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The influence of population density on education spread and economic development

by

José Pedro Pontes¹

Date: September 2026

Abstract: We seek to provide a reasonable explanation for the evidence that, while population density determines regional variation in schooling rates, it typically bears no significant relationship with individual income. To this end, we model a spatial economy composed of a traditional region, inhabited by farmers educated in the family, and a modern region populated by industrial workers trained in schools.

In theoretical terms, a proportional increase in demographic density at each location leads to an expansion of the school-educated region, although the overall effect also depends on the specific productivity associated with each type of technology. In addition, it reveals a non-monotonic relationship between density and individual income, which first decreases and subsequently increases.

The temporal evolution of an economy experiencing a proportional rise in population may also be described by an analogy with the spatial model.

Keywords: Education spread, economic growth, population density, education without development, space-time analysis.

JEL Classification: R11, I20, O15

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1. Introduction

The influence of population growth on economic development is not clear-cut. On the one hand, a rising population increases the intensity of land use and the pressure on other natural resources, thereby generating a decreasing-returns mechanism that hinders economic growth. On the other hand, economic growth is fostered by activities such as **R&D** and **education**, which rely on fixed assets such as laboratories and schools. The fixed outlays associated with this equipment are shared among local agents, meaning that they are more easily borne by a large population.

We examine the impact of population growth within a spatial framework. This inquiry builds on econometric estimation of the elasticity of labour productivity with respect to population density across small regions. A meta-analysis by Melo, Graham, and Noland (2009), covering the period 1965-2002, finds that productivity-to-density elasticities lie within the interval $(-0.800, 0.658)$, with a mean of 0.058 and a standard deviation of 0.115. This result indicates that the elasticity is usually positive – albeit small – but negative elasticities are not infrequent.

Furthermore, when controlling in the regression for variables correlated with population density, such as the average skill level of the population or the sectoral structure of the economy, the estimated elasticity remains positive, but its value is significantly reduced.

For instance, in a study across European NUTS3 regions, Ciccone (2002) estimated an elasticity of about 0.05 with a standard deviation of 0.0045. However, the estimate falls to 0.034, with a standard deviation of 0.009, when the share of valued added in agriculture is taken into account. These results imply that, in theoretical terms, the influence of population density on productivity is mediated by induced changes in the spatial pattern of schooling and the intensity of land use.

The importance of the spread of education for the causal relationship exerted by population density on labour productivity is also empirically confirmed. Significant positive elasticities of regional schooling levels with respect to population density are frequently reported in the literature.

Differences in demographic density directly determine spatial variation in educational attainment across a wide range of contexts. They concern both large density gaps between “rural” and “urban” areas, as in Newbold and Brown (2015),

and smaller differences across urban areas, as in Gibbons and Silva (2008), or among rural areas, as in Zhang and Rozelle (2022).

Moreover, evidence shows that density differences matter for both compulsory secondary education and post-compulsory education. For the latter, van Maarseveen (2021) estimated an elasticity of about 0.07 for the probability that a young person attends the university with respect to population density - a value coinciding with the upper bound of the interval of productivity-to-density estimates. This result suggests that the relative variation in university schooling rates exceeds the variation in productivity.

This positive association between schooling and density clearly follows from the fact that education is subject to significant economies of scale. Most educational inputs are fixed assets, such as professor training and physical infrastructure (buildings, libraries, labs and so forth). A dense population allows these facilities to be shared by a larger number of students, thereby reducing the per-student cost. In addition, high population density fosters schooling by widening the wage premium associated with an educational degree. Evidence shows that not only is the reward of completing college significantly higher in cities than in rural areas, but this gap has also been increasing (see Autor, 2019; Baum-Snow, Freedman and Pavan, 2018; Gould, 2007).

We model the influence of population density on per capita income through a space-time analysis drawing on Ciccone and Hall (1996), Boserup (1965) and Tamura (2002). The main intuition behind our analysis may be summarised as follows. When population increases in an area with a fixed amount of productive land, two opposing effects arise. First, in land-based activities such **agriculture** or the **production of housing services**, the region becomes congested and a decreasing-returns mechanism is set in motion, hindering economic growth. Second, in activities such as manufacturing, which rely primarily on labour, population growth allows educational infrastructure to be shared by a larger number of students and hence to become more efficient. A larger number of individuals raises per capita income and fosters economic development.

Our framework features a linear economy that consists of a closed, bounded space where each location is endowed with a unit of land. Population density decreases strictly with distance from the origin.

The economy produces a composite good under two alternative technologies: an “agricultural” technology where a farmer’s output is determined by the amount of land used in production; and an “industrial” technology, where output per worker is constant. These productive technologies correspond one-to-one with educational methods. While “farmers” are educated traditionally within the family,

thereby incurring a constant unit cost, “workers” bear a fixed schooling cost that is shared by all individuals living in a location.

Under the crucial assumption that individuals may not migrate - either to work or to educate themselves - we demonstrate straightforwardly that the economy is divided into two connected regions. The high-density region, composed by locations close to the origin, contains industrial activity and schooling, whereas the more distant area is occupied by agriculture and within-family education. We then show that the industrial region expands relative to the agricultural zone when population increases everywhere.

The following framework allows us to explain the time evolution of this economy. Suppose a “traveller” departs from the less populated region and moves towards the origin, crossing successively denser locations. Initially, he passes through locations where production is carried out by farmers trained traditionally within the family. He then crosses a boundary and reaches the region populated by industrial workers educated in schools. While travelling through the agricultural area, per capita income decreases as farmers are allowed successively smaller areas to cultivate.

In contrast, after passing the boundary, the traveller enters areas where industrial workers receive rising incomes and are educated in schools. This increase in per capita income derives from the improvement of schools, which benefit from rising population density.

The impact of a rising population at each point within the agricultural region resembles the effect of the traveller’s movement. Initially, he observes that a farmer’s per capita income decreases. Then, after crossing the boundary, the region shifts to industrial activity and schooling. From that moment onwards, any movement towards the origin raises per capita income. This model provides a reasonable explanation for the evolution of the college system in most economies.

2. Motivation

In Table 1 in the Appendix, we report data on three variables - namely population density, higher education attainment rate, and per capita GDP - across a set of Portuguese regions in 2021. These regions correspond essentially to NUTS2, although we separate the *Área Metropolitana do Porto* from the *Norte* region and include the islands of *Açores* and *Madeira*, which are formally NUTS1.

We estimate, in cross-section, the multiplicative model $y = \alpha x^\beta$, where y denotes higher education schooling rate and x stands for population density. We obtain an elasticity $\hat{\beta} \approx 0.136$ with an $R^2 = 0.70$. Clearly, population density explains *per se* the regional variation in college attainment.

An utterly different picture is obtained when we estimate the model $z = \alpha x^\beta$, where z is regional per capita GDP. The estimated elasticity is $\hat{\beta} \approx 0.065$, which is much lower than the one obtained for tertiary schooling rate, although it is consistent with most estimates reported in the literature. Furthermore, the R^2 is now only 0.18, so we cannot reject the assumption that population density does not *per se* explain the regional variation of per capita GDP. We plot in Figure 1 the estimated curve $z = \hat{\alpha} x^{\hat{\beta}}$.

Per capita income

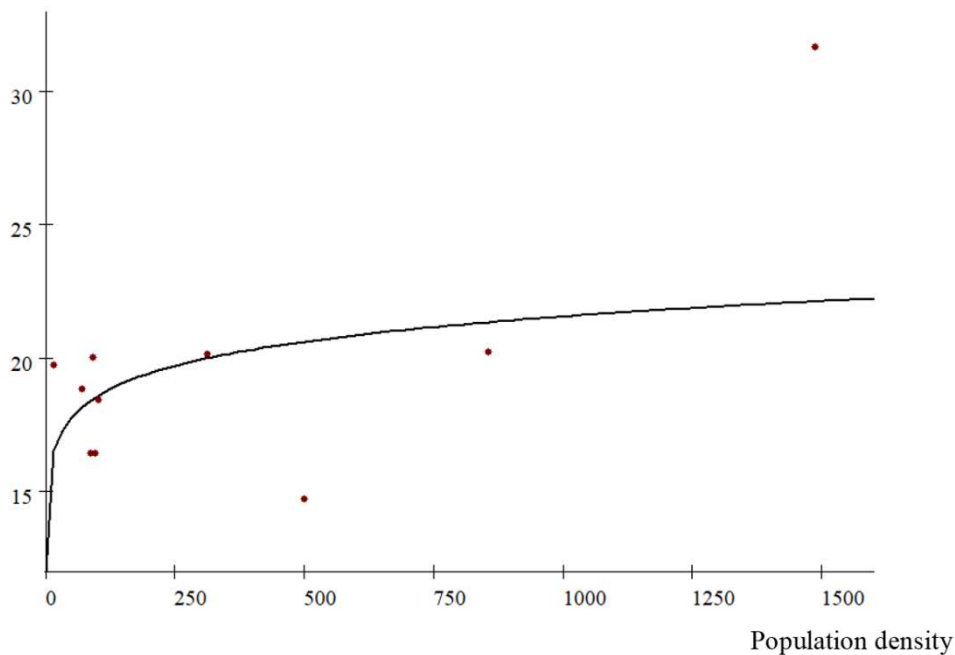


Figure 1: Per capita income to density average elasticity

We attempt to establish a non-monotonic relationship between population density and per capita GDP. To this end, we divide the set of regions into two groups: those with density equal to or below the median, and those with density above the median. The low-density group displays a negative elasticity $\hat{\beta} \approx -0.068$ with an $R^2 = 0.24$, whereas the high-density group displays a positive elasticity $\hat{\beta} \approx 0.154$ with an $R^2 = 0.32$. Figure 2 plots the estimated function for the low-density subgroup.

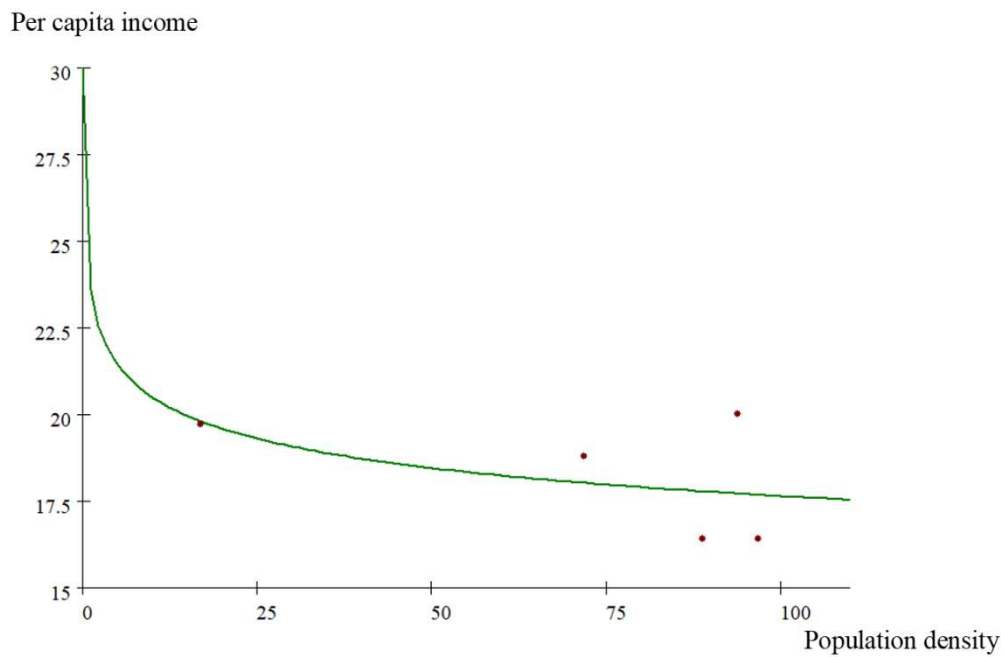


Figure 2: Per capita income to density elasticity for the low-density subgroup

The estimated function for the high-density subgroup is plotted in Figure 3.

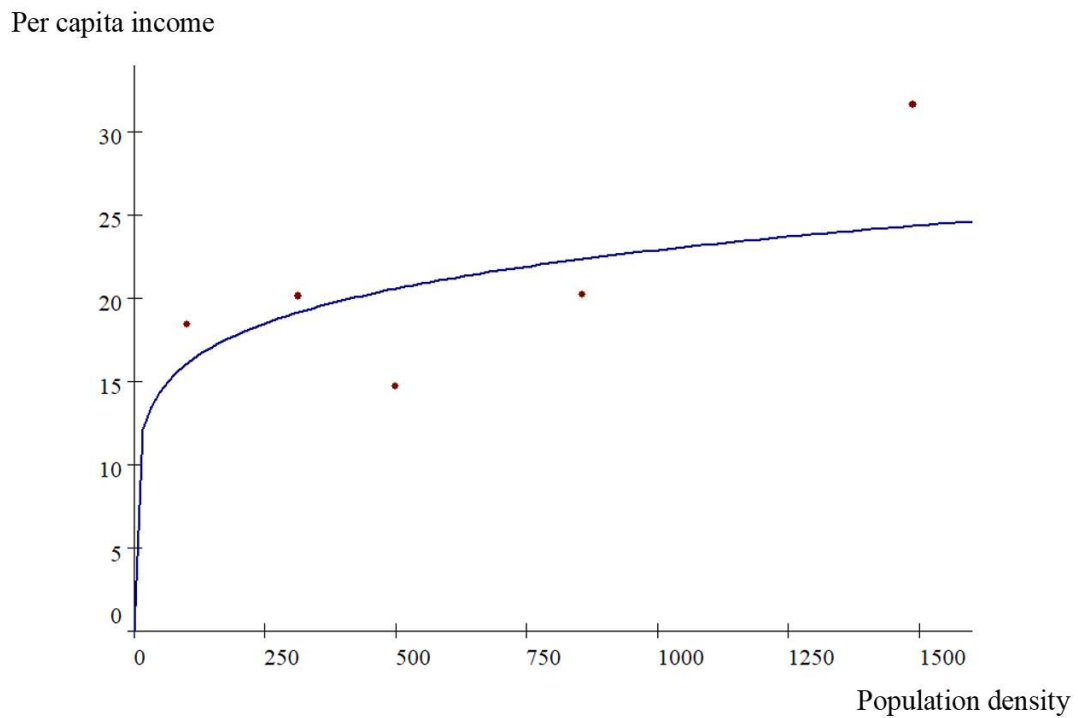


Figure 3: Estimated function for the high-density subgroup of regions

We superimpose the estimated functions of both subgroups in Figure 4, where the vertical line corresponds to the *Norte* region, which has with median density.

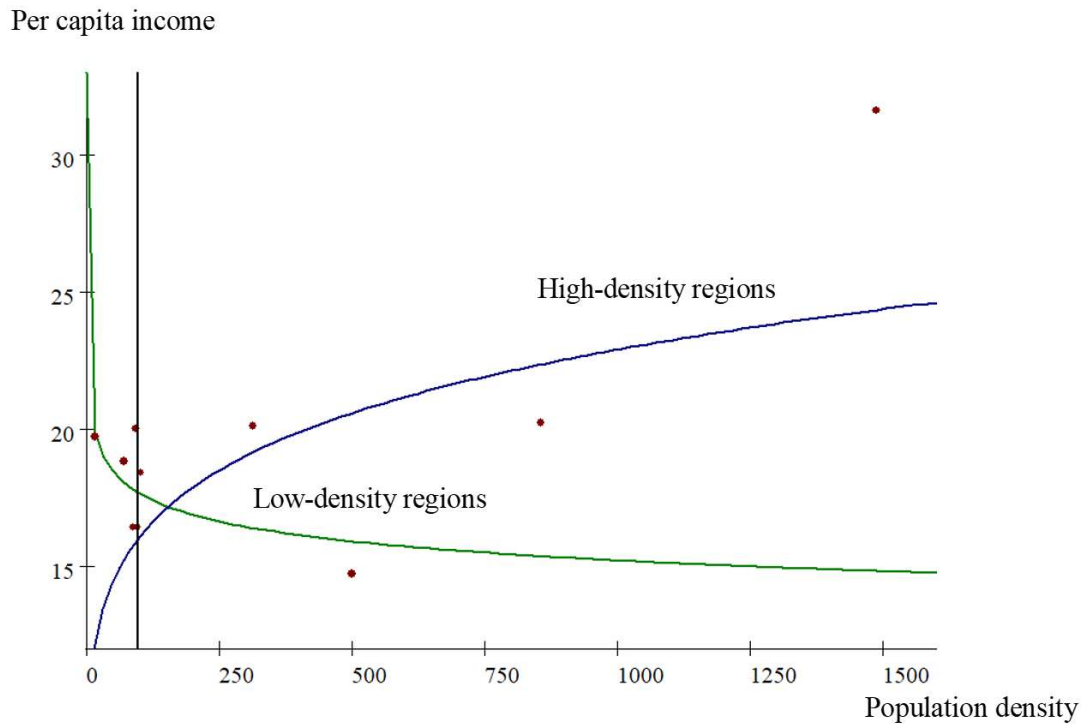


Figure 4: Estimated functions of the subgroups of regions

This result for Portuguese regions matches the one obtained by Pontes (2026), who estimated the elasticity of per capita GDP with respect to population density across 27 European countries – namely 24 EU Member States plus the UK, Norway, and Switzerland - in 2019. In that study, the elasticity for the whole sample was estimated at approximately 0.036, a value consistent with the literature, but with an $R^2 = 0.01$ that allows us to reject the assumption of a monotonic relationship between average income and density.

The estimated elasticity for the group of countries with density below the median was around -0.111 , although this result was not significant with an $R^2 = 0.05$. By contrast, the elasticity for the high-density group of regions was about 0.264 and this estimate explained roughly 40 per cent of the variation across regions. Hence, the conjecture of a non-monotonic relationship between density and per capita income does not seem unreasonable.

3. The geographical structure of the economy

We assume a spatial economy defined on the interval $[0,1]$. Let r denote a location measured by its distance from the origin. In each location, an amount S of land is available for productive use. Population density is given by a strictly decreasing function $L(r)$ that satisfies the condition $L(1)=0$. We plot $L(r)$ in Figure 5.

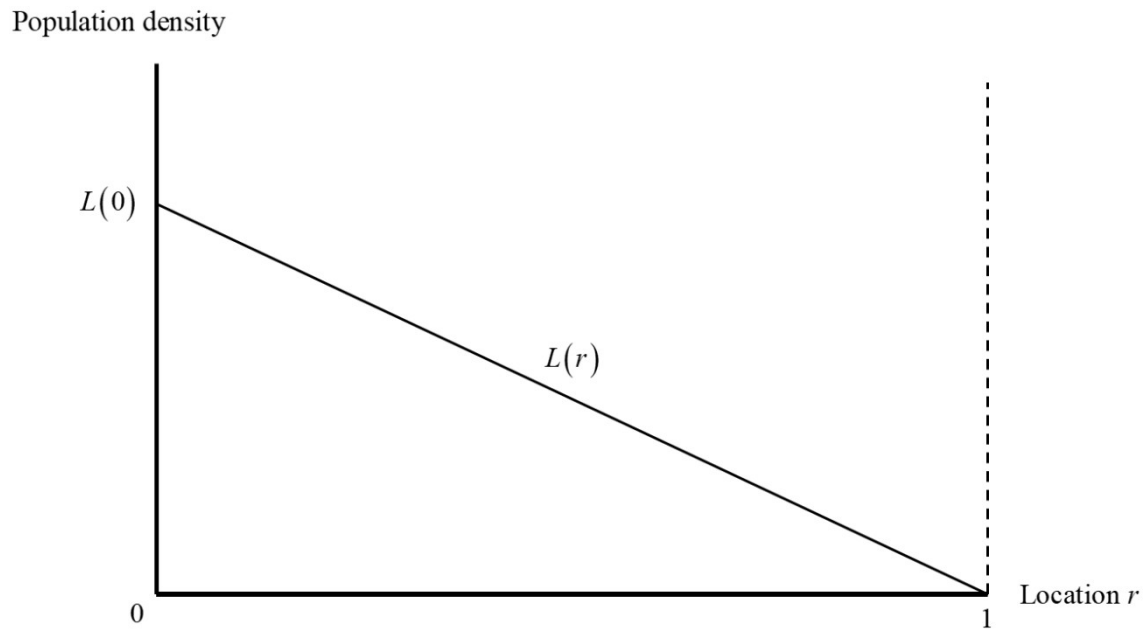


Figure 5: Population density curve

The economy produces a composite consumer good under constant returns to scale and uses education as an intermediate service. Migration is ruled out by assumption, so each individual lives, works and is educated in the same location.

At each point r , $L(r)$ individuals decide on their occupation. They may become farmers or industrial workers. By *farmer* we mean any agent who produces the composite good using land. This includes not only those engaged in agriculture but also producers of housing services. The output $Q_a(r)$ of farmers living at point r is given by a production function exhibiting constant returns to scale in labour and land. For simplicity, we assume a Cobb-Douglas function.

$$Q_a(r) = A_a L(r)^\alpha S^{(1-\alpha)} \quad (1)$$

where $\alpha \in (0,1)$ and A_a is TFP in land-based production.

Hence, a farmer's output in point r may be written as,

$$q_a(r) \equiv \frac{Q_a(r)}{L(r)} = A_a \left(\frac{S}{L(r)} \right)^{(1-\alpha)} \quad (2)$$

The output of a farmer is critically determined by the amount of land he may use. If we chose S as the unit of land, then $S = 1$ and (2) becomes,

$$q_a(r) = A_a L(r)^{(\alpha-1)} \quad (3)$$

Thus, a farmer's output decreases strictly with population density.

In addition to adopting a specific production technology, a farmer is characterised by receiving a traditional form of family-based education with a constant unit cost g , corresponding to the time spent in training a young person. Therefore, the farmer's net income in point r is,

$$y_a(r) = q_a(r) - g$$

or, from (3),

$$y_a(r) = A_a L(r)^{(\alpha-1)} - g \quad (4)$$

To ensure that $y_a(r) > 0$ in every location r , we assume that g is arbitrarily close to zero.

In contrast, an individual may choose to become an (industrial) worker. If point r is inhabited by workers, its aggregate output $Q_i(r)$ is produced under constant returns to labour as the sole production factor:

$$Q_i(r) = A_i L(r) \quad (5)$$

where is TFP in the industrial sector. Consequently, the output per worker is constant.

$$q_i(r) = \frac{Q_i(r)}{L(r)} = A_i \quad (6)$$

In addition to using technology expressed in (6), an industrial worker at each point r must receive school education. For this purpose, he incurs a fee

$p(r) = g + \frac{F}{L(r)}$, which is the sum a unit variable cost g , and a school fixed cost

F , assumed to be proportional to local population. While g has the same meaning as in (4), F denotes fixed outlays related to schooling such as professor training, buildings, libraries, labs and on.

The income earned by a worker in location r is,

$$y_i(r) = A_i - p(r)$$

or

$$y_i(r) = A_i - \left[g + \frac{F}{L(r)} \right] \quad (7)$$

Note that $y_i(r)$ is not necessarily positive for all r . However, it must be positive in every location where individuals choose to become industrial workers, as

$$y_i(r) \geq y_a(r) > 0 \quad (8)$$

We now demonstrate the following proposition.

Proposition 1: *If $L(0)$ is sufficiently high, then there exists a unique location $\tilde{r}$, interior to $[0,1]$, such that individuals in $r \in [0, \tilde{r})$ choose to become workers, while those in $r \in (\tilde{r}, 1]$ choose to be farmers, and the marginal producer in $\tilde{r}$ is indifferent.*

Proof: From (4) and (7), we know that $y_a(r)$ and $y_i(r)$ are continuous functions on $[0,1]$. We compute their first derivatives. Since $L'(r) < 0$ by assumption, we obtain respectively,

$$y_a'(r) = (\alpha - 1) A_a L(r)^{(\alpha-2)} L'(r) > 0 \quad (9)$$

and

$$y_i'(r) = \frac{FL'(r)}{L(r)^2} < 0 \quad (10)$$

Consequently, there is *at most* a location $\tilde{r}$ such that,

$$y_a(\tilde{r}) = y_i(\tilde{r}) \quad (11)$$

It remains to show that the threshold $\tilde{r}$ indeed exists. Consider the inequality

$$y_i(0) > y_a(0)$$

which from (4) and (7) is equivalent to

$$A_i - \frac{F}{L(0)} > A_a L(0)^{(\alpha-1)} \quad (12)$$

Clearly, inequality (12) is satisfied provided that $L(0)$ is sufficiently high.

Furthermore, when $r \rightarrow 1$, we have $y_i(r) \rightarrow -\infty$ and $y_a(r) \rightarrow +\infty$. By continuity of $y_a(r)$ and $y_i(r)$, there is a unique cut-off $\tilde{r}$, interior to $[0,1]$, satisfying

$$A_i - \frac{F}{L(\tilde{r})} = A_a L(\tilde{r})^{(\alpha-1)} \quad (13)$$

QED

We may now state the following corollary.

Corollary 1: *The per capita income curve in the spatial economy $y(r)$ is*

$$y(r) = \max \{y_i(r), y_a(r)\}$$

i., e., the upper envelope of $y_i(r)$ and $y_a(r)$, which is given by,

$$y(r) = \begin{cases} y_i(r) & \text{if } r \leq \tilde{r} \\ y_a(r) & \text{otherwise} \end{cases} \quad (14)$$

The curve $y(r)$ is plotted in Figure 6. It is non-monotonic, i.e., it first decreases and then increases with distance from the origin.

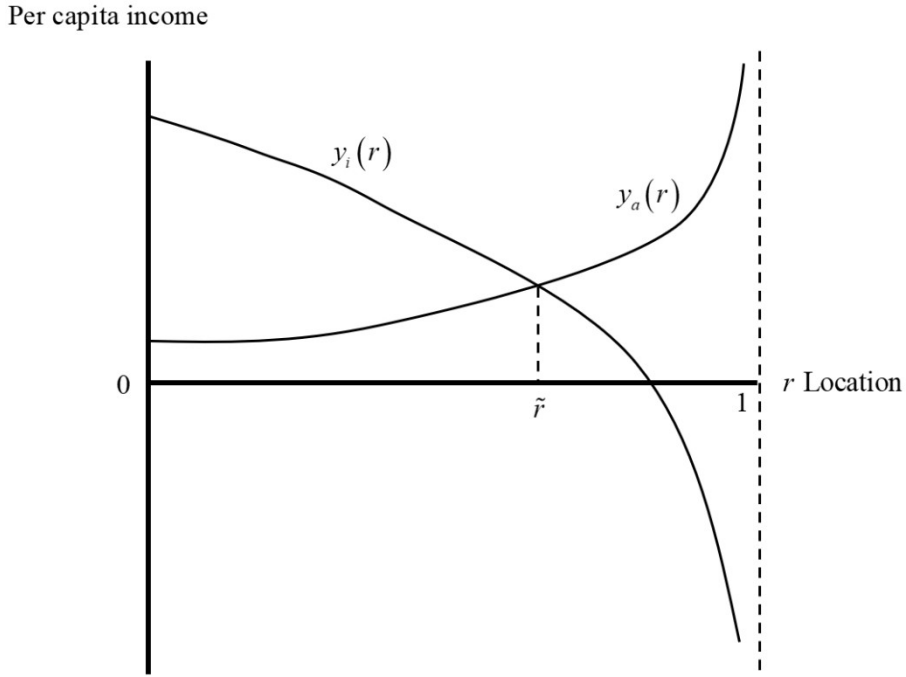


Figure 6: Per capita income curve in the spatial economy

It is also possible to establish that the location of the boundary $\tilde{r}$ depends on the density curve $L(r)$ and aggregate productivities A_i and A_a through the following proposition.

Proposition 2: *The boundary $\tilde{r}$, which separates the regions with industrial and agricultural methods, increases under the following parameter changes:*

1. *The density curve $L(r)$ shifts upwards while keeping the properties $L(1) = 0$ and $L'(r) < 0$.*
2. *Industrial productivity A_i increases.*
3. *Agricultural productivity A_a decreases.*

Proof: From (13), the condition defining $\tilde{r}$ is

$$A_i - \frac{F}{L(\tilde{r})} = A_a L(\tilde{r})^{(\alpha-1)} \quad (15)$$

We may write (15) as an implicit function of $\tilde{r}$ dependent on A_i, A_a , and $L(\tilde{r})$.

$$\begin{aligned} A_i - \frac{F}{L(\tilde{r})} - A_a L(\tilde{r})^{(\alpha-1)} &= 0 \\ \text{or} \\ H(\tilde{r}; A_i, A_a, L(\tilde{r})) &= 0 \end{aligned} \quad (16)$$

Suppose $L(r)$ increases everywhere while keeping $L(1) = 0$ and $L'(r) < 0$. For example, $L(r)$ may be multiplied by a constant factor $\delta > 1$. From Proposition 1, we know that for the new density curve, a unique $\tilde{r}$ continues to exist.

We may compute

$$\frac{\partial H}{\partial \tilde{r}} = \frac{L'(\tilde{r}) \left[F + (1-\alpha) A_a L(\tilde{r})^\alpha \right]}{L(\tilde{r})^2} < 0 \quad (17)$$

for each value of $\tilde{r} \in [0, 1)$. When $\tilde{r} \rightarrow 1$, we have $\frac{\partial H}{\partial \tilde{r}} \rightarrow -\infty$. Hence, for each $\tilde{r}$, there exists an explicit function $\tilde{r} = h(L(\tilde{r}), A_i, A_a)$.

We compute the partial derivatives of $h(\cdot)$.

1.

$$\frac{\partial \tilde{r}}{\partial L(\tilde{r})} = -\frac{\partial H / \partial L(\tilde{r})}{\partial H / \partial \tilde{r}}$$

Using the chain rule,

$$\frac{\partial H}{\partial \tilde{r}} = \frac{\partial H}{\partial L(\tilde{r})} L'(\tilde{r})$$

hence

$$\frac{\partial H}{\partial L(\tilde{r})} = \frac{\partial H / \partial \tilde{r}}{L'(\tilde{r})}$$

Consequently, we obtain

$$\frac{\partial \tilde{r}}{\partial L(\tilde{r})} = -\frac{1}{L'(\tilde{r})} > 0 \quad (18)$$

2.

$$\frac{\partial \tilde{r}}{\partial A_i} = -\frac{\partial H / \partial A_i}{\partial H / \partial \tilde{r}} > 0 \quad (19)$$

since from (17) we have $\frac{\partial H}{\partial \tilde{r}} < 0$, and $\frac{\partial H}{\partial A_i} = 1$.

3.

$$\frac{\partial \tilde{r}}{\partial A_a} = -\frac{\partial H / \partial A_a}{\partial H / \partial \tilde{r}} < 0 \quad (20)$$

since from (17), we have $\frac{\partial H}{\partial \tilde{r}} < 0$, and

$$\frac{\partial H}{\partial A_a} = -L(\tilde{r})^{(\alpha-1)} < 0$$

QED

Galor and Weil (2000) argue that the substitution of schooling for family-based education is fostered by the acceleration of technical progress, which requires new types of skills that cannot be transmitted through upbringing. In our model, this effect is represented by an increase of A_i relative to A_a .

4. The time evolution of industrial activity and school education – the “traveller” model.

We now address the issue of how the spatial economy changes over time following an increase in population at each location. We assume that the density curve shifts upwards between periods from $L_0(r)$ to $L_1(r)$ with $L_1(r) > L_0(r)$ for $r \in [0, 1)$. We restrict attention to $L_1(r)$ curves that continue to satisfy the same qualitative properties as $L_0(r)$, namely $L_1'(r) < 0$ for all r and $L_1(1) = 0$. A simple instance of this type of demographic change is $L_1(r) = \delta L_0(r)$ for a constant $\delta > 1$.

Clearly, this kind of demographic change shifts the boundary away from the origin, so that we have $\tilde{r}_0 < \tilde{r}_1 < 1$. For this reason, if all other parameters remain constant, the share of individuals who attend school and adopt industrial techniques expands when population increases everywhere.

The impact of increasing numbers of agent on the time evolution of the economy is less straightforward, and for this reason we introduce the following analogy. Consider an individual who lives at point $\bar{r}_0$ and sees the number of neighbours rising to $L_1(\bar{r}_0) > L_0(\bar{r}_0)$. This demographic change is analogous to a situation in which the density curve remains fixed, but the individual somehow “travels” to a point $\bar{r}_1 < \bar{r}_0$ such that the condition $L_0(\bar{r}_1) = L_1(\bar{r}_0)$ is satisfied. We plot this analogy in Figure 7.

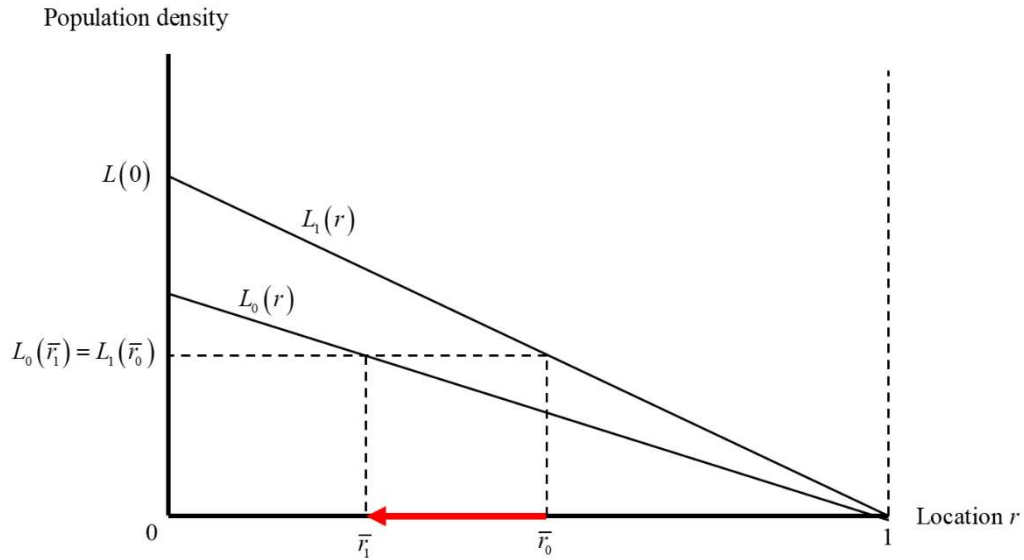


Figure 7: Evolution of the spatial economy in time: the “traveller” model

Population growth may have three types of impact, which can be assessed by recalling Figure 6.

First, when $\tilde{r}_1 < \bar{r}_1 < \bar{r}_0$, the “traveller” is initially a farmer, and he remains within the region characterised by traditional family-based education. Moreover, the “traveller” experiments a decrease in individual income.

Second, when $\bar{r}_1 < \bar{r}_0 < \tilde{r}_1$, the “traveller” is initially an industrial worker, and he remains within the region with schooling. In addition, his income increases along the journey.

Finally, when $\bar{r}_1 < \tilde{r}_1 < \bar{r}_0$, the “traveller” crosses the boundary between the two regions, so that he begins as a farmer from the start but then switches to industrial technology and schooling. The impact of this structural change on income is indeterminate.

5. Discussion

Up to this point, we have framed our model in terms of the agent's location r , which represents the distance from the origin. However, since the density curve $L(r)$ is strictly decreasing, it admits a decreasing inverse function $r = R(L)$. Consequently, the per capita income curves of farmers and industrial workers, previously plotted in Figure 6, may be drawn as a function of population density $L(r)$, as illustrated in Figure 8.

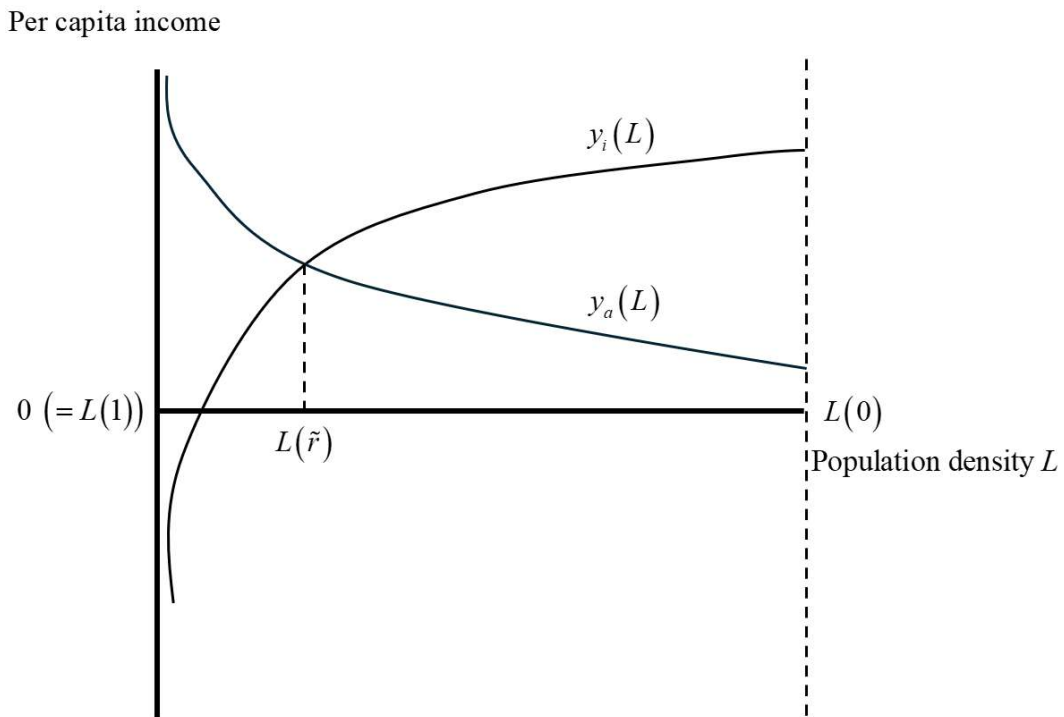


Figure 8: Individual income as a function of population density

We note that the theoretical curves in Figure 8 are qualitatively identical to the empirically estimated curves shown earlier in Figure 4.

In Section 4, we examined the impact of population growth on the boundary $\tilde{r}$, which separates the traditional and modern regions of the economy. However, the relative size of the regions also depends on the productivity terms A_i and A_a . For example, a substantial increase in population may fail to induce a structural change if it is accompanied either by a rise in A_a , or a fall in A_i .

In our framework, the regions characterised by family-based education and by formal schooling are interpreted as using different technologies to produce the same composite good. Nevertheless, we might instead consider an economy producing distinct – namely “food” and a “manufactured good” – with prices p_a and p_i respectively.

This extension does not alter the results provided that these prices are fixed, as occurs when the economy is small and open and both goods are traded, so that producers behave as price-takers. In that case, we would have $A_i \equiv p_i \hat{A}_i$ and $A_a \equiv p_a \hat{A}_a$, where $\hat{A}_i$ and $\hat{A}_a$ are the “physical” productivity terms of industry and agriculture, respectively.

When p_i and p_a are allowed to vary endogenously, the model becomes more complex, yet it still yields results that are similar to those obtain under the assumption of fixed prices (see, for instance, Boserup, 1965).

6. Concluding remarks

We seek to rationalise the evidence that per-capita income exhibits a non-monotonic relation with population density. This relationship is typically negative across low-density regions and becomes positive within a subset of high-density areas. Hence, regional per-capita income first decreases and then increases with demographic density.

This pattern arises from the fact that the economy is composed of two types of regions. On the one hand, there are regions where production is carried out using an agricultural technology in which a farmer's output is determined by the size of the cultivated area. As this is a traditional kind of activity, farmers are generally trained through family upbringing. On the other hand, production may be undertaken using industrial methods by workers trained in schools whose operation is subject to scale economies.

We have shown that the two types of technology used to produce goods and educate the young population occupy non-empty subsets of the spatial economy. Moreover, the modern type of region expands relative to the traditional one when demographic density rises proportionally in each location, although the net effect also depends on the productivity terms associated with each method of production.

In general, the impact of an increase in the number of inhabitants a given location on their individual income is indeterminate, although we may conjecture that it will be positive for central dense areas and negative elsewhere. A structural shift from the traditional regime to the modern one seems appears more likely in locations with intermediate levels of accessibility and density.

We leave for future research the modelling of a situation with endogenous prices for the agricultural and industrial goods. This projected research will likely build on Boserup's (1965) seminal approach, in which increasing agricultural intensity is viewed as a crucial determinant of economic development.

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Appendix

The following table contains data on population density, higher education attainment levels, and per-capita GDP for the Portuguese regions, which are essentially NUTS2 in this context. However, we include the *Área Metropolitana do Porto*, even though it is not a NUTS2 region, and remove its data from the *Norte* region. We also include the island regions of the *Açores* and *Madeira*, which are technically NUTS1. These data are produced by the *Instituto Nacional de Estatística* and retrieved from the PORDATA database.

Table 1

Region	<i>x</i>	<i>y</i>	<i>z</i>
Norte	97	14.7	16.4
Área Metropolitana do Porto	857	21.0	20.2
Centro	72	18.1	18.8
Oeste e Vale do Tejo	89	15.5	16.9
Grande Lisboa	1489	29.0	31.6
Península de Setúbal	501	20.5	14.7
Alentejo	17	14.4	19.7
Algarve	94	17.3	20.0
Azores (Islands NUTS1)	103	14.7	18.4
Madeira (Islands NUTS1)	315	16.5	20.1

Meaning of variables:

x $\equiv$ Population density, (inhabitants per km²)

y $\equiv$ Higher education attainment: percentage of the resident population aged 15 or older holding a completed tertiary degree (ISCED 5-8), according to the 2021 Census.

z $\equiv$ Per capita GDP (unit: 1000 euros)

