CAPÍTULO 7

PROBLEMS AND ADVANTAGES OF TERRITORIES WITH LOW POPULATION DENSITY

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ABSTRACT: We observe both territories with high and low population density. Low population density is often considered as disadvantage of a territory. Indeed, there should be reasons for people not to settle there: bad climate, natural disasters, remoteness from trade routes. But such areas often have an important advantage in high endowment of natural resources per capita. If all those resources belong to local inhabitants, they still can have low value without an access to the global market. Building infrastructure to create such an access and then to have sustainable development is a rational objective. However, it is a scale economy, which is cheaper per person if their quantity increases. Thus, low population density may become a self-reinforcing factor, preventing such development, and low populated territory can stay in a poverty trap. However, after passing some threshold with minimal infrastructure, the richness of such territory can grow fast, driven by still high endowment of natural resources per capita and ability to trade them. Yegorov (2009) presented a spatial economic model for spatially distributed resources, their harvesting and building road network with certain density, taking into account the difference in transport costs along a road and without it. It was shown that the profits of such territory are negative in the neighbourhood of zero population density and are maximal for a certain (optimal) population density. Then they start to decline for overpopulated territories. Yegorov (2016) considers an equilibrium between urban and rural areas and optimal rural population density. It depends on the global prices for energy and agriculture. Their high volatility in the last years undermined sustainability of such equilibria even when urban-rural harmony was formed in such country. The paper also analyses global heterogeneities in population density and infrastructure. Application of such models for different countries and regions can give important policy insights. Some territories can never

reach high population densities due to restrictions in climate (like Canada) and water scarcity (like Australia). Other territories (like India) have rich soil and sufficient road infrastructure, but suffer from low resource endowment per capita due to overpopulation. Many countries have heterogeneous regions, with pooper areas which have problems with climate or access, and thus are underpopulated. Such an approach allows for theoretical analysis of territorial development and to make forecasts, based both on economic and geographical parameters, as well as policies.
KEYWORDS: spatial economics, population density, territory, growth, profit.

INTRODUCTION

Spatial densities play a very important role in natural sciences (physics, chemistry, biology), where they are studied both theoretically and empirically. In physics they define state of matter (solid, liquid, gas) along with some other parameters, like pressure. Yegorov (2007a) suggests the analogies between physical and socio-economic states. In biology, density of certain plants or animals define interactions in ecosystems (for example, Lotka-Volterra model).

The situation is different in socio-economic sciences. On one hand, increasing possibilities of observations and data presentation in digital form allows for creation of many maps for socio-economic parameters including population density. On the other hand, only a small fraction of economic literature (regional science and urban economics) uses theoretical spatial models, while other models cannot use space (as it is not defined). Note that the concept of spatial density on a surface is applicable only for continuous 2-dimensional space, where density is defined as some quantity per unit of territory. While the surface of the Earth (where people live and economic activity takes place) is a two-dimensional manifold, it can be presented by a set of local 2-dimensional maps, with application of Euclidean geometry for distance and area.

Analytical approach for the role of population density on socio-economic activity is in the process of its elaboration. This paper will survey author's papers in this direction in its theoretical part (section 2). Section 3 will consider practical application of these results. Section 4 concludes. The paper contains several maps with densities of population, water resources and infrastructure, which can help in understanding spatial approach of the paper models.

THEORETICAL APPROACH

Von Thünen (1826) was the first scientist to develop spatial heterogeneity around a city, which emerges endogenously, driven by spatial asymmetries in the distance to the market. German school of regional science (Christaller, Lösch and others) continue development of spatial models in 1930s. American scientists, like Hotelling, were also contributing research in this direction, and the whole branch of Industrial Organization literature was also developing spatial models during most of the 20th century. A good survey is provided in Beckmann & Thisse (1986).

Since 1980 there was a shift to product differentiation literature, caused also by discovery of problems with Nash equilibrium in the model of Hotelling (1929), which was solved by introduction of quadratic transport costs in distance in abstract space of differentiated goods. However, the real transport cost in space is almost linear in distance, which was argued in Yegorov (2000), who also found conditions for equilibrium existence in 2-dimenstional space.

About Population Density

The population density is very heterogeneous around the world. Fig. 1 shows that very low population densities (below 2 person per sq.km) are observed in: a) water scarce areas (Sakhara desert, most of Australia, Central Asia, North-West China), b) forested areas with hard climate (Canada, Siberia, Amazonia). While physical water scarcity also sets the limit for vegetation and biological activity, forested areas present sustainable ecosystems and their under-development also has economic-geographical reasons.

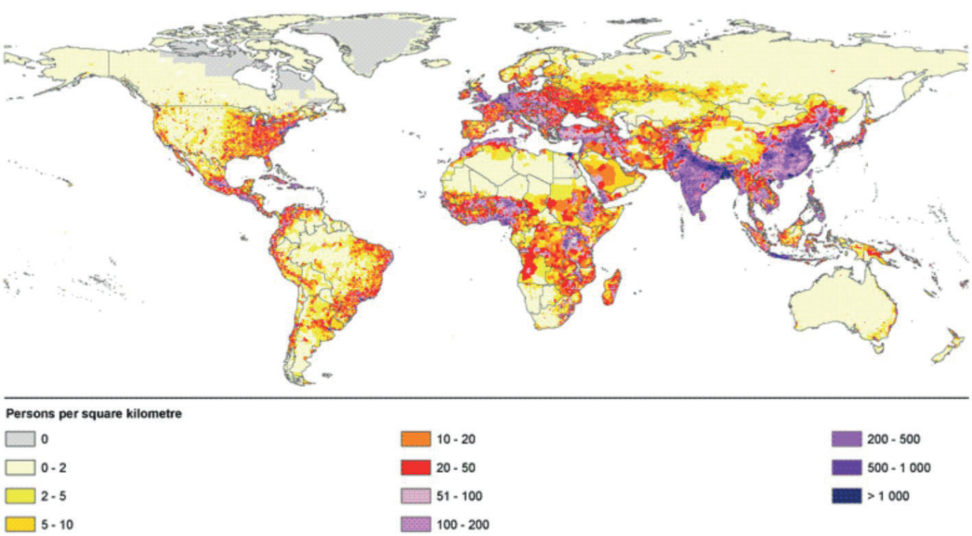

Fig. 1. Global population density estimates, 2015.

Source: Reliefweb (2007)

Fig. 2 shows European population density in 1915, when most of population have been rural, and the settlement was determined by both geographical and economic conditions. The low density of population can be observed in the north of Europe (Scandinavia, Russia), as well as in mountain areas (Alps). People concentrated in river plains in the Netherlands, Belgium, Northern Italy, and German lowlands. (Yegorov, 2021) The high population density in Northern Italy and Netherlands was also observed many centuries ago; it has high correlation with water supply. High population density in Ruhr area and regions of Britain came from industrial development in the 19th century. As time goes, people settle more in cities and sometimes in the areas with insufficient water supply (Middle East, oil revenues are used for water supply technologies).

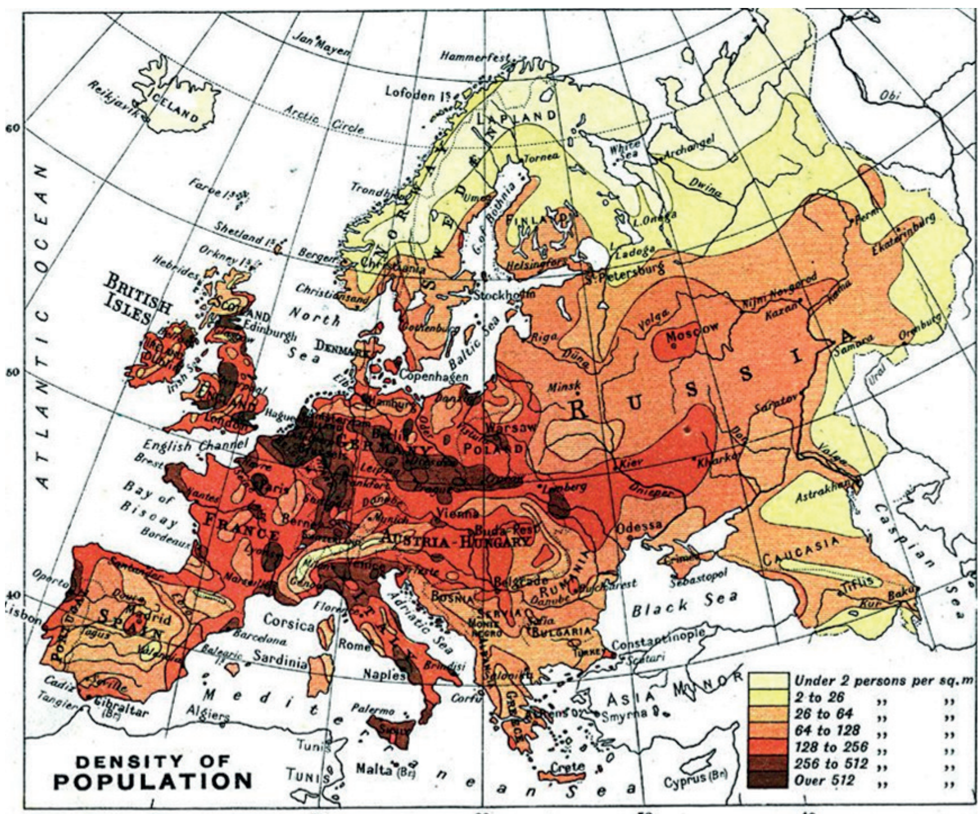

Fig. 2. European population density in 1915.

Source: Pinterest (2021)

About Structural Economics

Despite the fact that structures play an important role in economics, there are almost no studies of them at theoretical level, consistent with mathematical economic theory. Yegorov (2011) suggests the necessity to study economic structures analytically and presents their classification. Mathematical economics deals mostly with interaction of elements via markets. At the same time, structures exist as unions of elements. Examples of social structures include family, firm, community and nation. Like in chemistry, their stability depends on external parameters, and this question should be studied.

Other structures are physical, and infrastructures have also spatial structure. Yegorov & Wirl (2010, 2011) study natural gas infrastructures and their role in the global market for natural gas. A gas pipeline is the only way to export gas from land-locked countries, like Turkmenistan. Sometimes it is impossible to by-pass third counties, and this creates a possibility of gas transit games (bargaining on transit cost). Due to huge investment costs, only one pipeline is typically constructed between certain seller and buyer, and this creates a natural monopoly. This example shows a complex interplay between economics, geography and politics.

The role of spatial economics is in explicit accounting for transport cost and land use. Two theoretical models – forest exploitation and production and export of agriculture – have been considered by the author and are shortly presented below. They are based on optimal harvesting of the territory, either belonging to the country as a whole (forest) or agricultural harvesting and export with decentralized land ownership.

The Role of Geography on Transportation of Bulky Goods

While the role of transport costs was declining over time with technological development, they still play a very important role in transportation of bulky goods (like natural resources). Grohall & Yegorov (2011) estimated the distances at which the price of such goods doubles.

Water is the most expensive resource for transportation. While water for personal consumption can have price up to $1/liter (and mineral water can be exported worldwide), water for agricultural use cannot be more expensive than $2-3/ton, and thus its price doubles at already few km of distance by land transportation, and it should have regional price. Yegorov (2021) studies self-organizing property of water. Its regional scarcity influences both agricultural production and population density.

Wood is also a relatively cheap resource. Its ton is several times cheaper than oil. Contrary to oil, which is moderately dispersed over globe (but has high concentration of deposits in certain locations, like Persian Gulf), wood is very dispersed, and it needs a relatively dense network of roads for its harvesting. Yegorov (2007b) presents a dynamic optimization model of infrastructure development for forest exploitation.

In many locations (Canada, Siberia, Brazil) there is too low population density for substantial forest exploitation for local use (and regional price is very low), while the distance to potential consumers is too high (thousands of km) to make export profitable. Moreover, regions lack a dense road infrastructure. The situation with some agricultural goods (especially with a low price/weight ratio) is similar. The next subsections deal with the model of spatially distributed resource harvesting.

Forest Exploitation Model

This subsection briefly describes Yegorov (2007b). It shows how geography influences development. Many countries own huge deposits of forest (Canada, Russia; Brazil), but its domestic use is supressed by low population density in forested area and huge transport cost to the market for export. Note that sustainable exploitation of the forest is impossible in pure market economy, where it will be fully logged in the area with minimal transport cost. However, grants for forest preservation (as the benefit for mankind) can help with sustainable forest exploitation. At present, they are known only in small countries, like Costa Rica, while predatory exploitation of forest in Amazonia by foreign firms can bring global externality.

Consider Cournot competition with the rest of the world (that has fixed production level q), while one producer can expand capacity Q(t). Thus, the world price of wood at time t is:

$$P(Q(t),q) = A - Q(t) - q.$$

The spatial structure of forest is as follows. It covers a rectangular area with one side a (it can be, for example, US-Canadian border, or Russia-China border). The orthogonal coordinate X(t) shows the penetration of exploitation at time moment t. Thus, harvested area at moment t is: $S(t)=bX(t)$. For sustainability reason, only a fraction of forest is harvested. The average transport cost grows with penetration. Capacity expansion requires capital investment in infrastructure to expand road network to previously unexploited area. The firm (country) with a possibility of expansion strategically takes into account the dynamics of world price and solves dynamic optimization problem, provided in the paper. Typically, there is one saddle type solution. Economic interpretation is as follows. For a given level of world prices for wood, there exists a convergence to optimal level of forest exploitation. For example, if initially such penetration X(0) was at 200 km, it might be optimal to expand it to 500 km. Still, some fraction of forest (located at high distance from the market) remains unexploited.

Thus, we have endogenous decomposition of forest into exploited and non-exploited area, driven by market forces. In regulated economy, there might be incentives for forest preservation (as lungs of the planet). Creation of national parks is also important, but minimal infrastructure is also needed for that.

There are countries with large forested territories in low-populated areas, like Canada, Russia and Brazil. They need huge investment in infrastructure to exploit this forest, and even more investment for sustainable exploitation (with replacement of harvested areas with new forest). This model can be useful for those cases. Fig. 3 shows population density in Brasil, while Fig. 4 shows its forest density. There is negative correlation: forest is located in low-populated area of Amazonia. The situation in Canada and Russia are similar: forested areas have much lower population density. This brings development problem, considered theoretically in the following subsection.

Fig. 3. Population density in Brazil.

Source: https://www.researchgate.net/figure/Brazil-demographic-density-map-Source-IBGE_fig1_235635602

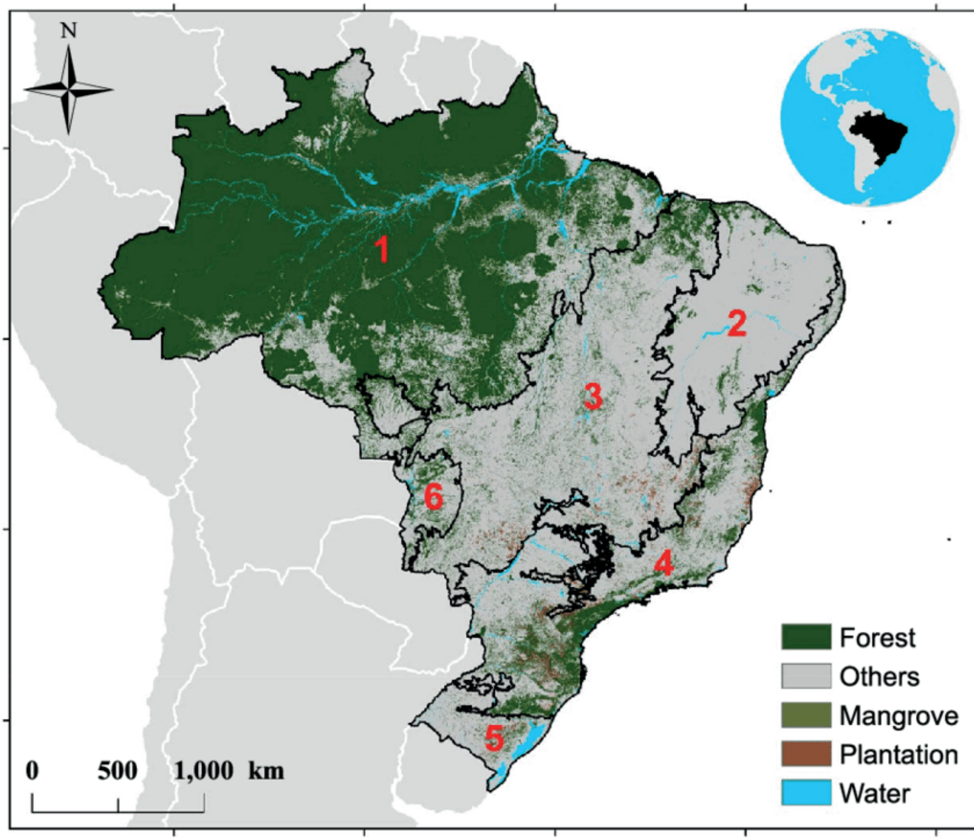

Fig. 4. Forest density in Brazil.

Source: https://www.researchgate.net/figure/Forest-cover-of-Brazil-In-the-main-map-black-lines-represent-the-Brazilian-biomes-1_fig1_343655355

The Model of Harvest-Export Economy

The model of harvest-export economy considers a country, specializing on harvesting of spatially distributed natural resources (Yegorov, 2009). It shows the influence of population density on production of agricultural or mining type that is spread in space. The initial dispersion of population in space comes from land-intensive activity (farming, forestry, hunting, mining) which historically has been a dominant source of economic output. It is still important, especially in countries with low population density (Russia, Canada, etc.). A space uniformly populated by small identical farms producing everything would be the optimal spatial infrastructure, since it would involve minimal transport costs. This article builds a simple theoretical model which captures the effect of differences in spatial densities across countries.

A country is assumed to contain homogeneous area S with population N. The population density is $\rho=N/S$. Land per capita is $l=S/N=1/\rho$. A country has access to capital K. The capital per capita is $k=K/N$. Different countries may differ in area S, population N and capital K, but they have identical technology

$Y= N k^a l^b$,

where 0<a<1, 0<b<1.The production is spread over space homogeneously. The formula for output can also be written as

$Y=N^{1-a} K^a \rho^{-b}$.

This means that for given population density the output is Cobb-Douglas in total capital K and total labour N, while total factor productivity captures here geographical difference across countries. While this formula suggests an advantage in harvesting productivity in for low populated countries, we have to consider transportation network as well.

It is also assumed that price for capital (r) and the output (p) are given exogenously. Assume that country is a square with side $A=S^{1/2}$, with its capital in the centre. In an autarky, production is consumed locally. This does not require dense road network, but also does not allow for economic growth. If population has low density, not all resources will be consumed.

In order to export harvested resources, it is necessary to collect them. We say that country has ε-dense road network, if ε is the highest distance between any point inside country and a closest road. Let us focus on a particular network which consists of one vertical road passing through the capital and several parallel horizontal roads with distance 2ε between each of them.

The transport-export firm (it can be government or natural monopoly) assumes responsibility for paying these transport cost. Thus, farmers receive payment c based on competitive wages, while the firm sells output at world price p and pays 3 components of transport costs: a) maintenance costs for road network (δ is depreciation rate, f – fixed cost of 1 km of road), b) integral transport cost along roads, c) without-road transport costs (unit distance transport cost is T> ε, higher per unit of distance, but their volume is lower for higher density of road network). B is spatial density of production (in kg harvested from 1 sq.m). The total transport costs are given by

$$TTC = FTC+VTC+WRTC = (\delta f /\varepsilon+A B t+ B \varepsilon T)S/2.$$

It is possible to find optimal density of road network as the function of other parameters:

$$\varepsilon^* = (\delta f/BT)^{1/2}.$$

Let c denotes wages of farmers (per unit of produced output), and TQ is total transport cost per unit of produced output. Then the profit of transport-export firm (for which population is assumed to be shareholders) is:

$$\Pi = k^a \rho^{-b} - [p - c - TQ] = k^a \rho^{-b} [p - c - (\delta f / \varepsilon + A t + \varepsilon T)/2].$$

Substitution of formulae for B and for ε* gives the expression for profits at the optimal road network:

$$\Pi = k^a \rho^{-b} (p - c - At/2) - k^{a/2} \rho^{-(1+b)/2} (\delta f T)^{1/2} .$$

We see two different negative powers in the expression for profits. Hence, profits are negative in some neighbourhood of zero population density. Profits are maximal for some intermediate (optimal) population density. For higher densities they start to decline.

Thus, a country with very low population density might never pass the threshold of profitability. While it has high resource endowment per capita, it might never be able to self-finance the optimal infrastructure (road network) for their extraction.

The term c being a negative term in a balance account for transport-export firm is not lost; it contributes to country's GDP through the income of producers (farmers). Assumes that there exists an alternative sector of the economy (manufacturing or services), where the profit Π can be invested. Then the growth rate of a country will be higher, when those profits per capita are higher. A country with optimal population density will show the highest growth rate, according to this model. But countries with too low population density might never show growth if they specialize on harvesting their territory.

Optimal Rural Population Density

There exist many papers about urban economics, which deal theoretically with urban structure, population density in a city, attractive and repelling forces responsible for its formation. However, the rural structure is studied theoretically much less. Here we should mention von Thünen (1826), who has described heterogeneity in the form of circles around an isolated city, with different types of agricultural activity.

Yegorov (2005, 2009) elaborates the concept of the economic role of population density. Rural population density can influence economic growth. There exists an optimal population density for resource-based economies (see 2.4).

Yegorov (2016) elaborated the ideas about optimal rural density further, making a link with price indices for food and energy. Assume that land is divided optimally between farmers, who develop it only with own labour. Let S be plot size, r - land rent, E - energy price, d- distance to agricultural market to sell the output, τ - unit distance transport cost. The profit of a farmer is given by:

$$\pi = AS^a - (R + cE)S - \tau d.$$

Profit maximization for this equation with respect to land size, S, leads to equation

$$Aa\, S^{a-1} = R + cE$$

that gives optimal plot size, S^*. In the case a = 1/2, the expression for S * is very simple:

$$r^* = (S^*)^{1/2} = A /(2(R + cE)).$$

This optimal land plot for a farmer depends positively on the food price index and negatively on the land rent (r) and energy price index (E). If we have a fixed rural population, N, and all rural arable land Q is divided equally among them, then a plot per person is S = Q/N. The corresponding rural population density is then $\rho = N/Q=1/S^*$.

Then the equilibrium split of the population in urban and rural is considered. It parametrically depends on world prices for food and energy. We observe very high volatility of those prices in the recent decades, and this is a shock for spatial settlement of the population.

PRACTICAL APPLICATIONS

Different countries and regions have different geography. It also influences the level of economic activity. Another influence comes from financial force, which nowadays plays the dominant role (Yegorov, 2023).

We observe heterogeneous population density, even rural, in many countries. It is the result of an interplay of market forces in a spatial framework, and will be considered in more detail in this section. There are also policy discussions about advantages and disadvantages of low density as the result of market outcome, possibility to influence it in regulated economy and further challenges, emerging from climate change.

Different Use of Territories. Rural and Urban Densities

While initially agriculture was dominating in the GDP, now the territories have a multiplicity of possible use. Land can be used for agriculture, mining area, forest, industrial zone, urban area, recreation area, natural park, etc.

Note that urban land rent is much higher than rural, and it was also the driver of urbanization from the supply perspective. On the other hand, it is less costly to have distributed population (Yegorov, 2017b).

Now about 50% of the global population live in cities, while in more developed countries this fraction is about 80%. Urban densities also differ, but are usually about 5000-20000 of citizens per sq.km. They are much higher than the densities of mostly densely populated countries. Rural densities also differ, from 1 person per sq.km (Rural Canada and Siberia) to 500 persons per sq.km (in India with fertile land).

The models above (subsection 2.5, 2.6) are more for rural densities. Industrial production and services are much less land intensive, contrary to agriculture and mining.

The Role of Infrastructure and Resources

As it was shown in the model above, resources and infrastructure are complementary for successful economic development and economic growth of a country.

Different resources are spread heterogeneously over the globe, but there are almost no territories with low resource endowment in all categories. Some territories are rich in particular mineral resources (different metals or hydrocarbons), while others have fertile land (and high agricultural productivity) or forests.

Thus, initial resource endowment is on average proportional to territory. Some territories have already used the potential for mining in the previous years of economic activity. Other territories experienced degradation, due to destruction of natural ecosystem.

Water is an important resource for living, and the land is very heterogeneous with respect to water scarcity (Fig. 5). Population density has high correlation with water supply, but is determined not only by it.

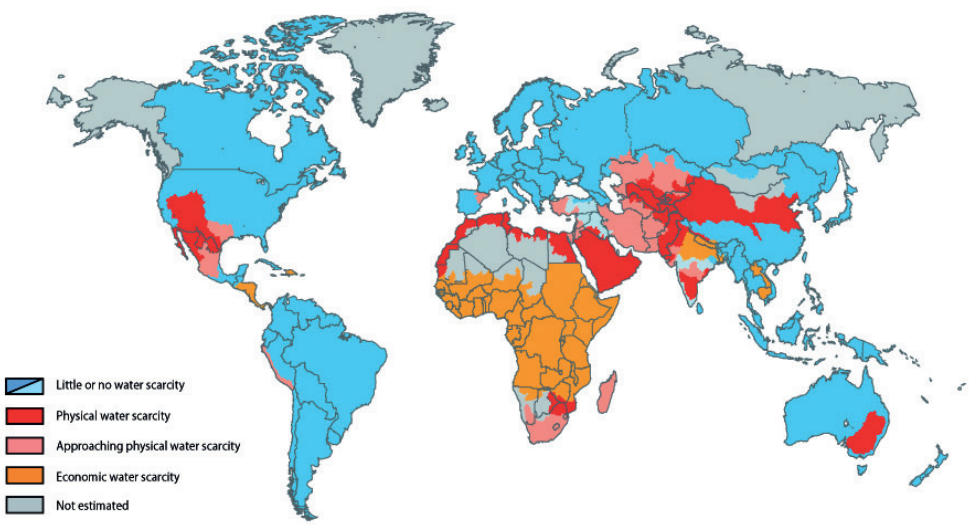

Fig. 5. Water scarcity

Source: Expedition Earth (2015)

A comparison of Fig. 1 and Fig. 5 shows that most water-scarce areas have also low population density (like non-coastal North Africa, western states in the USA). Population density is determined by local agricultural supply, while coastal areas enjoy cheaper imports due to lower transportation costs by sea. In India and Bangladesh, population density is extremely high. Even given favorable climatic conditions for agricultural production in South Asia, there is a critical economic scarcity of water.

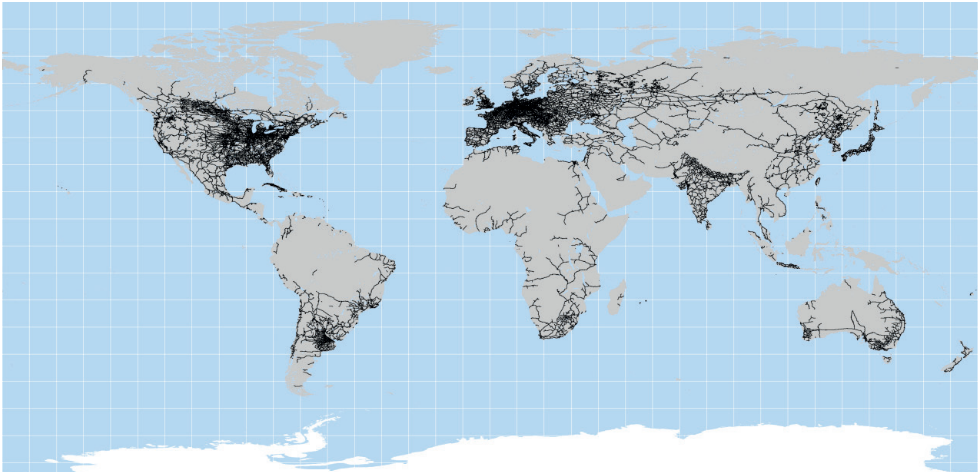

Fig. 6. Global map of railroads shows huge heterogeneity in the spatial density of railroads.

Source: http://bioval.jrc.ec.europa.eu/products/gam/images/large/railways.png

As for spatial density of infrastructure, it is also quite heterogeneous. Fig. 6 shows the spatial network (and density) of railroads, an important fraction of infrastructure. Low populated areas often have insufficient infrastructure, even when they are rich in natural resources.

High density of railroads positively correlates with population density (compare Fig. 1 and Fig. 6). This correlation is mutually driven by the demand and supply. Higher population density gives higher demand for transportation, especially in the era of globalization. But most of the railroads have been constructed in the end of 19th and the first half of the 20th centuries, and that time they were driven by economic demand, including resource exploitation and manufacturing. Still, resource rich areas in Northern America, North-East Asia, major parts of Latin America, Australia and Africa lack dense network of railroads, also due to low population density.

Railroads are not the only way of transportation. Roads and waterways are also important. The coastal location positively correlates with population density. As we can see from Fig. 1, coastal areas in both Americas have higher population density, than continent on average. Similar processes take place in other continents. For example, Spanish population today moves more to coastal areas. This is probably more linked to tourist demand for beaches, rather than advantages in trade.

Heterogeneous Population Density as the Outcome of Market Forces

The model of forest exploitation (subsection 2.4) shows endogenous decomposition of large forested areas into exploited and non-exploited areas, driven by market forces. In both cases this is typically an area of low population density. In the case of agriculture with decentralized land ownership (subsection 2.5) the average population density is taken as given. It is shown that some optimal (intermediate) population density is good for economic growth. But population growth in an external (demographic) force, and optimality changes over time. While rural Siberia and Canada are still under-populated, rural India is already overpopulated.

A country typically has areas with different natural zones, including forest and agricultural areas. Depending on intensity of natural exploitation, both areas can have different population density. Nowadays, cities also accumulate extra population which cannot live from harvesting.

Advantages and Disadvantages of Low Population Density

Low population density gives high per capita resource endowment. At the same time, low population density does not allow to self-finance dense infrastructure. We saw that profitability of a country with low population density that have chosen to harvest all resources can be negative because of inability to build dense infrastructure.

Canada, Siberia and Australia have low population density. They are unable to construct dense coverage of the countries by road network, and thus are unable to exploit their resources fully. In the 20th century Europe had a high density of infrastructure, but still relatively low population density (close to optimal), and this allowed it to become rich. Some regions in Europe still have too low or too high population density, and this does not allow for high growth.

The Case of Regulated Economy

It was shown that market forces lead to natural heterogeneity, including of population density, and it is driven by market forces. Sustainable development requires some regulation and creation of correct incentives. If there are global benefits from forest preservation, a country can theoretically receive some grants for that. Non-harvested areas can be turned into National parks. Their development can be also economically supported by natural tourism. However, this activity also required infrastructure, while low population density is a problem for that. For example, natural tourism in Alps is high, because of already existing network of roads and rather low distances inside Europe. At the same time, Siberia has many comparable tourist beauties (like Baikal Lake), but it lacks dense road infrastructure due to low population density.

Challenges from Climate Change

Global warming caused negative climate changes. In some areas of Europe (Mediterranean) they may cause growing water scarcity (see also Yegorov, 2021). In those conditions previously optimal population density might become no longer optimal, and this will create incentives for migration. Thus, it is important to consider future effects of climate change on sustainable settlement of population, which also depends on local water supply. This is an important special question that has already attracted a lot of studies and will not be developed here further.

CONCLUSIONS

Theoretical approach to the influence of population density on economics requires structural spatial approach. Any independent economy requires building infrastructure. There are several levels of economic activity, with harvesting natural resources at the lower level. The price of unit of weight of natural resources is typically low, and thus transport cost pays an important role in the final cost.

The forest exploitation model is solved in a dynamic set up with heterogeneous distance between forest in different locations and the market. It is necessary to invest in the infrastructure (network of roads) to expand production possibility frontier. Both investment costs and rising average transport cost contribute to an increase in the average cost. Hence, such a problem typically has a unique steady state. All forested area is divided into exploited part (closer to the market) and unexploited part.

The model of harvest-export economy considers a country with spatially distributed resources. In an autarky it can consume those resources locally, but will not have economic growth. In order to export resources, it is necessary to collect them. The model about transport-export company finds an optimal road network density to minimize the total transport cost. Agents in this model use their labour to produce primary output. Another part of income they get from the activity of export-transport company as its shareholders. It is shown that the profit of shareholder of export-transport firm is maximized for a certain population density. For very low densities profit is negative, while for high density it vanishes to zero.

Another model is about optimal rural population density. It parametrically depends on the world price indices for energy and food. The volatility of such indices destroys the optimality of spatial allocation of people in rural areas.

The outcome of market economy is heterogeneous population density. Its local optimality is subject to external pressures, in the form of global price volatility of food and energy and future challenges from climate change, which can result in growing water scarcity and further migration.

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