sample; 1975 and 2000 are out-of-sample.

6 Counterfactuals

Equipped with estimated parameters in 1950 and 2020, we perform a series of counterfactuals to disentangle the mechanisms driving land use reallocation over the period and to evaluate policy changes—notably possible reforms of the common agricultural policy.

---

[21] Scatter plots of the predicted cross-sectional employment and land use against the 1975 and 2000 data are relegated to the appendix.



(a) Model fit, 1975

(b) Model fit, 2000

Figure 10: Model predicted change in land-use share relative to 1950 against data.

Notes: Model-predicted change in the share of land use for 1975 and 2000 (solid). Percentage points change in the share of land use by sector by bins of urban land use in 1950. Dashed lines are data for comparison.

6.1 Disentangling the mechanisms

Agricultural productivity growth reallocates labor and land out of agriculture, while agricultural subsidies partly offset this process. To disentangle these two forces, we vary productivity and subsidies while holding all other fundamentals, namely amenities and the urban land premium, fixed at their baseline values in both periods.[22] Baseline counterfactuals are performed with an exogenous urban land premium, $m_{i,t}$, holding parameters common across space to their calibrated value, including the wood preference shift, $\gamma_{f,t}$.

The effect of technology-driven structural transformation Starting from the 1950 calibration, we shift TFP residuals uniformly across regions to their 2020 targets while holding agricultural subsidies fixed at their 1950 level, thereby isolating the effect of technological change from subsidies and spatial heterogeneity. Figure 11 compares the resulting change in land-use shares (model, solid) to the 2020 data (dashed), both in change from 1950. Homogeneous technology-driven structural transformation alone already reproduces the main features of the 2020 land-use data: agricultural

---

[22] The extent of structural transformation is also impacted by change in population, in urban amenities and land premium. These drivers of reallocation are kept constant in the counterfactuals to focus on the effect of technology and subsidies on factor reallocation.

land contracts, forests expand in rural areas, and cities sprawl. The model, however, predicts a decline of agriculture in excess of the data, particularly in the most rural regions and in areas with more mixed land use in 1950, already suggesting an important role for agricultural subsidies. Finally, rapid agricultural productivity growth is crucial for forest expansion. Had aggregate agricultural TFP grown by only 1% rather than 2.3%, forest cover would instead have declined, an effect that would have been even larger under faster population growth (see the appendix).

However, this close fit with homogeneous TFP shifts masks two countervailing forces that it averages over: spatially heterogeneous shifts in technology (which pushes more land out of agriculture) and in subsidies (which pull it back in). The two offset eachother even though both forces are sizeable—as the next steps show.

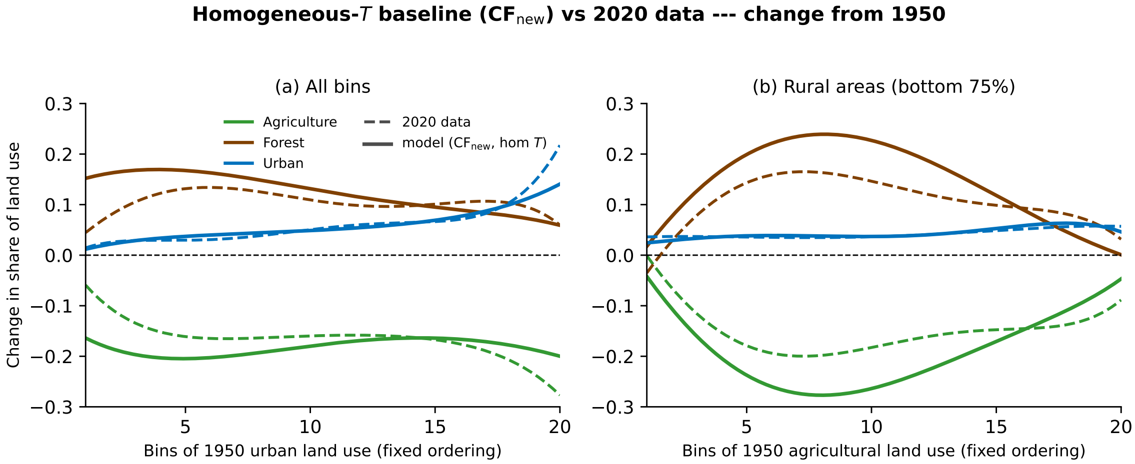
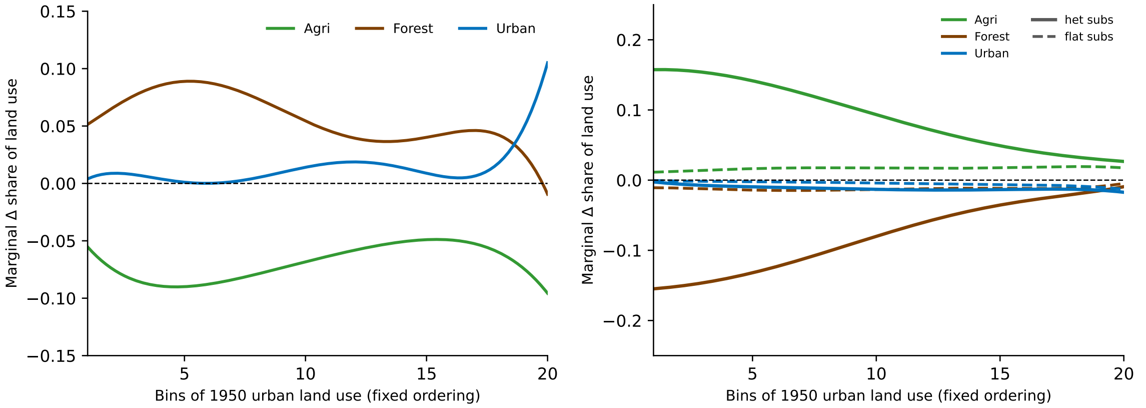


Figure 11: The role of homogeneous TFP shifts on land use reallocation (1950-2020)

Notes: Counterfactual change in the land use shares with homogeneous sectoral TFP shifts (solid). Subsidies to their 1950 value. Baseline calibration for other parameters. Percentage points change in the share of land use by sector in the counterfactual by bins of land use specialization in 1950 (left panel by share of urban land use, right panel by share of agricultural land use in rural areas). Dashed lines are data for comparison.

The effect of heterogeneous productivity shifts across space We let the shifts in sectoral productivity, $T_{j,s,t}$ varying across regions in line with the 2020 calibration—leaving all other parameters equal to their value in the previous counterfactual exercise. Figure 12a plots the marginal effect (heterogeneous TFP minus homogeneous TFP) across bins of urban land use in 1950—illustrating the additional effect of the spatial dispersion of technology. It is remarkable that with heterogeneous technological shifts, agricultural land use drops significantly more, amplifying reforestation (in more rural areas) and urban sprawl. The effect is sizable as aggregate agricultural land shrinks by about 10%. The aggregate effects of these heterogeneous productivity shifts are driven primarily by faster agricultural productivity growth in initially more productive regions.[23] This spatial concentration of agricultural production increases aggregate productivity, reducing the land required to satisfy subsistence needs and freeing land for both forests and urban development.



(a) Marginal effect of heterogeneous TFP (b) Marginal effect of heterogeneous subsidies

Figure 12: The role of heterogeneous TFP and subsidies on land use

Notes: Left panel: marginal change in the land use shares in a counterfactual with heterogeneous TFP shifts relative to a counterfactual with homogeneous TFP shifts. Subsidies to their 1950 value. Right-panel: Marginal change in the land use shares in a counterfactual with heterogeneous agricultural subsidies relative to a counterfactual with 1950 subsidies (solid). Marginal change with a uniform shift in the subsidy rate for comparison (dashed). Marginal change across bins of urban land use in 1950 in both panels.

The effect of agricultural subsidies We now consider a counterfactual which adds agricultural subsidies, $s_{a,j,2020}$. Figure 12b plots the marginal effect (heterogeneous subsidies minus heterogeneous shifts with 1950 subsidies) across bins. Agricultural subsidies preserve agricultural land that would otherwise have been converted to forests, particularly in the most rural regions and, in regions with more mixed-

---

[23] Agricultural TFP growth across regions is positively correlated with initial TFP. Regressing $\log(T_{j,a,2020}/T_{j,a,1950})$ on $\log(T_{j,a,1950})$ gives a slope of 0.17 and the dispersion of $\log(T_{j,a,t})$ widens from 0.52 to 0.75.

land use, a weaker comparative advantage in agriculture. Overall, subsidies increase agricultural land by almost (10%). This reflects the larger subsidy increases in less productive regions, which shift production away from high-productivity locations. This reallocation lowers agricultural aggregate productivity, limiting forest expansion to meet subsistence needs (agricultural extensification). By contrast, a uniform increase in subsidies would have a much smaller effect on land use, as it raises production incentives without distorting the spatial allocation of agricultural production; in general equilibrium, its effects are further dampened by lower agricultural prices.

Lastly, while subsidies to agriculture severely limited forest expansion, they also limited conversion into urban built-up by preserving farmland values. While small in magnitude for land use as displayed in Figure 12b, this effect is possibly meaningful in terms of emissions—built-up areas being more emissions intensive. The ambiguous environmental impact of subsidies (reducing carbon sinks but limiting conversion into urban built-up) deserves a quantitative assessment performed in the following section.

6.2 Counterfactual Emissions

To compute the impact of the counterfactual scenarios on carbon emissions, we hold all emission parameters fixed at their 2020 values. This isolates the effects of structural transformation and agricultural policies from changes in emission intensities.[24]

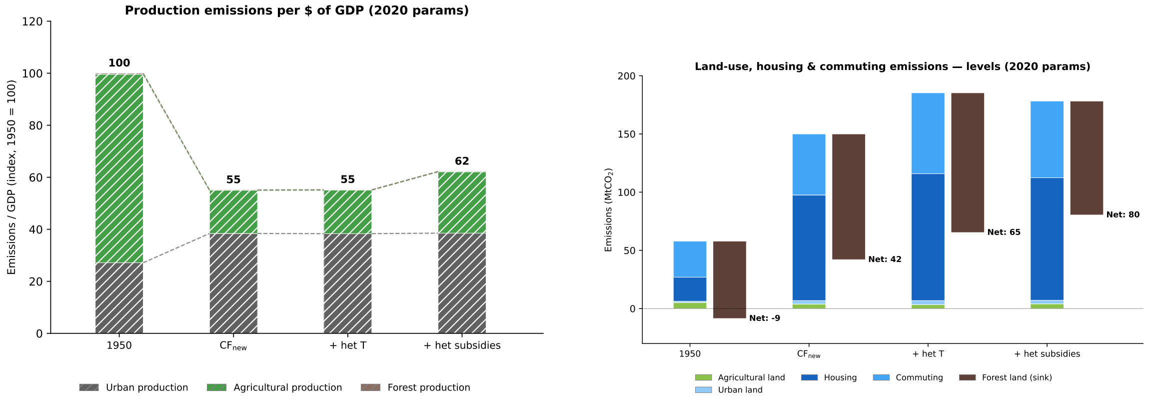
The effect of structural transformation Relative to the 1950 benchmark (evaluated using 2020 emission factors), total emissions in the counterfactual with structural transformation heterogeneous across space increase. Part of this increase, however, simply reflects higher population and production levels. To better understand the underlying mechanisms, we decompose emissions into two broad categories. First, we consider production emissions in the urban, agricultural, and forestry sectors. Since these emissions increase mechanically with the level of economic activity, we report them relative to real GDP, keeping prices fixed at their 2020 levels. Second, we examine emissions associated with land use, housing, and commuting. These sources depend directly on how land and people are allocated across space and are therefore reported in levels (MtCO$_2$).

---

[24] Emission intensities changed substantially between 1975 and 2020, reflecting cleaner production technologies, changes in the energy mix, and improvements in energy efficiency. For completeness, the appendix reports the same exercises using 1975 emission factors.

Figure 13a reports the effects on production emissions. Structural transformation reduces production emissions per unit of GDP by 55% relative to 1950. The dominant force is a sharp decline in emissions from agricultural production, driven by large productivity gains in the sector. Evaluated at 2020 emission intensities, agriculture remains the most emission-intensive sector, so the contraction of agricultural activity generates substantial reductions in production-related emissions.

Figure 13b compares the increase in emissions associated with urban expansion, housing and commuting (blue bars) with the additional carbon sequestration generated by reforestation (black bars), highlighting the tradeoff discussed above. In 1950, these two forces roughly offset one another. Structural transformation subsequently increased forest land use, strengthening the role of forests as carbon sinks. At the same time, however, it induced urban expansion and longer commuting distances, raising emissions from housing and commuting. The results from our quantification exercise indicate that the increase in housing and commuting emissions more than offsets the additional carbon absorbed by forests. While part of this increase reflects population growth, the conclusion is not driven by demographics alone. A figure in the appendix repeats the exercise holding population fixed at its 2020 level. Although the growth in housing and commuting emissions is attenuated, it remains larger than the additional carbon sequestration generated by forests.



(a) Production emissions per $ of GDP

(b) Other emissions in levels

Figure 13: Emissions: structural transformation and subsidies

Notes: Panel (a) presents production emissions as a share of GDP, while panel (b) presents commuting, housing and land-use emissions in levels (MtCO$_2$). Both panels use 2020 emission factors.

The effect of subsidies Introducing agricultural subsidies increases total emissions by about 10%. Production emissions rise by 13%, entirely driven by the expansion of emission intensive agricultural output induced by the subsidies. By increasing the profitability of agriculture, subsidies also slow the reallocation of land toward forests and thereby reduce the economy's carbon sequestration capacity. The resulting loss of carbon sinks accounts for the largest share of the increase in emissions. By contrast, the effects on urban form are relatively modest. Agricultural subsidies slightly limit urban expansion, reducing commuting emissions from 71 to 67 $MtCO_2$, but this effect is quantitatively small compared with the increase in emissions arising from reduced forest cover. This can be partly explained by the fact less productive and more rural locations were more heavily subsidized, with limited effects on urban sprawl.

Using 1970 emission parameters The results above use 2020 emission factors, under which agricultural production is substantially more emission-intensive than urban production. This contrast is less pronounced using 1975 emission factors, the earliest year for which reliable estimates are available, as emission intensities have declined much more in urban production than in agriculture over the period. A figure in the appendix repeats the counterfactual exercises using 1975 emission factors. Although the quantitative contribution of production emissions changes, the qualitative conclusions remain unchanged: structural transformation continues to reduce production emissions relative to GDP while increasing housing and commuting emissions, and agricultural subsidies continue to raise emissions primarily through their effects on land use and the reduction in forest carbon sequestration.

6.3 Policy counterfactuals

Reforming the CAP In progress.

Subsidizing high-sequestration forests In progress.

7 Conclusion

We develop a quantitative spatial framework linking structural transformation, land use, and carbon emissions, and combine it with newly assembled long-run spatial data for France over 1950–2020. The model is calibrated to the evolution of land use across roughly 1,500 regions and used to decompose the drivers of land-use change and to evaluate policy counterfactuals with spatial land reallocation.

Technology-driven structural transformation reallocates land out of agriculture: as productivity rises, forests expand in rural areas and cities spread at their fringe. Agricultural subsidies distort this reallocation. Tilted toward less productive regions, they preserve agricultural land, slow reforestation, and raise carbon emissions by about 10%. The geography of support, more than its level, shapes these aggregate effects.

Looking ahead, the framework can be applied to land-use policies—such as green belts or forest subsidies—to weigh their climate gains against their economic costs, and extended to other settings using global satellite data.

References

Ahlfeldt, G. M., and E. Pietrostefani (2019): "The economic effects of density: A synthesis," *Journal of Urban Economics*, 111, 93–107.

Ahlfeldt, G. M., S. J. Redding, D. M. Sturm, and N. Wolf (2015): "The economics of density: Evidence from the Berlin Wall," *Econometrica*, 83, 2127–2189.

Araujo, R. (2024): "When Clouds Go Dry: an integrated model of deforestation, rainfall, and agriculture," *mimeo.*

Araujo, R., J. Assunção, M. Hirota, and J. A. Scheinkman (2023): "Estimating the spatial amplification of damage caused by degradation in the Amazon," *Proceedings of the National Academy of Sciences*, 120.

Assunção, J., R. McMillan, J. Murphy, and E. Souza-Rodrigues (2023): "Optimal Environmental Targeting in the Amazon Rainforest," *The Review of Economic Studies*, 90, 1608–1641.

Bairoch, P. (1989): "Les trois révolutions agricoles du monde développé: rendements et productivité de 1800 à 1985," *Annales. Économies, Sociétés, Civilisations*, 44, 317–353.

Balboni, C. A., and J. S. Shapiro (2025): "Spatial Environmental Economics," Working Paper 33377, National Bureau of Economic Research.

Baum-Snow, N. (2007): "Did Highways Cause Suburbanization?" *The Quarterly Journal of Economics*, 122, 775–805.

——— (2020): "Urban Transport Expansions and Changes in the Spatial Structure of U.S. Cities: Implications for Productivity and Welfare," *The Review of Economics and Statistics*, 102, 929–945.

Bilal, A., and E. Rossi-Hansberg (2023): "Anticipating Climate Change Across the United States," *forth. Econometrica.*

Boppart, T., P. Kiernan, P. Krusell, and H. Malmberg (2026): "The Macroeconomics of Intensive Agriculture," *forth. Journal of Political Economy.*

Boyer, P. (1999): "La dépense publique en faveur de l'agriculture française en longue période," *Notes et Etudes Economiques*, 10.

Budí-Ors, T., and J. Pijoan-Mas (2025): "Macroeconomic Development, Rural Exodus, and Uneven Industrialization," *mimeo.*

Caselli, F., and W. J. I. Coleman (2001): "The U.S. Structural Transformation and Regional Convergence: A Reinterpretation," *Journal of Political Economy*, 109, 584–616.

Coeurdacier, N., F. Oswald, and M. Teignier (2025): "Structural Change, Land use and Urban Expansion," *forth. The Review of Economic Studies.*

Combes, P.-P., G. Duranton, and L. Gobillon (2019): "The costs of agglomeration: House and land prices in French cities," *The Review of Economic Studies*, 86, 1556–1589.

——— (2021): "The production function for housing: Evidence from France," *Journal of Political Economy*, 129, 2766–2816.

Conte, B., K. Desmet, D. K. Nagy, and E. Rossi-Hansberg (2021): "Local sectoral specialization in a warming world," *Journal of Economic Geography*, 21, 493–530.

Conte, B., K. Desmet, and E. Rossi-Hansberg (2025): "On the Geographic Implications of Carbon Taxes," *forth. The Economic Journal.*

Costinot, A., D. Donaldson, and C. Smith (2016): "Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World," *Journal of Political Economy*, 124, 205–248.

Cruz, J.-L., and E. Rossi-Hansberg (2024): "The Economic Geography of Global Warming," *The Review of Economic Studies*, 91, 899–939.

Delacote, P., A. Lobianco, S. Caurla, J.-D. Bontemps, A. Lungarska, P. Mȳrian, M. Rivière, and A. Barkaoui (2021): "The Loop Effect: How Climate Change Impacts the Mitigation Potential of the French Forest Sector," *Journal of Forest Economics*, 36, 201–264.

Desmet, K., and E. Rossi-Hansberg (2014): "Spatial Development," *American Economic Review*, 104, 1211–43.

Domínguez-Iino, T. (2026): "Efficiency and Redistribution in Environmental Policy: An Equilibrium Analysis of Agricultural Supply Chains," *Journal of Political Economy*, 134, 1075–1109.

Du Puy, E. (2026): "Unintended Environmental Policies: The Impact of European Agricultural Subsidies on Pollution," *mimeo*.

Duarte, M., and D. Restuccia (2010): "The Role of the Structural Transformation in Aggregate Productivity," *The Quarterly Journal of Economics*, 125, 129–173.

Duranton, G., and D. Puga (2015): "Urban Land Use," *Handbook of Regional and Urban Economics*, 5, 467–560.

Eckert, F., and M. Peters (2025): "Spatial Structural Change," *forth. Review of Economic Studies*.

Eeckhout, J., and H. Christoph (2021): "Green urbanization," *PLoS ONE*, 16.

Ellis, E. C., J. O. Kaplan, D. Q. Fuller, S. Vavrus, K. K. Goldewijk, and P. H. Verburg (2013): "Used planet: A global history," *Proceedings of the National Academy of Sciences*, 110, 7978–7985.

Fajgelbaum, P., and S. J. Redding (2022): "Trade, Structural Transformation, and Development: Evidence from Argentina 1869–1914," *Journal of Political Economy*, 130, 1249–1318.

Farrokhi, F., E. Kang, H. S. Pellegrina, and S. Sotelo (2025): "Deforestation: A Global and Dynamic Perspective."

Fuglie, K. (2015): "Accounting for growth in global agriculture," *Bio-based and Applied Economics*, 4, 201–234.

Glaeser, E. L., and M. E. Kahn (2004): "Sprawl and urban growth," *Handbook of Regional and Urban Economics*, 4, 2481–2527.

——— (2010): "The greenness of cities: Carbon dioxide emissions and urban development," *Journal of Urban Economics*, 67, 404–418.

GORIN, C., P.-P. COMBES, G. DURANTON, AND L. GOBILLON (2025): "Measuring Land Use Changes by (Machine) Learning from Historical Maps," Discussion Paper 20946, CEPR.

GROSSET-TOUBA, F., A. PAPP, AND C. A. TAYLOR (2024): "Rain Follows the Forest: Land Use Policy, Climate Change, and Adaptation," *mimeo.*

HEBLICH, S., S. J. REDDING, AND D. M. STURM (2020): "The Making of the Modern Metropolis: Evidence from London," *The Quarterly Journal of Economics*, 135, 2059–2133.

HERRENDORF, B., R. ROGERSON, AND A. VALENTINYI (2014): "Growth and structural transformation," *Handbook of economic growth*, 2, 855–941.

HERRENDORF, B., R. ROGERSON, AND VALENTINYI (2013): "Two Perspectives on Preferences and Structural Transformation," *American Economic Review*, 103, 2752–89.

HSIAO, A. (2026): "Coordination and Commitment in International Climate Action: Evidence From Palm Oil," *Econometrica*, 94, 1–33.

HSIAO, A., J. MOSCONA, B. A. OLKEN, AND K. SASTRY (2026): "Climate Change, Deforestation, and the Expansion of the Global Agricultural Frontier," Working Paper 35029, National Bureau of Economic Research.

IMBERT, C., K. HOUNGBDEJI, S. MARSHALL, J. WOLFERSBERGER, AND L. WREN-LEWIS (2026): "Deforestation and Structural Transformation in Sub-Saharan Africa," *mimeo.*

IPCC (2022): "Climate Change 2022: Mitigation of Climate Change," Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Chapter 7, Agriculture, Forestry, and Other Land Uses (AFOLU).

JONES, C., AND D. M. KAMMEN (2014): "Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density," *Environmental Science & Technology*, 48, 895–902.

MATSUYAMA, K. (1992): "Agricultural productivity, comparative advantage, and economic growth," *Journal of Economic Theory*, 58, 317–334.

MICHAELS, G., F. RAUCH, AND S. J. REDDING (2012): "Urbanization and Structural Transformation," *The Quarterly Journal of Economics*, 127, 535–586.

MONTE, F., S. J. REDDING, AND E. ROSSI-HANSBERG (2018): "Commuting, migration, and local employment elasticities," *American Economic Review*, 108, 3855–90.

Prakash, M. (2026): "The Global Allocative Efficiency of Deforestation," *mimeo.*

Redding, S. J., and E. A. Rossi-Hansberg (2017): "Quantitative spatial economics," *Annual Review of Economics*, 9.

Ribeiro, H. V., D. Rybski, and J. P. Kropp (2019): "Effects of changing population or density on urban carbon dioxide emissions," *Nature Communications*, 10.

Salazar Restrepo, V., and G. Leite Mariante (2024): "Does Conservation Work in General Equilibrium?" *mimeo.*

Sotelo, S. (2020): "Domestic trade frictions and agriculture," *Journal of Political Economy*, 128, 2690–2738.

Souza-Rodrigues, E. (2019): "Deforestation in the Amazon: A Unified Framework for Estimation and Policy Analysis," *The Review of Economic Studies*, 86, 2713–2744.

Szerman, D., J. Assuncao, M. Lipscomb, and A. M. Mobarak (2026): "Electricity, Agricultural Productivity, and Deforestation: Evidence from Brazil," *forth. Journal of the Association of Environmental and Resource Economists.*

Turner, B. L., E. F. Lambin, and A. Reenberg (2007): "The emergence of land change science for global environmental change and sustainability," *Proceedings of the National Academy of Sciences*, 104, 20666–20671.

Valentinyi, , and B. Herrendorf (2008): "Measuring factor income shares at the sectoral level," *Review of Economic Dynamics*, 11, 820–835.

Winkler, K., R. Fuchs, M. Rounsevell, and M. Herold (2021): "Global land use changes are four times greater than previously estimated," *Nature Communications*, 12.

Appendix

This appendix proves the analytical results of the theory section: Lemma 1 and Proposition 1 (the cross-section of a small region taking traded-good prices as given), Proposition 2 (the aggregate general-equilibrium response of land use to an aggregate shock), and the cross-regional incidence of such a shock discussed thereafter. A final section extends Proposition 2 to imperfect sectoral mobility. We use the primitives and equilibrium conditions of Section 2 throughout and do not reproduce them; notation is as in the main text. We write $\delta_r \equiv 1 - \nu_r = 1 - \alpha_r - \beta_r \geq 0$ for the degree of decreasing returns in rural sector $r \in \{a, f\}$, and maintain the empirically relevant ordering that forest is the more land-intensive sector,

$$\frac{\beta_a}{\alpha_a} < \frac{\beta_f}{\alpha_f} \qquad \Big(\iff \alpha_a > \alpha_f \text{ under common returns } \nu_a = \nu_f\Big). \tag{LI}$$

A The cross-section of a small region

We work under the assumptions stated in the main text for the cross-section: a small region takes the traded prices p_a, p_f as given, housing uses only land ($\alpha_h = 0$), there is no urban land premium ($m_i = 1$), no policy and no commuting, and preferences are homothetic ($\underline{a} = 0$); land and firms are held by absentee landlords, so residents' income is labour income. We drop the region index i.

A.1 Reduction to a single equation in the land rent

The urban good is the numeraire and the urban sector uses only labour, so $w_u = T_u$ ((8) with $\alpha_u = 1$). Inverting the rural relative input-demand condition (9) gives the land–labour ratio

$$q_r \equiv \frac{Q_r}{L_r} = \frac{\beta_r}{\alpha_r}\frac{w_r}{\rho}, \qquad r \in \{a, f\}. \tag{17}$$

With only housing entering the local cost of living, Fréchet sorting ((6)–(7), specialised to $\underline{a} = 0$, $\pi = 0$, $p_{i,h} = \rho^{\gamma}$) delivers the sectoral labour supplies of the region,

$$L_s = \Psi_0\, A^{\kappa} \rho^{-\gamma\kappa} w_s^{\kappa}, \qquad s \in \{u, a, f\}, \tag{18}$$

where Ψ_0 collects the national denominator, taken as given by the small region. Land used in rural production is $Q_r = q_r L_r$, and housing land bought out of sector-s labour income is $h_s \equiv \gamma w_s L_s/\rho$; homothetic housing demand (condition 3 at $\alpha_h = 0$, $m_i = 1$ and absentee landlords, so $\rho Q_h = \gamma I$, $I = \sum_s w_s L_s$) makes $Q_h = h_u + h_a + h_f$. Hence the five land uses sum to total land (condition 1),

$$Q_h = h_u + h_a + h_f, \qquad Q_a + Q_f + h_u + h_a + h_f = \bar{Q}, \tag{19}$$

From (17)–(18), rural land and "own-sector" housing are proportional,

$$\frac{Q_r}{h_r} = \frac{\beta_r}{\gamma \alpha_r}, \tag{20}$$

so (LI) is the statement $\frac{\beta_a}{\gamma\alpha_a} < \frac{\beta_f}{\gamma\alpha_f}$.

Solving the land first-order condition for w_r as a power of ρ and substituting into (18) expresses every land use as a monomial in the rent:

$$Q_r,\ h_r \ \propto\ (p_r T_r)^{m_r}\, A^{\kappa\alpha_r/\Phi_r}\, \rho^{-B_r}, \qquad h_u \ \propto\ T_u^{1+\kappa}\, A^{\kappa}\, \rho^{-B_u}, \tag{21}$$

where $\Phi_r \equiv \alpha_r + (1+\kappa)\delta_r > 0$, $m_r \equiv (1+\kappa)/\Phi_r$, $B_u \equiv 1 + \gamma\kappa$, and

$$B_r = \frac{(1+\gamma\kappa)\,\alpha_r + (1+\kappa)(1-\alpha_r)}{\Phi_r} > 0. \tag{22}$$

Positivity of B_r holds for all admissible parameters (both terms in the numerator are positive). Land clearing (19) therefore reads

$$G(\rho; T_u, T_a, T_f, A) \ \equiv\ Q_a + Q_f + h_u + h_a + h_f \ =\ \bar{Q}, \tag{23}$$

in which each term is a positive coefficient times ρ^{-B_k}, $B_k > 0$. Thus G is continuous and strictly decreasing from $+\infty$ (as $\rho \to 0$) to 0 (as $\rho \to \infty$), and (23) has a unique solution $\rho > 0$. The fundamentals (T_u, T_a, T_f, A) enter G only through positive coefficients; only the rent appears in the exponents.

A.2 Proof of Lemma 1

From (22), $B_u < B_a$ and, under (LI), $B_a < B_f$. Because $Q_a \propto \rho^{-B_a}$ is strictly monotone, we may parametrise the cross-section by Q_a and, eliminating ρ from (21), write each use as a power of Q_a: $Q_f \propto Q_a^{B_f/B_a}$, $h_a \propto Q_a$, $h_f \propto Q_a^{B_f/B_a}$, $h_u \propto Q_a^{B_u/B_a}$.

Demand for rural land. With $Q_f = \Omega\, Q_a^{B_f/B_a}$ for a constant $\Omega > 0$ depending on (p_aT_a, p_fT_f, A), rural land $Q_r^D = Q_a + Q_f$ satisfies

$$Q_r^D = \mathbb{R}(Q_a)\, Q_a, \qquad \mathbb{R}(Q_a) = 1 + \Omega\, Q_a^{\zeta}, \qquad \zeta \equiv \frac{B_f}{B_a} - 1. \tag{24}$$

Under (LI), $B_f > B_a$, so $\zeta > 0$: $\mathbb{R} > 1$ and $\mathbb{R}' > 0$. The forest share of rural land, $Q_f/Q_r = 1 - 1/\mathbb{R}$, is therefore increasing in Q_a, and $dQ_r^D/dQ_a = \mathbb{R} + \mathbb{R}'Q_a > 1$: rural land grows faster than agricultural land, so the demand curve $Q_r^D = Q_a + \Omega Q_a^{1+\zeta}$ is convex (this needs only $\zeta > 0$, i.e. (LI)).

Supply of rural land. This curve uses housing clearing alone, with forest land treated as the residual $Q_f = Q_r - Q_a$. Labour income in rural sector r is $w_rL_r = \frac{\alpha_r}{\beta_r}\rho Q_r$ (general DRS), so total income is $I = T_uL_u + \frac{\alpha_a}{\beta_a}\rho Q_a + \frac{\alpha_f}{\beta_f}\rho Q_f$. Substituting into $\rho Q_h = \gamma I$ with $Q_h = \bar{Q} - Q_a - Q_f$ and collecting the rural terms yields

$$Q_r^S = \frac{\beta_f}{\beta_f + \gamma\alpha_f}\,\bar{Q} - \frac{\gamma\beta_f}{\beta_f + \gamma\alpha_f}\,\mathbb{H}(Q_a), \quad \mathbb{H}(Q_a) = \frac{T_uL_u}{\rho} + \Big(\frac{\alpha_a}{\beta_a} - \frac{\alpha_f}{\beta_f}\Big)Q_a. \tag{25}$$

The linear coefficient is positive by (LI). The first term, $T_uL_u/\rho \propto \rho^{-B_u} \propto Q_a^{B_u/B_a}$, is increasing in Q_a; adding the positive linear term, $\mathbb{H}$ is increasing. Hence Q_r^S is decreasing in Q_a: more agricultural land lowers the rent and cheapens housing, crowding out rural land.

Existence and uniqueness. $Q_r^S(\cdot)$ falls from the positive intercept $\frac{\beta_f}{\beta_f+\gamma\alpha_f}\bar{Q}$ at $Q_a \to 0$, while $Q_r^D(\cdot)$ rises from 0; the two loci cross once, pinning down (Q_a, Q_r) and hence (Q_a, Q_f, Q_h). $\square$

A.3 Proof of Proposition 1

Land rents. Since the fundamentals enter G in (23) only as positive coefficients and the rent only through the negative exponents $-B_k$, $\partial G/\partial x > 0$ for $x \in \{T_u, T_a, T_f, A\}$ and $\partial G/\partial \rho < 0$. The implicit function theorem on $G(\rho;\cdot) = \bar{Q}$ gives $\partial\rho/\partial x = -(\partial G/\partial x)/(\partial G/\partial\rho) > 0$ and $\partial\rho/\partial\bar{Q} = 1/(\partial G/\partial\rho) < 0$. Land is the only fixed factor (urban uses none and labour enters elastically), so with traded prices given any local productivity or amenity gain capitalises into the rent.

Quantities. Log-differentiate (23). Writing $D \equiv B_a Q_a + B_f Q_f + B_u h_u + B_a h_a + B_f h_f = -\partial G/\partial \ln \rho > 0$ and using that only Q_a, h_a carry T_a (elasticity m_a), only h_u carries T_u (elasticity $1+\kappa$), and only Q_f, h_f carry T_f (elasticity m_f), the rent elasticities are

$$\varepsilon_{T_a} = \frac{m_a(Q_a + h_a)}{D}, \qquad \varepsilon_{T_f} = \frac{m_f(Q_f + h_f)}{D}, \qquad \varepsilon_{T_u} = \frac{(1+\kappa)h_u}{D}, \tag{26}$$

all positive. Each quantity sign then follows from $Q_k \propto (\text{fund})\, \rho^{-B_k}$.

(i) Own effects. $\partial \ln Q_a/\partial \ln T_a = m_a - B_a \varepsilon_{T_a} = \frac{m_a}{D}\big[B_f Q_f + B_u h_u + B_f h_f\big] > 0$, using $B_{h_a} = B_a$, $B_{h_f} = B_f$, $B_{h_u} = B_u$ from (20) and (21); symmetrically $\partial Q_f/\partial T_f > 0$.

(ii) Cross effects through the rent. A sector's rural land has no own term in the other shocks, so $\partial \ln Q_f/\partial \ln T_a = -B_f \varepsilon_{T_a} < 0$, and likewise $\partial Q_a/\partial T_u, \partial Q_f/\partial T_u, \partial Q_a/\partial T_f < 0$: the un-shocked rural use recedes as the rent rises. In particular $\partial Q_{i,f}/\partial T_{i,a} < 0$ is unambiguous in this given-price cross-section (forest land moves only through ρ); the sign reversal that can arise when T_f, T_u are both high is an endogenous-price effect of the full model, outside the scope of this proposition.

(iii) Housing. With $Q_h = h_u + h_a + h_f$ and $P \equiv B_u h_u + B_a h_a + B_f h_f$,

$$\frac{\partial Q_h}{\partial \ln T_u} = \frac{(1+\kappa)h_u}{D}\big(B_a Q_a + B_f Q_f\big) > 0, \qquad \frac{\partial Q_h}{\partial \ln T_f} = \frac{m_f}{D}\Big[B_a\, h_a h_f\, \tfrac{\beta_a \alpha_f - \beta_f \alpha_a}{\gamma \alpha_a \alpha_f} - B_u h_u Q_f\Big] < 0$$

under (LI). For T_a the analogous expression is $\frac{m_a}{D}\big[B_f\, h_a h_f\, \frac{\beta_f \alpha_a - \beta_a \alpha_f}{\gamma \alpha_a \alpha_f} - B_u h_u Q_a\big]$, whose two terms have opposite signs: housing land falls with T_a where the region is urban enough (the negative term $\propto h_u \propto T_u^{1+\kappa}$ dominates) and rises in the most rural regions. This is the sole quantity ambiguity.

(iv) Rural specialisation $S \equiv Q_a/(Q_a + Q_f)$. The sign of $\partial \ln S/\partial x$ is that of $\partial \ln(Q_a/Q_f)/\partial x$. From (i)–(ii), S rises with T_a and falls with T_f. For T_u, $\partial \ln(Q_a/Q_f)/\partial \ln T_u = (B_f - B_a)\varepsilon_{T_u}$, positive iff $B_f > B_a$ (forest land is more rent-elastic). Under common returns $\nu_a = \nu_f$ this is exactly (LI); with $\nu_a \neq \nu_f$ it must be assumed separately, as (LI) orders β_r/α_r but not B_a, B_f. ☐

B Aggregate general equilibrium

We now close the economy and let prices adjust. Consider the homogeneous-region benchmark of Proposition 2: one representative region with land $\bar{Q}$ and labour L, constant returns in the rural sectors, the urban good as numeraire, land-only housing, and Stone–Geary preferences with subsistence $\underline{a} > 0$ in agriculture. With a closed economy the land rent must be spent domestically, so land rents are rebated per capita, $r = \rho\bar{Q}/L$, and per-capita income net of subsistence is $I \equiv T_u + r - p_a\underline{a}$. We take perfect sectoral mobility ($\kappa \to \infty$), as in the statement of Proposition 2; Section D treats finite κ. Write $\beta \equiv 1 - \alpha_a$, $\theta_h \equiv \gamma$, $\theta_r \equiv (1 - \alpha_r)(1 - \gamma)\gamma_r$ and $\Theta \equiv \sum_s \theta_s < 1$.

B.1 Proof of Proposition 2

The land-share formula. Perfect mobility equalises all wages to T_u. Land's share of revenue is $1 - \alpha_r$ and goods markets clear (conditions 3 and 4, revenue equals expenditure), so housing, agricultural and forest land payments are

$$\rho Q_h = \gamma L I, \quad \rho Q_a = (1 - \alpha_a) L\big[(1 - \gamma)\gamma_a I + p_a\underline{a}\big], \quad \rho Q_f = (1 - \alpha_f)(1 - \gamma)\gamma_f L I.$$

Summing and using land clearing $Q_a + Q_f + Q_h = \bar{Q}$,

$$\frac{LI}{\rho}\big[\Theta + \beta x\big] = \bar{Q}, \qquad x \equiv \frac{p_a\underline{a}}{I}, \tag{27}$$

and dividing the Q_a payment by (27) delivers the share formula of Proposition 2,

$$\frac{Q_s}{\bar{Q}} = \frac{\theta_s + \beta x\, \mathbf{1}_{s=a}}{\Theta + \beta x}, \qquad s \in \{a, f, h\}.$$

Thus all of non-homotheticity enters land use through the single scalar x, the subsistence burden, and $Q_a/\bar{Q}$ is increasing in x while $Q_f/\bar{Q}$ and $Q_h/\bar{Q}$ decrease (since $\Theta > \theta_a$).

The burden depends only on T_a and L. From (27), $r = \rho\bar{Q}/L = I(\Theta + \beta x)$, so $I = T_u + r - p_a\underline{a}$ gives

$$I = \frac{T_u}{1 - \Theta + \alpha_a x}. \tag{28}$$

The zero-profit agricultural price is the unit cost ((8)), $p_a = c_a T_u^{\alpha_a} \rho^{1-\alpha_a}/T_a$ with $c_a = \alpha_a^{-\alpha_a}(1-\alpha_a)^{-(1-\alpha_a)}$, and $\rho = (L/\bar{Q})I(\Theta + \beta x)$ from (27). Substituting these and (28) into $x = p_a \underline{a}/I$, the factor $T_u^{\alpha_a}$ cancels and the system collapses to a single equation in x,

$$\frac{x}{\Psi(x)} = \frac{(L/\bar{Q})^{1-\alpha_a}}{T_a}, \qquad \Psi(x) \equiv c_a \underline{a}\,(1 - \Theta + \alpha_a x)^{\alpha_a}\,(\Theta + \beta x)^{1-\alpha_a}. \tag{29}$$

The elasticity of Ψ is $\frac{\alpha_a^2 x}{1-\Theta+\alpha_a x} + \frac{\beta^2 x}{\Theta+\beta x} < \alpha_a + \beta = 1$, so $x/\Psi(x)$ is strictly increasing, rising from 0 to the finite ceiling $1/(c_a \underline{a}\,\alpha_a^{\alpha_a}\beta^{1-\alpha_a})$; hence (29) has a unique root whenever agricultural output clears subsistence (the right-hand side lies below this ceiling), which we maintain throughout. Reading off the right-hand side,

$$\frac{dx}{dT_a} < 0, \qquad \frac{dx}{dL} > 0, \qquad \frac{dx}{dT_u} = \frac{dx}{dT_f} = 0. \tag{30}$$

Urban productivity scales income and the agricultural price together and so cancels; forest productivity never enters, as forest carries no subsistence and its land share is fixed by its expenditure weight. With $Q_s/\bar{Q}$ monotone in x, the land-share comparative statics of Proposition 2 follow. □

B.2 The agricultural price

The cross-regional analysis below feeds the equilibrium price change into the cross-section, so we record how p_a moves. Both statements are corollaries of (30).

Proposition A.1 (Agricultural price)**.** *In the aggregate equilibrium, $\partial p_a/\partial T_a < 0$ and $\partial p_a/\partial L > 0$. Moreover the product $p_a T_a$ is decreasing in T_a if and only if agriculture is more land intensive than the economy on average, $1 - \alpha_a > \Theta$.*

Proof. From $x = p_a \underline{a}/I$ and (28),

$$\frac{p_a}{T_u} = \frac{x}{\underline{a}\,(1 - \Theta + \alpha_a x)}, \qquad \frac{d}{dx}\left[\frac{x}{1 - \Theta + \alpha_a x}\right] = \frac{1-\Theta}{(1 - \Theta + \alpha_a x)^2} > 0,$$

so p_a/T_u is strictly increasing in the burden. By (30), p_a then falls with T_a and rises with L. For the composite, eliminating ρ and I through (27)–(28) gives

$$p_a T_a = c_a\, T_u\, (L/\bar{Q})^{1-\alpha_a}\, \varphi(x)^{1-\alpha_a}, \qquad \varphi(x) \equiv \frac{\Theta + \beta x}{1 - \Theta + \alpha_a x}, \tag{31}$$

in which T_a enters only through x. Since $\varphi'(x) = \big[(1-\alpha_a) - \Theta\big]/(1 - \Theta + \alpha_a x)^2$ and $dx/dT_a < 0$, the elasticity $d\ln(p_a T_a)/d\ln T_a$ has the sign of $-\operatorname{sign}\varphi'(x) = -\operatorname{sign}(1 - \alpha_a - \Theta)$. Hence $\partial(p_a T_a)/\partial T_a < 0$ iff $1 - \alpha_a > \Theta$. The condition is mild: Θ is the expenditure-weighted average land intensity, and urban production uses no land, pulling Θ below $1 - \alpha_a$. $\square$

Remark A.1 (Population and the Malthusian hump). Differentiating $Q_a/\bar{Q} = (\theta_a + \beta x)/(\Theta + \beta x)$, $\partial(Q_a/\bar{Q})/\partial \ln x = \beta(\theta_f + \theta_h)\, x/(\Theta + \beta x)^2$, which is hump-shaped in x, peaking at $x^* = \Theta/\beta$ where $Q_a/\bar{Q} = (\theta_a + \Theta)/2\Theta$. Since population raises the burden ((30)), the reallocation toward agriculture it induces is largest at intermediate burdens and weaker both in rich economies (low x) and near full agricultural specialisation. Below the peak the response strengthens as the economy grows poorer.

C Cross-regional incidence of an aggregate agricultural shock

We now combine the two preceding parts: an aggregate rise in agricultural productivity lowers p_a (Proposition A.1), and we trace how this common price decline is absorbed across heterogeneous regions, using the given-price cross-section of Section A. Because p_a and $T_{i,a}$ enter region i only through the composite $p_a T_{i,a}$, a uniform productivity gain that lowers p_a by more than it raises T_a—which holds under $1-\alpha_a > \Theta$ (Proposition A.1), and unconditionally for a fall in p_a at fixed $T_{i,a}$—acts on every region as a common proportional fall $\Delta \ln(p_a T_{i,a}) = -d$, $d > 0$. Region i's response is $-d$ times the $p_a T_{i,a}$-elasticities of Section A.3, holding p_f fixed.

It is convenient to group the five land uses of (19) into $G_a \equiv Q_a + h_a$ (agricultural land plus housing financed out of agricultural income), $G_f \equiv Q_f + h_f$, and h_u (housing financed out of urban income), so that $G_a + G_f + h_u = \bar{Q}$ and, by (20), $Q_r = \frac{\beta_r}{\beta_r + \gamma\alpha_r} G_r$. Here $h_u \propto T_{i,u}^{1+\kappa}$ indexes how urban the region is and G_a/G_f its rural specialisation. Write $D = B_a G_a + B_f G_f + B_u h_u$ and $\varepsilon \equiv m_a G_a / D = \varepsilon_{T_a}$.

Proposition A.2 (Incidence)**.** *Under* (LI) *and a common fall* $\Delta \ln(p_a T_{i,a}) = -d < 0$ *(small region,* p_f *given), in every region:*

- *(R1) agricultural land falls,* $\Delta Q_{i,a} \le 0$ *(with equality only in the degenerate all-agriculture region* $G_f = h_u = 0$*);*

(R2) forest land weakly rises and never falls, $\Delta Q_{i,f} \geq 0$*;*

(R3) the forest gain is $\Delta Q_{i,f} = d\,B_f m_a \frac{\beta_f}{\beta_f+\gamma\alpha_f}\,F$ *with* $F \equiv G_a G_f / D$*, which vanishes when* $G_a \to 0$*,* $G_f \to 0$ *or* $h_u \to \bar{Q}$ *and is single-peaked in the rural mix* G_a/G_f*; afforestation is largest in mixed rural regions and negligible in regions specialised in either rural use or in cities;*

(R4) housing absorbs the land freed by agriculture, and expands, if and only if $\dfrac{h_u}{G_f} > \dfrac{B_f\,\gamma(\beta_f\alpha_a - \beta_a\alpha_f)}{B_u\,\beta_a(\gamma\alpha_f + \beta_f)}$*, i.e. in urban or in agriculture-specialised regions; otherwise housing contracts and forest absorbs both the freed agricultural land and the released housing land (rural, forest-leaning regions).*

Proof. (R1) $\Delta Q_{i,a} = -d\,Q_a(m_a - B_a\varepsilon) = -\frac{d\,m_a}{D}\,Q_a(B_f G_f + B_u h_u) \leq 0$, strict unless $G_f = h_u = 0$.

(R2)–(R3) Q_f has no direct $p_a T_{i,a}$, so $\partial \ln Q_f / \partial \ln(p_a T_{i,a}) = -B_f\varepsilon$ and $\Delta Q_{i,f} = d\,B_f Q_f \varepsilon = d\,B_f m_a \frac{\beta_f}{\beta_f+\gamma\alpha_f}\,G_a G_f/D \geq 0$, which is (24)'s claim with $F = G_a G_f / D$. Fixing h_u and writing $G_f = \bar{Q} - h_u - G_a$, $F = G_a(\bar{Q} - h_u - G_a)/[(B_a - B_f)G_a + B_f(\bar{Q} - h_u) + B_u h_u]$ vanishes at the endpoints $G_a = 0$ and $G_a = \bar{Q} - h_u$ and is positive between, hence single-peaked; and $F \to 0$ as $h_u \to \bar{Q}$.

(R4) By land clearing $\Delta Q_{i,h} = -\Delta Q_{i,a} - \Delta Q_{i,f}$; from Section A.3(iii) its sign is that of $B_u h_u Q_a - B_f h_a h_f \frac{\beta_f\alpha_a - \beta_a\alpha_f}{\gamma\alpha_a\alpha_f} \propto B_u \frac{\beta_a}{\gamma\alpha_a} h_u - B_f \frac{\beta_f\alpha_a - \beta_a\alpha_f}{\alpha_a(\beta_f+\gamma\alpha_f)} G_f$, giving the stated threshold. (Both bracket terms require $\beta_f\alpha_a > \beta_a\alpha_f$ for the threshold to bind.) □

The polar cases are transparent: a pure city ($T_{i,u} \to \infty$, $h_u \to \bar{Q}$) sends the little freed land to housing with forest barely moving, while a mixed rural region with $T_{i,u} \to 0$ has housing contract and forest absorb both the freed agricultural land and the released housing land. The destination of freed land is thus set by how urban the region is (R4), and the size of afforestation by its rural composition (R3).

D Finite sectoral mobility

Proposition 2 is stated for perfect mobility. We record that its two ingredients survive at any finite κ: the land-share formula is exactly mobility-free, and the burden comparative statics extend under a single transparent condition. Throughout we maintain the constant-returns rural technology of §B ($\delta_r = 0$), and the closed economy rebates rents per capita, $r = \rho\bar{Q}/L$, and $I = W + r - p_a\underline{a}$ with $W = \sum_s \ell_s w_s$ aggregate labour income per worker, $\ell_s = L_s/L$.

Lemma A.1 (Mobility-free land shares)**.** *For any finite κ and any equilibrium with burden $x = p_a\underline{a}/I$, the land shares are exactly those of Proposition 2, $Q_h/\bar{Q} = \theta_h/(\Theta + \beta x)$, $Q_f/\bar{Q} = \theta_f/(\Theta + \beta x)$, $Q_a/\bar{Q} = (\theta_a + \beta x)/(\Theta + \beta x)$.*

Proof. Goods-market clearing and the per-capita rebate give the same land-payment identities as in Section B.1 with I now per-capita supernumerary income; summing and using land clearing reproduces (27), and dividing through gives the shares. No step uses κ. □

Conditional on x, the labour allocation does depend on κ. Let $\tilde{z}_s \equiv (w_s + r - p_a\underline{a})/I$ be the normalised net wage that drives Fréchet sorting, $\ell_s = \tilde{z}_s^\kappa / \sum_m \tilde{z}_m^\kappa$, and let $c \equiv \alpha_a x - \Theta$ be the common net-vs-gross wedge. Goods clearing and factor shares give the labour-income identities $y_s\ell_s = b_s(x)$ with $y_s \equiv w_s/I$ (the b_s are labour-income shares, not the rent elasticities B_r of §A), $b_u = (1-\gamma)\gamma_u$ (γ_u the urban expenditure weight, $\sum_s \gamma_s = 1$), $b_f = \alpha_f(1-\gamma)\gamma_f$ and $b_a(x) = \alpha_a[(1-\gamma)\gamma_a + x]$, which reduce to the scalar system

$$b_s(x) = c\,\ell_s + t\,\ell_s^{1+1/\kappa}, \qquad s \in \{u, a, f\}, \tag{32}$$

for a common $t > 0$. A monotonicity argument shows (32) has a unique solution (ℓ_s, t) with $\ell_s \in (0,1)$ for every $x \geq 0$. The agricultural unit-cost condition then yields the finite-κ analogue of (29),

$$\frac{x}{\Psi_\kappa(x)} = \frac{c_a\underline{a}}{T_a}\Big(\frac{L}{\bar{Q}}\Big)^{1-\alpha_a}, \qquad \Psi_\kappa(x) = \big[\Theta + \beta x\big]^{1-\alpha_a}\Big[\frac{\alpha_a\big((1-\gamma)\gamma_a + x\big)}{\ell_a(x)}\Big]^{\alpha_a}, \tag{33}$$

whose only mobility-dependent object is the agricultural employment share $\ell_a(x)$. Differentiating, $d\log\Psi_\kappa/d\log x < 1$ whenever

$$\frac{d\ell_a}{dx} \geq 0, \tag{34}$$

i.e. whenever the agricultural employment share is non-decreasing in the burden; in that case $x/\Psi_\kappa(x)$ is strictly increasing and the comparative statics (30) go through unchanged.

Proposition A.3 (Finite-κ comparative statics)**.** *If* (34) *holds then the equilibrium of* (33) *is unique and the burden comparative statics of Proposition 2 hold at finite* κ*:* $\partial x/\partial T_a < 0$*,* $\partial x/\partial L > 0$*,* $\partial x/\partial T_u = \partial x/\partial T_f = 0$*; the land-share signs of Lemma A.1 follow, and the agricultural price corollary (Proposition A.1) is unchanged.*

Condition (34) is the sole channel through which finite mobility could matter. At $\kappa \to \infty$ net wages equalise, $\ell_a = \alpha_a((1-\gamma)\gamma_a + x)/(1 - \Theta + \alpha_a x)$, and $d\ell_a/dx = \alpha_a(1-\gamma)(\gamma_u + \alpha_f\gamma_f)/(1-\Theta+\alpha_a x)^2 > 0$, so it holds strictly and in closed form; intuitively, a heavier subsistence burden raises the agricultural labour-income claim $b_a(x)$ relative to the fixed b_u, b_f and draws labour into agriculture, while the common wedge c shifts all net wages alike.[25]

E The Calibration as a System of Equations

This appendix explains the logic of the calibration. It lists the system of equations that, conditional on the data, jointly pins down the residuals of the model. The system is solved simultaneously — wages, land rents, prices, the rebate and the sorting of workers are mutually dependent — so there is no recursive closed form: the calibrated objects are defined implicitly as its (unique) solution. We describe one cross-section and restore the date t only where it matters.

Unknowns and data. Given the externally-set parameters $\{\alpha_s, \beta_s\}_s$ (with $\nu_r = \alpha_r + \beta_r$, $\alpha_u = 1$, $\nu_u = \nu_h = 1$), α_h, γ, κ, and the internal-distance elasticity ζ, the calibration conditions on the data

$$\{\, N^d,\ N_i^d,\ \bar{Q}_i^d,\ Q_{i,f}^d,\ Q_{i,h}^d,\ d_{ij}^d,\ w_{j,u}^d,\ R_{j,a}^d,\ L_{j,u}^d,\ \mathcal{T}_s^d,\ \bar{w}_a^d/\bar{w}_u^d,\ \bar{d}_{2020}^d,\ S_a^d \,\},$$

where $R_{j,a}^d$ is observed local agricultural revenue (inclusive of subsidies), S_a^d is the aggregate subsidy share, and $\mathcal{T}_s^d$ is the data aggregate productivity of sector $s \in \{a, f, u\}$. The calibration uses subsidies only through the aggregate $\mathbb{S}_a \equiv S_a^d \sum_j w_{j,a}L_{j,a}/\alpha_a$ (the subsidy share times aggregate agricultural revenue); the local rates $s_{j,a}$ are introduced only at the end, to split productivity from subsidies.[26] It solves for the spatial

---

[25] At finite κ the inequality no longer reduces to closed form; the $\kappa \to \infty$ limit above is the case we establish analytically.

[26] $\mathcal{T}_s^d$ is the Solow residual of aggregate sectoral output, normalised to a common 1950 base and matched to the volume growth of output between the two dates; for agriculture it is subsidy-

residuals $\{\widetilde{T}_{j,a}, \widetilde{T}_{j,f}, T_{j,u}, A_i, A_{j,u}, m_i\}$, the equilibrium objects $\{w_{j,a}, w_{j,f}, w_{j,u}, \rho_j, p_a, p_f, \pi, L_{j,s}, Q_{j,a}\}$, and the aggregate elasticities $\{\gamma_a, \underline{a}, \gamma_{f,t}, \xi\}$. We write the individual net income (the analogue of the per-capita income I of Section 2.4) and the net income of the residents of i as

$$I_{i,j,s} \equiv w_{j,s} - p_a\underline{a} + \pi, \qquad I_i \equiv \sum_{j,s} N_{i,j,s}\, I_{i,j,s}. \tag{35}$$

Objects pinned directly by the data. Three objects follow immediately. Land market clearing gives agricultural land,

$$Q_{j,a} = \bar{Q}^d_j - Q^d_{j,f} - Q^d_{j,h}. \tag{36}$$

Urban wages equal urban productivity ($\alpha_u = 1$) and are known from the data up to one scalar ϕ fixed by aggregate urban productivity,

$$w_{j,u} = T_{j,u} = \phi\, w^d_{j,u}, \qquad \phi = \mathcal{T}^d_u \, \frac{\sum_j L^d_{j,u}}{\sum_j w^d_{j,u} L^d_{j,u}}. \tag{37}$$

The agricultural land first-order condition states that land earns a share β_a of (subsidy-inclusive) agricultural revenue, $\rho_j Q_{j,a} = \beta_a R^d_{j,a}$, so the local land rent is pinned by revenue and land,

$$\rho_j = \beta_a \, \frac{R^d_{j,a}}{Q_{j,a}}. \tag{38}$$

The simultaneous system. The remaining unknowns solve the following equations jointly. The *local conditions* hold region by region. Workers sort over workplace and sector; conditional on residence i (whose population N^d_i is data), the housing cost and residential amenity cancel, leaving

$$\frac{N_{i,j,s}}{N^d_i} = \frac{A^{\kappa}_{j,s}\left(I_{i,j,s}/d^{\xi}_{ij}\right)^{\kappa}}{\sum_{j',s'} A^{\kappa}_{j',s'}\left(I_{i,j',s'}/d^{\xi}_{ij'}\right)^{\kappa}}, \qquad L_{j,s} = \sum_i N_{i,j,s}, \qquad A_{j,a} = A_{j,f} = 1. \tag{39}$$

---

inclusive. Off-diagonal d^d_{ij} are time-invariant geographic distances; the within-region $d^d_{i,i,t} = d^d_{i,i,2020}(Q^d_{i,h,t}/Q^d_{i,h,2020})^{\zeta}$.

Local agricultural revenue pins the agricultural wage, and forest labour-market clearing (the forest land FOC, with $L_{j,f}$ supplied by (39)) pins the forest wage:

$$w_{j,a}\,L_{j,a} = \alpha_a\,R^d_{j,a}, \tag{40}$$

$$w_{j,f}\,L_{j,f} = \frac{\alpha_f}{\beta_f}\,\rho_j\,Q^d_{j,f}. \tag{41}$$

The urban work amenities reproduce the data distribution of urban employment across workplaces: inverting the location choice (39) with $L_{j,u} = \sum_i N_{i,j,u}$ matched to $L^d_{j,u}$, and up to the common level fixed below by (45),

$$A^\kappa_{j,u} \;\propto\; \frac{L^d_{j,u}}{\sum_i N^d_i\left(I_{i,j,u}/d^\xi_{ij}\right)^\kappa/\Phi_i}, \qquad \Phi_i \equiv \sum_{j',s'} A^\kappa_{j',s'}\left(I_{i,j',s'}/d^\xi_{ij'}\right)^\kappa, \tag{42}$$

Φ_i being the denominator of (39) (so this is implicit in $A_{j,u}$). Housing-market clearing pins the urban land premium,

$$m_i\,\rho_i\,Q^d_{i,h} = (1-\alpha_h)\,\gamma\,I_i. \tag{43}$$

The *aggregate (scalar) conditions* close the economy-wide unknowns. The rural prices match aggregate productivity, for $s \in \{a, f\}$:

$$p_s\,\mathcal{T}^d_s = \frac{1}{\beta_s^{1-\nu_s}\left(\sum_j Q_{j,s}\right)^{\nu_s-1}} \cdot \frac{\sum_j\left(w_{j,s}L_{j,s}\right)^{\alpha_s}\left(\rho_j Q_{j,s}\right)^{1-\alpha_s}}{\left(\sum_j L_{j,s}\right)^{\alpha_s}\left(\sum_j Q_{j,s}\right)^{1-\alpha_s}}. \tag{44}$$

The level of the urban work amenities is fixed by the aggregate agricultural-urban wage gap, with $\bar{w}_s = \sum_j w_{j,s}L_{j,s}/\sum_j L_{j,s}$:

$$\frac{\bar{w}_a}{\bar{w}_u} = \left(\frac{\bar{w}_a}{\bar{w}_u}\right)^d. \tag{45}$$

The rebate equals land rents plus decreasing-returns profits net of the cost of subsidies; only the aggregate subsidy $\mathbb{S}_a$ enters (using $p_r(1+s_{j,r})Y_{j,r} = w_{j,r}L_{j,r}/\alpha_r$):

$$\pi N = \sum_j \rho_j\left(Q_{j,a} + Q^d_{j,f}\right) + \sum_j m_j\rho_j Q^d_{j,h} + \sum_r (1-\nu_r)\sum_j \frac{w_{j,r}L_{j,r}}{\alpha_r} - \mathbb{S}_a. \tag{46}$$

Rural goods-market clearing pins the demand parameters. The value of (pure) output equals aggregate revenue net of the aggregate subsidy, $p_s \sum_j Y_{j,s} = \sum_j w_{j,s} L_{j,s}/\alpha_s - \mathbb{S}_s$ (with $\mathbb{S}_f = 0$), so for $s \in \{a, f\}$ and $t \in \{1950, 2020\}$,

$$\sum_j \frac{w_{j,s,t} L_{j,s,t}}{\alpha_s} - \mathbb{S}_{s,t} = \underline{s}\, p_{s,t} N_t + (1-\gamma)\, \gamma_{s,t} \sum_i I_{i,t}, \qquad \underline{a} > 0,\ \ \underline{f} = 0, \tag{47}$$

where $\gamma_{f,t}$ is date-specific while γ_a and $\underline{a}$ are common to both dates (which is what couples the two cross-sections and identifies $\underline{a}$). Finally, the commuting elasticity matches the average commuting distance in 2020,

$$\bar{d}^d_{2020} = \frac{\sum_{i,j,s} \mathbf{1}\{d_{ij} < 100\}\, d_{ij}\, N_{i,j,s}}{\sum_{i,j,s} \mathbf{1}\{d_{ij} < 100\}\, N_{i,j,s}}. \tag{48}$$

Equations (39)–(48) are as many conditions as unknowns; their joint solution is the calibrated equilibrium.

Residuals recovered from the solution. Given that solution, the remaining residuals are read off. Residential amenities follow from the residence margin of the location choice (normalised to mean one), with the housing price $p_{i,h} = (m_i \rho_i)^{1-\alpha_h}$:

$$A_i^{\kappa} \propto \frac{N_i^d\, p_{i,h}^{\gamma\kappa}}{\Phi_i}, \tag{49}$$

with Φ_i from (42). The productivity residuals follow explicitly by inverting the firms' price condition: for $s \in \{a, f\}$,

$$\widetilde{T}_{j,s} = \frac{w_{j,s}^{\alpha_s}\, \rho_j^{1-\alpha_s}}{\beta_s^{1-\nu_s}\, p_s\, Q_{j,s}^{\nu_s - 1}}, \qquad \widetilde{T}_{j,u} = T_{j,u} = w_{j,u}. \tag{50}$$

Only at this final stage do the *local* subsidy rates $s_{j,a}$ enter, and they are not solved for inside the equilibrium. They are constructed from the data: the locally-observed *direct* subsidies are combined with a spatially *uniform* rate of *indirect* subsidies (those operating through prices and market regulations, which are not observed across space), the uniform rate being chosen so that the implied total reproduces the observed aggregate subsidy $\mathbb{S}_a$. The resulting local rate $s_{j,a}$ then separates productivity from the subsidy-augmented residual, $T_{j,a} = \widetilde{T}_{j,a}/(1 + s_{j,a})$ (Section 5).