Letters in Spatial and Resource Sciences (2023) 16:16
https://doi.org/10.1007/s12076-023-00341-z

ORIGINAL PAPER

# The burden of big spaces: Russian regions and cities in the COVID-19 pandemic

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Received: 15 October 2022 / Accepted: 1 April 2023


## 1 Introduction

An analysis of the geography of the spread of the COVID-19 pandemic has already been the subject of numerous studies. Similar studies have already been conducted for many other countries (Akinwumiju et al. 2022; Alfaro at al. 2022; Bag et al. 2020; Boumahdi et al. 2021; Blangiardo et al. 2020; Ghosh and Cartone 2020; Kuebart and Stabler 2020; Martines et al. 2021). There are similar studies for entire macro-regions (Rodríguez-Pose and Burlina 2021) and, conversely, individual regions within countries (Gallo et al. 2021; Gibertini et al. 2021; Java and Former 2021). Most of these works are characterised by the use of methods of clustering municipalities by a basic indicator (hot-spot analysis, spatial autocorrelation tests) and spatial econometric models. This indicates a significant role of the spatial factor in the spread of coronavirus. Moreover, it works both ways: both the areas most affected by the pandemic and the least affected have a tendency to clusterisation. There is also no single dominant factor in the vast selection of models explaining the spread of COVID-19 at the municipal level in different countries. The increased vulnerability of territories near large agglomerations, with high mobility of the population, transport accessibility, high population crowding (for large cities) is often indicated. The well-being factor in countries with different levels of development may have the opposite effect on the

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potential demographic damage from a pandemic. The role of the institutional factor is also noted: in European countries, areas with a high degree of autonomy turned out to be more effective in countering the virus (Rodríguez-Pose and Burlina 2021).

However, the study of this process in the Russian spaces, based on the data of monthly excess mortality in the regions, complicates the picture even more.

Already in the first months of the pandemic, "strange" patterns were revealed, and in particular, on the one hand, the very rapid spread of the disease to very remote areas (for example, the Yamalo-Nenets autonomous region) and, on the other hand, a relatively weak and / or late manifestation of COVID-19 in some areas, which can be considered central — these are, for example, some large cities of Siberia or, on the contrary, some regions of Central Russia, seemingly not far from Moscow as the main (for Russia) focus of infection.

The coronavirus pandemic in the regions revealed numerous paradoxes: when in the case of an open system the polycentric structure of urban settlement exacerbated the demographic damage, and in the case of a closed system, on the contrary, it dampened it (here, many spaced infection centers of medium power were better than single strong one, because wave interference didn't happen between them). Population density and transport infrastructure, which were considered classic factors in the spread of a pandemic in space, catalysts for its spatial diffusion, on the contrary, were often not significant or even gave a negative correlation.

Similar values of indicators could hide different forms of space organization and, as a result, different course of the pandemic. For example, the general group for St. Petersburg and the Kaliningrad region, based on the excess mortality rate, actually hides completely different types of space and the mechanism of spatial diffusion of infection. For a deep understanding of the essence of the processes behind the differences in the spread of coronavirus, it is not enough to use only quantitative methods of analysis.

Currently single studies have been conducted considering the spatial diffusion of the COVID-19 pandemic in Russia (Zemtsov and Baburin 2020; Pilyasov et al. 2021; Kravchenko and Ivanova 2021; Kotov et al. 2022; Tarkhov 2022). The models of the spread of coronavirus across the regions of Russia in these works were based on the first wave, which occurred in April–August 2020, or for the whole of 2020, by the end of which the second wave reached its peak. Different methods of analysis, approaches to the selection of independent variables and a baseline indicator[1] of damage from the COVID-19 pandemic led to a different final set of factors explaining the spread of the coronavirus. Such factors include: airport passenger traffic (for international traffic), population density, proximity to the largest urban agglomerations, the intensity of interregional transport links, the proportion of people employed in certain sectors of the economy, the age structure of the population and even climatic conditions (humidity level). One of the main conclusions of the aforementioned models is the multifactorial nature of the coronavirus spread process. It is impossible to

[1] The indicators of the number of detected cases of the disease, the number of deaths from coronavirus and excess mortality relative to 5-year average prepandemic mortality in 2015–2019 were used. The last indicator becomes available with a slight delay, but it is the most accurate, because it doesn't depend on the quality of morbidity detection and the method of registering mortality from coronavirus at the regional level.

identify one dominant factor influencing the course of the pandemic. Moreover, the set of factors can change dramatically at its different stages (Zemtsov and Baburin 2020). The most vulnerable territories during the first wave are large centers that are most intensively connected with other regions. Whereas at later stages, internal factors of socio-economic development or the effectiveness of restrictive measures may become more significant.

Our hypothesis, taken as a first approximation, is that different parts of the vast expanses of Russia have different dominant mechanisms for the spread of infection. Roughly speaking, for the most densely populated areas, the spread of coronavirus infection can be investigated along the same lines as the spread of innovations according to T. Hagerstrand's concept of the hierarchical transfer of innovation from center to center, which was the key for the second half of the 20th century. In some cases, even the concept of "knowledge spillovers" can be considered as a kind of prototype of "virus spillovers" around the main foci of infection. However, for sparsely populated areas, it may be more appropriate to use more "ancient" concepts, including numerous features and patterns studied by the classics of Soviet epidemiological geography (Shoshin 1962; Chaklin 1977; Keller et al. 1984). They dealt mainly with sparsely populated territories, poorly affected by urbanization and industrialization, where the limited number of transport routes allowed the infection to spread from the foci-nosoareals along the linear transport channels (road or railroad, river routes), forming an easily diagnosed and mapped chain of infection. Moreover, apparently, a fundamentally new model of the predominant spread of the virus through the air route network is needed (as is typical for remote, completely roadless regions of Russia, such as the Yamalo-Nenets Autonomous Okrug mentioned above). Of course, similar processes of territorial differentiation of the spread of the virus are not unique to Russia. On the territory of internally extremely heterogeneous countries (which include, of course, not only Russia, but also, for example, India, Brazil, China, etc.) these processes manifest themselves extremely clearly, and in this regard the space of Russia serves as a good testing ground for research.

However, the task of testing different methods of modeling the spread of infection for different types of spaces is obviously unaffordable for one article. Therefore, let's narrow our view on the research gap. Based on the fundamental formulation of the problem as "different spaces – different models of the spread of the virus", let us turn to a more specific research gap, which arises already when trying to separate the factors of the actual spread of the virus from place to place and the strength of the demographic manifestation of the epidemic in a particular place.

As far as we know, there are practically no works that would separate the factors contributing to the transfer of the virus from place to place and the factors of the "depth of damage" by the pandemic of a particular place. However, it is easy to assume that factors of the first type, apparently, are, for example, the parameters of transport communication, factors of the second type, for example, the general level of immunity of residents of a particular place and the quality of available medical care, the nature of daily contacts of people inside the settlement, etc. However, as for the factors of the first type, we can rely on a group of works by researchers of COVID-19, revealing the special role of the first wave. However, the results vary: (Linka et al., 2021) showed a significant difference between waves, on the contrary, (Pandey et al., 2022) showed unexpectedly weak differences between waves for the case of India. A noteworthy paper (Eggo, Dawa, Kucharski et al., 2021) shows that it is better to use different models for different stages of a pandemic: «It is unrealistic to expect that models will be able to include a range of setting-specific intricacies and complexities at the start of a pandemic of a newly emerged virus. What models are most useful for and what insights they can provide changes as an epidemic proceeds: early projections may need to be a ‘reasonable worst case scenario’, for which broad conclusions are most important, and later, as policy questions or needs become more specific, precise mechanisms can be added when there are data to support it».

Based on this thesis, we are talking not only about the difference in patterns at different phases of the pandemic, but also about the fact that at different phases different types of regions are more susceptible.

We accept the hypothesis that the first wave of the COVID-19 wave covers «more open» territories (communities), which were especially affected as a result of quick spread of the disease from one place to another. The second and subsequent waves seemed to be more powerful from the point of view of internal spread of the pandemic. We will (very conditionally) call such territories affected mostly by the second and third waves of the coronavirus as relatively «closed».

Thus, our research question narrows down to diagnosing «open» and «closed» territories, which were, respectively, more severely affected by the rapid introduction of the virus from the outside (usually during the first wave) or the widespread distribution of the virus within the territory (mainly in the second and third waves).

The task is solved in this article in three stages. At the first stage, the general spatial picture of the Russian territories damaged by the COVID-19 pandemic is considered. At the second stage, different types of Russian territories by permeability of space (openness / closeness to external relations, features of settlement systems) are compared with the peculiarities of the course of different waves of coronavirus infection. This is the key part of the article. The third, additional stage, is an attempt to capture at a qualitative level the influence of the type of coronavirus spread in different spaces on the differentiation of local authorities’ measures to counteract the pandemic.

## 2 Data and methods

### 2.1 Selecting baseline mortality indicator

The ratio of monthly mortality for the period from April 2020 to December 2021 and the average monthly mortality in the five years before the pandemic (in 2015–2019) for the regions and municipalities of Russia was used as a baseline indicator to measure the consequences of the pandemic. The calculation was made according to the formula:

$$EM_x = \frac{M_{2020;2021x}}{0{,}2 \times \sum_{2015?2019} M_x},$$

where *EM* is a ratio indicating excess mortality in the region in one of the months from April 2020 to December 2021; *M* is the number of deaths in this month; *x* is the month. Accordingly, all values above 1 indicate an excess of mortality (excess mortality) relative to the average for the previous five years. Mortality trend adjustment, which is sometimes included in country-level pandemic analyzes (Wang et al. 2022), has not been applied, despite mortality in Russia decreased by 1.5%. from 2015 to 2019.

Other indicators that were used in our analysis were taken from the Russian Statistic Agency database, like collections "Regions of Russia. Socio-economic indicators".

## 2.2 Clustering the russian space in the pandemic

Figure 1 demonstrates distribution of 2257 municipalities by excess mortality in 2020. The shape of the graph is close to Gaussian distribution. Median and mean values are almost identical, both around 10%. Paradoxically, 378 municipalities (16,7%) were demographically unaffected during the COVID-19 outbreak in 2020. Indeed, during the first wave, about half of the regions avoided a surge of disease. The second wave completely covered the country's territory, but it dragged on until March 2021.

On the next stage we calculate global Moran's index for the baseline indicator to identify if the coronavirus spread is subject to spatial clusterisation:

$$I = \frac{\sum_i \sum_j z_i W_{ij} z_j}{\sum_i z_i^2},$$

where *i, j* – municipalities, *z* – excess mortality indicator, adjusted (z-score), $W_{ij}$ – spatial weight between *i* and *j* (row-standardised) (Anselin et al. 2010). The whole set of values $W_{ij}$ forms spatial weights matrix *W* indicating proximity between municipalities. It can be measured in different ways based on contiguity (sharing common border) or distance between features (Ghosh and Cartone 2020). The latter method is more common since it is associated more directly with notions of spatial interactions, gravity and hierarchical models (Getis 2009). So, using distance as a basis for calculating spatial weights we manage to detect broader range of spatial interconnec-

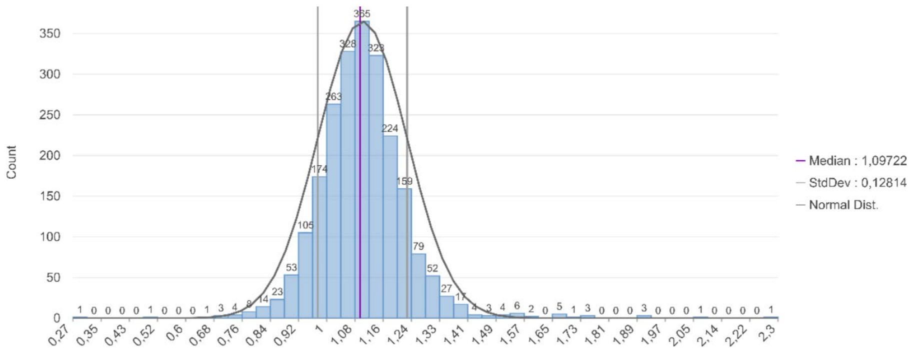


**Fig. 1** Histogram showing distribution of municipalities by excess mortality in 2020 relative to 2015–2019 average

tions not restricted to the nearest neighbours which is substantial for analysing vast heterogenous and highly hierarchical spaces like Russia. For this study, considering the regular configuration of the Russian territory, inverse distance function is chosen in order to consider distance decay effect:

$$W_{ij} = 1/d_{ij}^{\alpha},$$

where $d_{ij}$ – distance between municipalities $i$ and $j$, $\alpha$ – parameter set to a fixed value $\alpha=1$ (simple inverse distance) (Anselin 1988).

Global Moran's index equals 0.137, given the z-score of 41.6 (p-value<0.0001), there is a less than 0.1% likelihood that clustered pattern obtained could be the result of random chance. These calculations clearly indicate the presence of spatial dependence in terms of distribution of excess mortality across Russian municipalities. Moran scatterplot provides the classification of municipalities (Fig. 2). Each quadrant of the scatterplot corresponds to a different type of spatial correlation. Most municipalities concentrate in lower-left and upper-right quadrant that form low-low and high-high clusters correspondingly. Municipalities in other two quadrants represent spatial outliers with high mortality within low-low cluster (lower-right) and low mortality within high-high cluster (upper-left).

Further we apply local Moran (LISA) test to explore the extent of spatial heterogeneity. We calculate local Moran's for each administrative unit to detect statistically significant clusters and outliers and map them (Fig. 3). Local Moran's $I_i$ is defined as

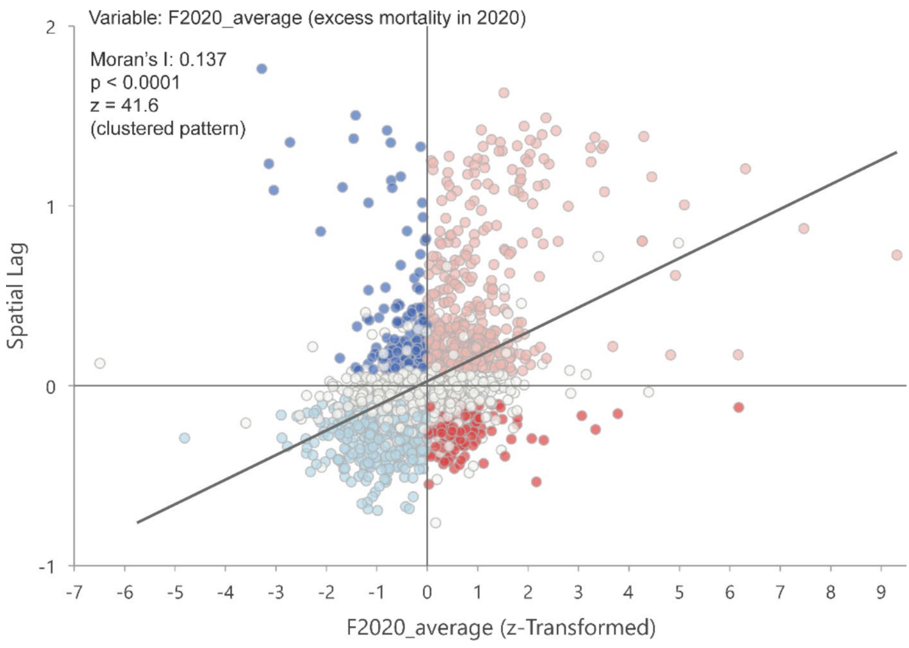


**Fig. 2** Moran's I scatterplot

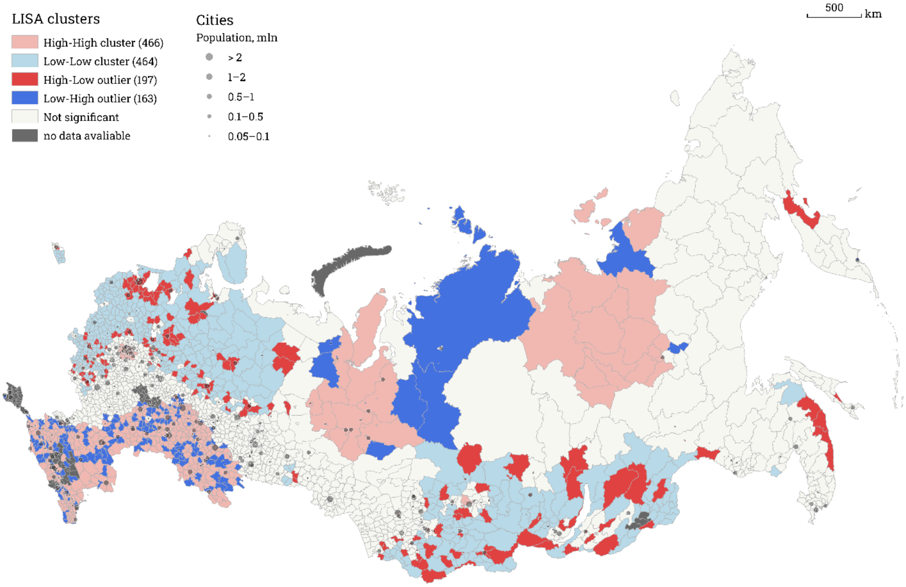


**Fig. 3** Spatial clustering (Local Moran's I) of excess mortality in 2020

$$I_i = \frac{z_i \sum_j W_{ij} z_j}{\sum_i z_i^2}, j \neq i.$$

Features with positive $I_i$ potentially form clustering pattern with high or low values of selected indicator. Features with negative $I_i$ tend to be defined as spatial outliers.

Other common metrics of spatial dependence and heterogeneity such as the general $G$ and local $G_i$ were also tested (Getis and Ord 1992):

$$G = \frac{\sum_{i=1} \sum_{j=1} W_{ij} x_i x_j}{\sum_{i=1} \sum_{j=1} x_i x_j},$$

$$G_i = \frac{\sum_j W_{ij} x_j}{\sum_j x_j}, j \neq i,$$

where $x_i$, $x_j$ – excess mortality in municipality $i$ and $j$. General $G$ statistics value is close to the expected value, which implies that number of clusters with high and low values of excess mortality is nearly equal. Local $G_i$ statistics demonstrate low sensitivity in determining hot and cold spots within large clusters of high and low values and provide similar spatial pattern to local Moran's. So, we opt to concentrate on local Moran's clusters in our typology of spaces experiencing different impact from the pandemic.

### 2.3 Uneven waves of COVID-19: spatial patterns

For the initial clarification of the picture, specialized studies were carried out, reflecting the spatial and temporal nature of the formation of excess mortality in the regions of Russia. First of all, the month of exceeding the mortality threshold in each region was identified; the median of the monthly difference in the mortality rate for the previous five "non-COVID" years (2015–2019) was chosen as the threshold for mortality – such a relatively complex indicator was chosen to exclude the influence of random indicators and determine the beginning of a truly significant increase in the mortality rate in 2020.

Based on the results of calculating the excess mortality for 21 months of the pandemic from April 2020 to December 2021 in relation to the average for the previous five years, the question arose of the method for identifying waves of the spread of coronavirus infection. To do this, it was decided to analyze the monthly fluctuations in mortality in the regions (year-on-year) in 2015–2019. As a result, a sample was compiled from the maximum values of excess monthly mortality in each of the regions, and the median value was calculated from it – 1.14, i.e. on a long time series in the pre-pandemic period in the central Russian region, the number of deaths per month relative to the number of deaths in the corresponding month of the previous year did not increase by more than 14%. We assume that all values above this threshold, especially those observed for two or more months in a row, with a high degree of probability can serve as an indicator of the acute phase of the spread of COVID-19 in the region. At the next stage, the excess mortality trend was divided into three periods corresponding to three pandemic waves (Fig. 4). However, in 29 regions, the first wave of the pandemic was not observed (in none of the months from April to August 2020, the mortality rate exceeded the threshold value of 1.14). The second and third waves of the pandemic were noted in all regions without exception.

Four parameters were calculated for each wave by regions: basic – average monthly excess mortality (according to the unified periodization of waves at the national level); peak excess mortality (maximum monthly mortality during the wave, but not less than the threshold value of 1.14); wave start month (month in which mortality first exceeded the threshold of 1.14); wave length (number of consecutive months when mortality exceeded the threshold value of 1.14).

To get inside the black box of the regional space in the COVID-19 pandemic, we decided to recall the basic postulates of the system approach. It is known that systems differ in the properties of open-closedness and integral-dispersed (polycentric) (Bogdanov 1989). So, we have four types of regional spatial systems: open fused (centralized), open decentralized, closed fused (centralized), closed corpuscular (dispersed).

The degree of openness-closedness well conveys the share of intra-regional migrants for entry and exit in their total flow (counting also Russian migration from other regions and international migration from other countries). It is conditionally possible to consider an open region in which the arithmetic average of the share of arrivals and departures within the region is less than half, closed — where more than 50% of all arrivals and departures to the region per year (or as an average over several years).

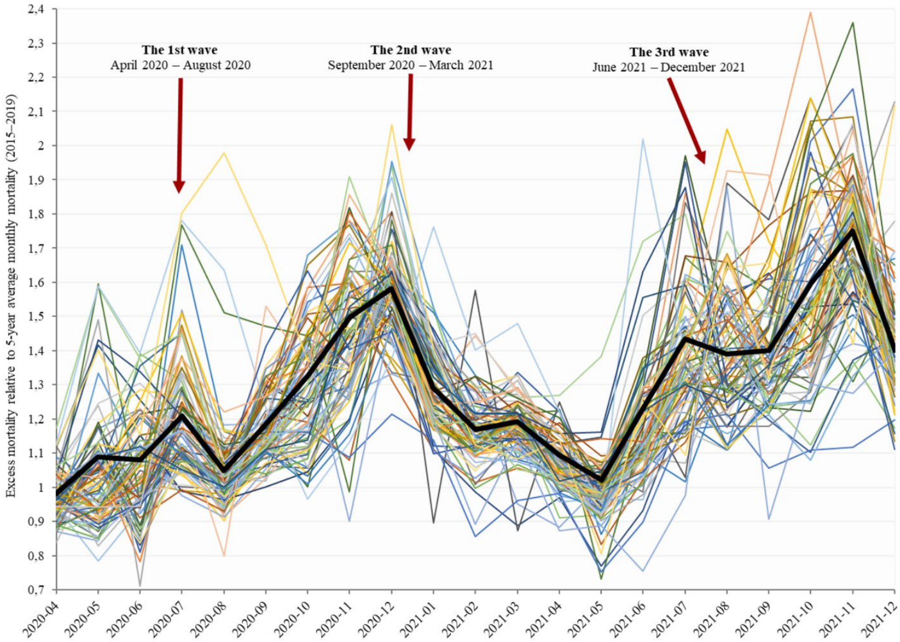


**Fig. 4** Monthly dynamics of excess mortality in Russian regions from April 2020 to December 2021: first wave – April-August 2020; second wave – September 2020-March 2021; third wave – June 2021-December 2021

The degree of fusion of the regional space can be evidenced by the share of the capital in the population of the region: after all, we are interested not in the physical, but in the "social" area of the region, that is, in that part of it is interconnected by communities of people. According to their behavior, it is necessary to measure the degree of fusion, openness of regional spatial (in fact, socio-spatial) systems and not abstractly physically. We will consider 50% as a conditional boundary between centralized (central-peripheral) and decentralized (polycentric) systems: the capital city, which concentrates more than 50% of the population of the region, forms a centralized system of regional space, and if less, then decentralized (polycentric, when the capital is explicitly does not dominate, but is one of the leading cities, along with others).

## 2.4 Regulatory responses to the COVID-19 pandemic: evidence from russian regions

To analyze the measures taken in the regions of Russia in response to the diffusion of the virus in Russian spaces, legal documents of the regions and municipalities of the Consultant+database have been used. In total, ten thousand documents were reviewed, including about a thousand in detail.

During the COVID-19 pandemic, there were all-Russian, set at the federal level, restrictions on spatial mobility, and regional ones. We were interested in additional measures taken by the regional authorities, based on the specifics of the course of the pandemic in their “spaces”.

A generalization of the “COVID-19” regulatory legal framework in all Russian regions for 2020 of the first wave of the pandemic revealed five areas of additional restrictions on the spatial movement of people: (1) restrictions on intra-regional transportation/flights of passengers and baggage at airports and/or checkpoints (yes/no); (2) “extended” (i.e., more strict) self-isolation of visitors against all-Russian norms (yes/no); (3) transfer to a remote (distant) work format (yes / no) and in what specific version from the point of view of mass character (percentage, category of workers, etc.); (4) introduction of quarantine at the regional level (and not just by mayors of cities and heads of municipal districts) for individual municipalities/territories (yes/no); (5) whether a fine is provided for violating the spatial movement regime (yes/no).

## 3 Results

### 3.1 Clustering the Russian space in the pandemic

Conducted clustering clearly demonstrates the complexity and high spatial heterogeneity of the big Russian spaces affected by the COVID-19 pandemic. Six major clusters can be identified (Fig. 3). Four of them are clusters with high excess mortality:

1. Moscow agglomeration – the smallest by area, almost indistinguishable on the map, but accounts for around 15% of the state population.
2. The South, The Volga Region and South Urals – an extended continuous cluster in the South of European Russia.
3. The North of West Siberia – the main region of oil and natural gas extraction and high level of fly-in-fly-out migrations.
4. The Northwest of the Republic of Sakha (Yakutia) – one of the most inaccessible territories of Russia with some sparsely located diamond fields (fly-in-fly-out workforce).

There are two large clusters with low excess mortality.

1. European North and the West of Central Russia – mostly economically stagnant territory (excluding large regional centres and areas rich in mineral resources) with vast outback (‘glubinka’).
2. The South of East Siberia – the territory remote from more developed European Russia with large presence of autochthonous national republics, the agglomeration of the largest city of Krasnoyarsk is distinguished as separate cluster with high excess mortality.

The distribution of spatial outliers is also worth considering. Municipalities with high excess mortality within European North and the West of Central Russia follow predominantly centre-periphery model: they are adjacent to regional centres and other major cities. St. Petersburg, expectedly, has the largest zone of influence. It is not identified as high-high cluster only due to model parameters[2]. Outliers with low excess mortality within the South of European Russia, in general, follow the same pattern, they coincide inversely with more peripheral areas such as regional boundaries. Outliers of both types in Siberian clusters are arranged differently, in general, they are located far from major regional centres. Nevertheless, their spatial distribution is complicated to analyse due to potential high year-over-year fluctuations in mortality in districts with low population.

We assume that Russian space, which is extremely unevenly developed, at the same time produces different patterns of the COVID-19 diffusion. The case of remote sparsely populated spaces looks very interesting, which clearly demonstrate the property of "openness", which is usually not characteristic of the centres, but not for the periphery, we have mentioned this paradox earlier (Zamyatina et al. 2020). Now we witness this phenomenon in the case of Yamal-Nenets and Khanty-Mansi autonomous regions, which turned out to be among the most vulnerable to the pandemic in the country.

For another illustration of uneven COVID-19 spread across the vast spaces of Russian territory we go up to the regional level of analysis and classify regions on the basis of excess mortality in 2020 and variation in excess mortality by municipalities (Fig. 5). Regions are divided into two equal parts by the median values of both indicators and then allocated into four types.

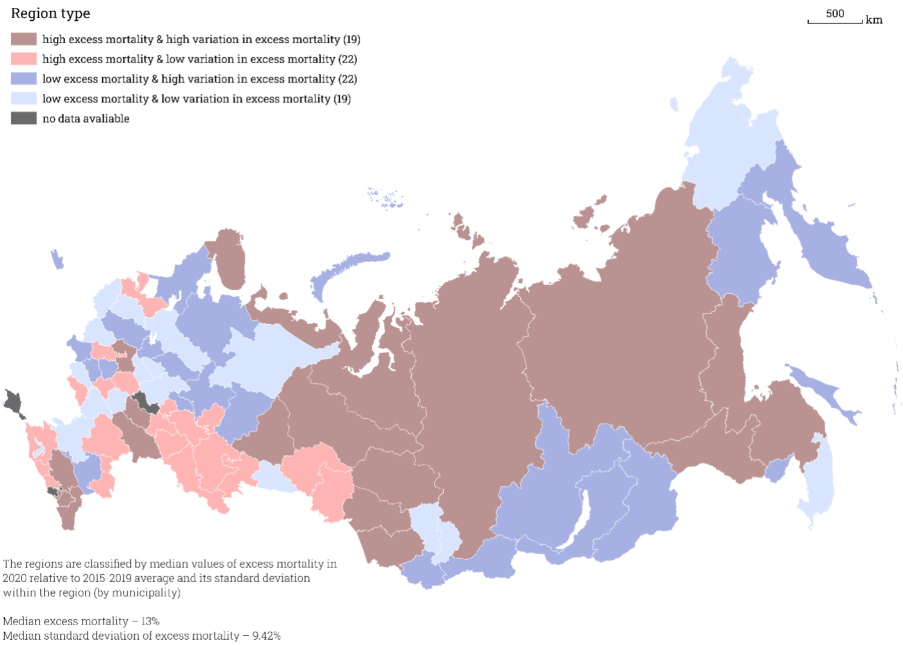


**Fig. 5** Typology of Russian regions based on excess mortality rate and standard deviation of excess mortality by municipality

[2] All municipalities within 800 km radius are taken into account for computing Local Moran's index.

It is noteworthy that regions of Siberia and the Far East with a larger area (although often with a small population) are characterised by a large variation in excess mortality. In this regard, we guess that these regions require the most detailed development of geographically differentiated restrictive measures to tackle the infection spread. Low variation in excess mortality can be found predominantly in densely populated regions (the South of European Russia). The presence of large agglomerations tends to result in high average excess mortality in the region, but not necessarily in high variation in excess mortality (i.e. Krasnodar Krai, Rostov Oblast, Samara Oblast, Leningrad oblast with million-plus centres were relatively evenly affected by the pandemic).

### 3.2 Uneven waves of COVID-19: spatial patterns

The features of the spatial distribution of the first wave of the COVID-19 pandemic, to a greater extent than subsequent waves, reflect the fundamental properties of the structure of space (and in particular, the center-periphery connections, expressed in the intensity of human interactions of all types collectively). The definition of local features of the spread of the pandemic in the Russian regions was carried out in comparison with other regions, at the level of the Russian Federation, from the level of macroregions (geographically contiguous blocks of regions) and individual key regions, in which expert surveys were conducted.

The first wave of the COVID-19 pandemic (April–August 2020) is the shortest and lowest: the regions are distributed extremely heterogeneously (Fig. 6). Some central regions, especially those with million-plus cities, despite tough restrictive measures, suffered the most in the first months, while in many peripheral regions, the coronavirus infection did not spread as quickly or arrived with a great delay.

The most obvious differences are in the time of the beginning and duration of the first wave, among the most affected by the first wave were the regions of Central Russia, St. Petersburg and Leningrad region, the republics of the Northern Caucasus and the oil and gas producing Yamalo-Nenets and Khanty-Mansi autonomous regions.

The polarization is also high in terms of mortality values. Thus, in the Chechen Republic, the excess of mortality on average in the first wave is 44%, while in the Republic of Tyva it is only 6%.

The second wave (September 2020—March 2021), on the contrary, is the most uniform and homogeneous with a pronounced peak in December (Fig. 7). The regions show almost synchronous dynamics of excess mortality, and its dispersion is decreasing (the standard deviation of the average excess mortality is 6.1% against 11.8% in the first wave). On average, the second wave is 40% higher than the first. The pandemic is spreading across all regions, new outbreaks are emerging in the Far East, the severity of lockdowns is softened, mainly for economic reasons, as a result of which the effects of barriers and inertia in the center-periphery space of Russia are gradually leveled.

The third wave (June—December 2021) in spatial projection is very similar to the second wave (Fig. 8). Although the dynamics of excess mortality is different: there are two peaks in mortality. The first occurred in July 2021. After a slight decline and stabilization, mortality soared to record levels (1.75 national average) in Novem-

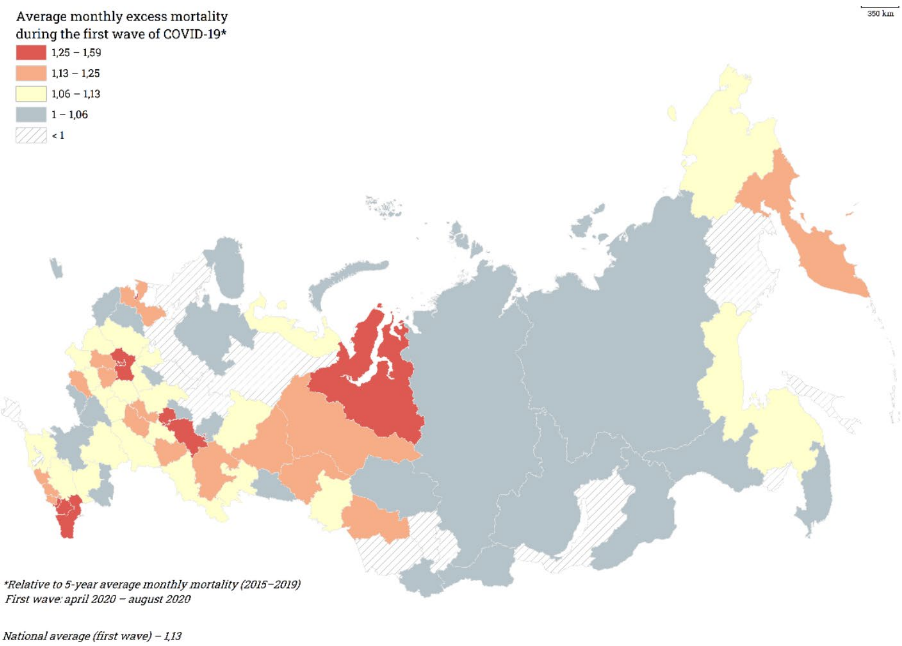


**Fig. 6** Average monthly excess mortality during the first wave of COVID-19[4]

[4] Complete dataset and visualisations (Figs. 6, 7 and 8) in: (Nikitin and Zamyatina 2023)

ber due to the spread of a new delta variant of the SARS-CoV-2 virus. The adult vaccination rate in November 2021 was still around 40%, which did not effectively reduce COVID-19 deaths. Despite the fact that, according to the weighted average parameters, the regions passed the third wave relatively homogeneously (the standard deviation of the average excess mortality was 8.5%), the dynamics of mortality was contradictory.

Most followed the standard pattern, repeating the general trend with two peaks in mortality and record values in November-December (up to 2.4). However, in some regions there was only one pronounced peak in late autumn, and in some regions (mainly Siberian and Far Eastern regions) the summer peak was higher than the autumn one. Such discrepancies in the third wave are most likely associated with the interference of pandemic waves: at the time the delta strain began to spread in the country (June 2021), the regions of the European part of Russia and individual open regions of Siberia, which had passed through two full-fledged waves, were in antiphase in terms of in relation to the peripheral regions of Siberia and the Far East, where the virus reached late.

Linking the four above-mentioned types of regional spatial systems (open centralized, open decentralized, closed centralized, closed dispersed) and the rating of the region in terms of excess mortality for 2020–2021 using the example of Siberian regions made it possible to identify four types of spatial systems—from the most to the least vulnerable to COVID-19:

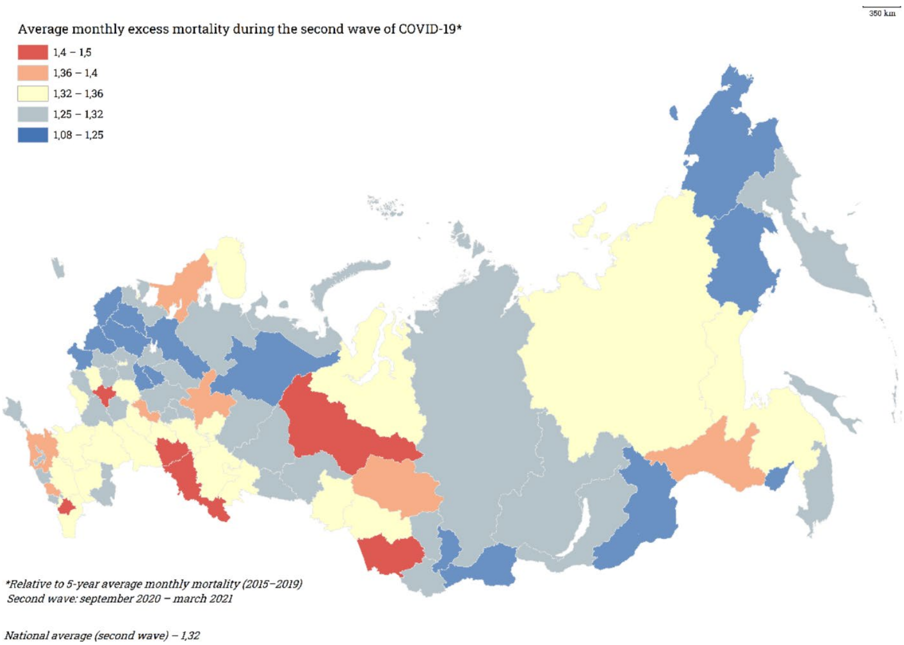


**Fig. 7** Average monthly excess mortality during the second wave of COVID-19

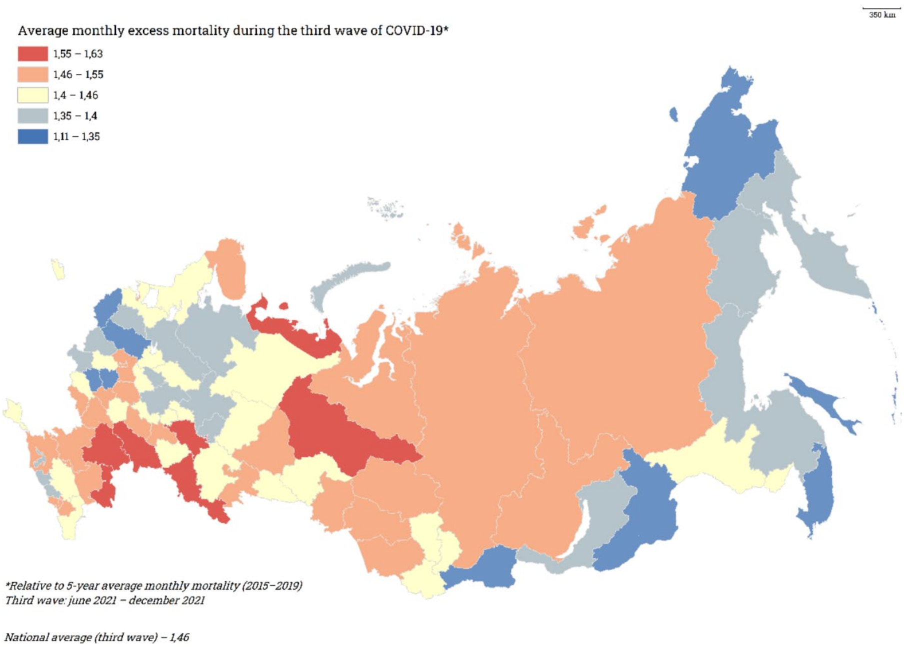


**Fig. 8** Average monthly excess mortality during the third wave of COVID-19

1. *The most vulnerable open corpuscular (dispersed) regional spatial system*: Yamalo-Nenets autonomous region, Khanty-Mansi autonomous region-Yugra. This type of regional space (regions of the extractive industry) is characterized by a polycentric mechanism of infection, with a large number of isolated foci of disease, usually as a result of redeployment (airborne) spatial diffusion of the virus from outside the region to shift camps, mono-industrial cities, new construction sites, etc. It is not surprising that the early first peak in the incidence of coronavirus infection was observed here and the highest relative rates of excess mortality among the Siberian regions are typical. For the "purity" of the definition of this type, an additional sign of a vast area is extremely important, which makes polycentricity (decentralization, corpuscular) genuine.
2. *Highly vulnerable open centralized regional spatial system*: Novosibirsk, Omsk, Tomsk regions. This type of regions with a developed manufacturing industry is characterized by a center-peripheral mechanism of infection from a large metropolitan city, which, due to its status as a transport hub of interregional significance, itself received the induction of the virus through external redeployment (air) or horizontal (railway and road) networks, to the periphery, or by hierarchical spatial diffusion to centers of lower order[3]. All these regions are characterized by a high level of excess mortality: industrial enterprises of a continuous cycle (for example, oil refining or mining), which are the basis for the local economy, did not allow the introduction of strict restrictions (hard lockdown) — constant personal contact between workers of large production teams remained here throughout the entire during the pandemic, an increased mortality rate was noted during its peak periods.
3. *Medium vulnerable closed centralized regional spatial system*: Tyumen region and the Republic of Khakassia. This type of industrial-agrarian regions is characterized by a central-peripheral road infection mechanism within the region (from the capital city to the countryside) and "horizontal" spatial diffusion along the contour of the labor market of the capital city and its suburbs (through public transport, roads and railways). The role of external airborne relocation diffusion of the virus is reduced compared to the first and second types. Strict additional restrictions by regional authorities were introduced in this group of regions precisely because here, due to the relative compactness of these regions and their initial greater closeness from the outside world, they were easier to implement and control. The Republic of Khakassia in October 2021 introduced the most severe lockdown in Russia, including a curfew from 10 p.m. to 6 a.m. and stopping public transport. The Tyumen region was characterized by periodic, by outbreaks, the formation of foci of coronavirus infection in the Ioanno-Vvedensky Convent, the Vinzilinsky Psychoneurological Boarding School, the Medical City Cancer Center, the Tyumensky Rehabilitation Center for Drug Addicts, the Snezhinka Rehabilitation Medicine Center, etc. In its nature (dozens of "compulsorily"

[3] In order to determine what type of internal spatial diffusion dominated further, already within the region, studies of the course of the pandemic within the municipalities of these regions are needed: the center-peripheral, from the capital city to its peripheral rural suburbs, or the classical hierarchical spatial diffusion, from the capital city to lower-order city centers.

compactly ill people) was similar to local outbreaks of COVID in the Novgorod region (only here it happened later), and on a European scale, to mass cases of COVID in Swedish nursing homes in 2020.

4. *The least vulnerable closed corpuscular regional spatial system*: Republic of Altai, Zabaykalsky Krai, Krasnoyarsk Krai, Republic of Buryatia, Altai Krai, Irkutsk Region, Kemerovo Region, Tyva Republic (multifocal type of internal spatial diffusion). This type of agrarian and industrial regions is characterized by a mechanism of internal infection from many centers. With the exception of the Altai and Krasnoyarsk Territories, all regions of this group had minimal levels of excess mortality. A single sharp surge in excess mortality in the summer of 2021 in some regions was apparently associated with a significant recreational influx of Russians from other regions of the country to Lake Baikal and Altai.

From the point of view of the demographic damage from the pandemic, this type was the most favorable in terms of the structure of the regional space: insufficiently powerful regional sub-centers were not able to drive the pandemic wave further into space, and it seemed to die out in the process of its movement. The degree of corpuscularity, that is, the average distance between the largest cities, is of great importance for the spread of the virus: other things being equal, the larger it is, the weaker the spatial diffusion was, because there was no interference of the opposite waves of two neighboring cities. The authorities here often introduced a complete temporary quarantine in separate areas-foci, which broke communication social networks.

### 3.3 Regulatory responses to the COVID-19 pandemic: evidence from Russian regions

All regions of the Russian Federation were evaluated in binary logic (yes-no) by the presence of five types of regional or local restrictions. None of the regions received the maximum five points.

In the context of this paper, a special role is played by the ratio of measures related to the regulation of movements across the borders of the region (city) and measures related to the regulation of behavior within the region or city (for example, transfer to remote work). Let us consider specific measures of regional authorities to counteract spatial diffusion using the Baltic macroregion as an example (Table 1).

Already using the example of this macro–region, it can be seen that, paradoxically, measures to restrict movement were taken not in those regions where, it would seem, the maximum volume of connections with the outside world (large cities as St. Petersburg), but in more remote regions (in this example, the Murmansk Region, the Republic of Karelia).

And vice versa the severity of the norms for transferring workers to a remote work format differed significantly: from the maximum in the industrial Udmurt Republic, Bryansk and Yaroslavl regions, in the Trans-Baikal Territory (at least 70% of all employees) to only those who are over 65 years old (Stavropol Territory, Ivanovo, Magadan, Samara, Smolensk regions and Sevastopol) and at least 30% of those over 65 years old (Republic of Khakassia, Kemerovo, Rostov regions, etc.).

**Table 1** Measures taken by the authorities of the Baltic macroregion to counteract the spatial diffusion of coronavirus as of the end of December 2020 Compiled according to the legal information system Consultant+ "Coronavirus (COVID-19). Restrictions on movement and access control in the constituent entities of the Russian Federation"

| Region | Measures to regulate behavior within the territory | Measures to regulate movements across the border of the territory | Comment |
|---|---|---|---|
| St. Petersburg | Transfer to a remote mode of operation of at least 30% of the city authorities, employees of executive bodies over 65 years of age and those with chronic diseases in organizations and individual entrepreneurs | No | An administrative fine of 4000 rubles, for committing an offense repeatedly or using a vehicle—a fine of 5000 rubles. |
| Leningrad Oblast | Transfer of employees aged 65 years and older to remote work | Citizens moving through the territory of the Leningrad Region by road must follow without stopping to the final destination | — |
| Kaliningrad Oblast | Transfer to a remote mode of work of at least 50% of office workers, incl. pregnant women, persons with certain diseases | No | — |
| Republic of Karelia | The use of a remote work format, primarily for people over 60 years of age and with certain diseases (if possible, in the case when it is impossible to ensure the isolation of the workplace). Priority remote work and self-isolation for people over 65 in the largest settlements | Persons arriving on a business trip to the territory of the Republic from other subjects of the Russian Federation must have negative COVID-19 test results received no more than two days before arrival | The following major cities and urban-type settlements are listed as priority for transferring to remote mode: Petrozavodsk, Belomorsk, Kem, Kondopoga, Lakhdenpokhya, Medvezhyegorsk, Olonets, Pitkyaranta, Pudozh, Segezha, Sortavala, Kostomuksha, Suoyarvi, urban-type settlements Kalevala, Loukhi, Muezersky, Pryazha |
| Novgorod Region | Transfer to a remote mode of work of at least 5% of employees; workers with certain diseases, pregnant women | No | — |
| Pskov Region | Transfer to a remote mode of work of at least 30% of employees | No | Mask mode not by points of concentration of people in space (markets, fairs, shopping centers), but by the type of activity (in places where goods are purchased, services are provided, at work) |

**Table 1** (continued)

| Region | Measures to regulate behavior within the territory | Measures to regulate movements across the border of the territory | Comment |
|---|---|---|---|
| Murmansk Region | Transfer to remote mode of employees aged 65 years and older; belonging to the category of administrative and managerial personnel (at least 50% of the headcount); employees of regional executive power and local self-government bodies (at least 50% of the staff) | Restrictions on entry by road for citizens who do not have registration at the place of residence within the boundaries of the urban district of the city of Kirovsk and the city of Apatity. Entry of citizens and passage of vehicles through the checkpoint if there is an agreement on entry into the territory with a special regime | The concept of a territory with a special regime was introduced, where stronger quarantine measures were introduced |

The regional authorities of regions with poor infrastructure for land transport in the north and south of Russia introduced various anti-COVID restrictions. In the north, in open spatial systems, the fight against the diffusion of coronavirus passed through the regulation of the rotational method of organizing work. On the other hand, in the south, in closed spatial systems, this struggle was carried out mainly due to the large-scale application of quarantine measures in certain municipal districts.

## 4 Discussion

The different susceptibility of regions to the COVID-19 pandemic, linked to the degree of openness and the configuration of the settlement network, indirectly indicates a difference in the models of pandemic damage to the territory. More open regions suffer more from the first wave of the pandemic, a new infection comes to them quickly. In contrast to the classical Hegerstrand model, in which innovation spreads either to a close distance or along the hierarchy of centers, some remote regions are affected in the first wave, especially with a high intensity of shift migrations. Here, openness seems to be more important than the traditional hierarchy. We can also offer a different interpretation, changing the hierarchical system itself: very small settlements are being promoted to the role of centers in remote regions. Hierarchies peculiar to densely populated spaces, and with which both classical models from Christaller to Hegerstrand and modern models of the geography of innovation are associated, are not quite suitable for such sparsely populated spaces. But not all remote spaces fit this model. In fact, we need to talk about different types of peripheries – open (such as frontier) and closed. The closed periphery is traditional, the open one is a new, specific field of research. Of course, remote open areas could be considered an exception. However, in Russia they occupy a significant part of the territory, and deserve a special approach. It can be assumed that a similar situation occurs in the interior of other large countries – in Brazil, India, China, as well as in Canada, Australia, etc.

Of course, this article demonstrates rather the possibility of the existence of different models of diffusion of innovation in different types of spaces than fully proves it. Further research may be devoted to more detailed econometric modeling, including on the coronavirus material. For example, one model can be developed for open spaces, another for closed ones, and based on a comparison of the quality of each of the models, it would be possible to identify the optimal application area for each of them. While we cannot confidently assert the success of such an approach, however, many years of experience with the analysis of spatial patterns of Russia's development suggests that this path is justified for large and heterogeneous countries.

With the further development of the research of "different spaces", it is interesting to combine Castells' concept of the difference between the "space of places" and the "space of flows" (Castells 1996) and the concept of diffusion of innovations. In most modern works, as a rule, larger centers are considered more "innovative". And only in some approaches (for example, in Copus 2001), the center and the periphery differ not so much in the size of settlements as in connections. The proposed approach opens the way to combining these concepts. Apparently, there are territories where the flow space dominates the configuration of socio-economic processes. At the same time, there are more "calm" territories with a low level of connections between individual settlements, that is, the "space of places". Our study, in fact, showed that excess mortality was caused by different causes in the Castels "flow space" (the introduction of the virus from the outside) and in the "place space" (internal infection processes).

The development of the proposed approach may have a number of practical consequences.

Firstly, let's pay attention to the fact that in remote regions there was also a maximum variation in excess mortality. According to our hypothesis, individual outbreaks of morbidity here were associated with an unexpectedly rapid introduction of infection. This conclusion is confirmed by a qualitative analysis of the mass media about outbreaks of the disease in certain isolated communities, in particular, in shift camps, etc. Thus, measures for emergency "closure" of such territories, apparently, could effectively mitigate the damage from COVID-19 in the early phases, when measures to combat the virus (especially vaccination) haven't been worked out enough yet. Interestingly, spontaneous measures to counteract infection, as a rule, were common in such territories.

Secondly, important conceptual conclusions can be drawn regarding the traditional centers of the center-peripheral model, large cities. An unexpected result of modeling the COVID-19 pandemic in Russian regions was the significant role of the share of employed in the trade sector (positive correlation) and the number of retail facilities per 1000 population (negative correlation with excess mortality) (Kotov et al. 2022). Employment in the trade sector implies an increased intensity of interactions, which ultimately leads to an increase in the rate of infection. A high level of employment in the trade sector is typical for large agglomerations, where, in general, the level of random interactions in urban space is the highest (as follows from modern concepts of urbanism). In fact, all the latest concepts of urban development pointed out the strengthening of interaction in the urban space as a factor of innovative development and in the context of a pandemic, this factor, which until recently underpinned the successful urban development, turned out to be fraught with increased epidemiological tension.

## 5 Conclusions

The new coronavirus infection, as a specific negative innovation, clearly showed the division of the Russian space into "open" and "closed" zones, center and periphery. The transportation-wise (and, apparently, socially) open regions were the first to bear the brunt of the pandemic and showed a higher excess mortality in the first wave and a longer duration of the remaining waves.

We studied the regions and cities of Russia as socio-economic systems — communication platforms, recognized that all their diversity can be aggregated into four modifications — open centralized, open decentralized, closed centralized, closed decentralized. Open communication platforms turned out to be the most susceptible to the coronavirus in the first wave and later had the most extended pandemic waves due to the constant injection of the virus from outside by its new carriers. On the other hand, closed sites were more defensible during the first wave, but then they often showed even higher morbidity rates due to an immediate mass outbreak of the disease in an isolated local focus of infection.

### Declarations

**Conflict of interest** The authors reported no potential conflict of interest.

## References

Akinwumiju, A.S., Oluwafemi, O., Mohammed, Y.D., Mobolaji, J.W.: Geospatial evaluation of COVID-19 mortality: Influence of socio-economic status and underlying health conditions in contiguous USA. Appl. Geogr. **141**, 102671 (2022). https://doi.org/10.1016/j.apgeog.2022.102671

Alfaro, T., Martinez-Folgar, K., Vives, A., Bilal, U.: Excess mortality during the COVID-19 pandemic in cities of Chile: Magnitude, Inequalities, and urban determinants. J. of Urban Health. 1–14 (2022). https://doi.org/10.1007/s11524-022-00658-y

Anselin, L.: Spatial Econometrics: Methods and Models, p. 284. Kluwer, Dordrecht (1988)

Anselin, L., Syabri, I., Kho, Y.: GeoDa: An introduction to spatial data analysis. In: Fischer, M.M., Getis, A. (eds.) Handbook of Applied Spatial Analysis, pp. 73–89. Springer, Berlin (2010). https://doi.org/10.1007/978-3-642-03647-7

Bag, R., Ghosh, M., Biswas, B., Chatterjee, M.: Understanding the spatio-temporal pattern of COVID-19 outbreak in India using GIS and India's response in managing the pandemic. Reg. Sci. Policy Pract. **12**(6), 1063–1103 (2020). https://doi.org/10.1111/rsp3.12359

Blangiardo, M., et al.: Estimating weekly excess mortality at sub-national level in Italy during the COVID-19 pandemic. PloS one. **15**(10) (2020). https://doi.org/10.1371/journal.pone.0240286 e0240286

Bogdanov, A.A.: Tektology. General organizational science. Volume 1 and volume 2.Moscow: Economics.304p. (1989). (In Russian)

Boumahdi, I., Zaoujal, N., Fadlallah, A.: Is there a relationship between industrial clusters and the prevalence of COVID-19 in the provinces of Morocco? Reg. Sci. Policy Pract. **13**, 138–157 (2021). https://doi.org/10.1111/rsp3.12407

Castells, M.: The Rise of the Network Society (the Information Age: Economy, Society and Culture, vol. 1, p. 518. Wiley-Blackwell, Hoboken, NJ (1996)
Chaklin, A.V.: Medical geography. Moscow: Publishing house “Knowledge”.128p. (1977). (In Russian)
Copus, A.K.: From core-periphery to Polycentric Development: Concepts of spatial and Aspatial Peripherality. Eur. Plan. Stud. **9**(4), 539–552 (2001). https://doi.org/10.1080/713666491
Eggo, R.M., Dawa, J., Kucharski, A.J., et al.: The importance of local context in COVID-19 models. Nat. Comput. Sci. **1**, 6–8 (2021). https://doi.org/10.1038/s43588-020-00014-7
Gallo, E., et al.: Excess of all-cause mortality is only partially explained by COVID-19 in Veneto (Italy) during spring outbreak. BMC Public. Health. **21**(1), 1–6 (2021). https://doi.org/10.1186/s12889-021-10832-7
Getis, A.: Spatial weights matrices. Geographical Anal. **41**(4), 404–410 (2009). https://doi.org/10.1111/j.1538-4632.2009.00768.x
Getis, A., Ord, J.K.: The analysis of spatial association by Use of Distance Statistics. Geographical Anal. **24**(3), 189–206 (1992). https://doi.org/10.1111/j.1538-4632.1992.tb00261.x
Ghosh, P., Cartone, A.: A spatio-temporal analysis of COVID-19 outbreak in Italy. Reg. Sci. Policy Pract. **12**(6), 1047–1062 (2020). https://doi.org/10.1111/rsp3.12376
Gibertoni, D., et al.: Patterns of COVID-19 related excess mortality in the municipalities of Northern Italy during the first wave of the pandemic. Health & place. **67**, 102508 (2021). https://doi.org/10.1016/j.healthplace.2021.102508
Jaya, I.G.N.M., Folmer, H.: Bayesian spatiotemporal forecasting and mapping of COVID-19 risk with application to West Java Province. Indonesia J. Reg. Sci. **61**(4), 849–881 (2021). https://doi.org/10.1111/jors.12533
Keller, A.A., Podolyan, V.Y., Shpilenya, S.E., Alfimov, N.N.: Concepts of medical geography. In: Soviet geography. L.: Science. P. 312–320. (In Russian) (1984)
Kotov, E.A., Goncharov, R.V., Kulchitsky, Y.V., Molodtsova, V.A., Nikitin, B.V.: Spatial modelling of key regional-level factors of COVID-19 mortality in Russia. GEOGRAPHY, ENVIRONMENT. SUSTAINABILITY. **15**(2), 71–83 (2022). https://doi.org/10.24057/2071-9388-2021-076
Kravchenko, N.A., Ivanova, A.I.: The spread of coronavirus in Russia: regional peculiarities. Region: ekonomika i sotsiologiya [Region: Economics and Sociology]. 2(110), 78–99 (2021). https://doi.org/10.15372/REG20210204
Kuebart, A., Stabler, M.: Infectious diseases as socio-spatial processes: The COVID-19 outbreak in Germany. Tijdschr Econ. Soc. Geogr. **111**(3), 482–496 (2020). https://doi.org/10.1111/tesg.12429
Linka, K., Goriely, A., Kuhl, E.: Global and local mobility as a barometer for COVID-19 dynamics. Biomech. Model. Mechanobiol. **20**, 651–669 (2021). https://doi.org/10.1007/s10237-020-01408-2
Martines, M.R., et al.: Detecting space–time clusters of COVID-19 in Brazil: Mortality, inequality, socioeconomic vulnerability, and the relative risk of the disease in brazilian municipalities. J. Geogr. Syst. **23**(1), 7–36 (2021). https://doi.org/10.1007/s10109-020-00344-0
Nikitin, B.V., Zamyatina, N.Y.: Waves of the COVID-19 pandemic in Russia: regional projection.Regional Research of Russia. 13(2), 273–288 (2023). (in print).
Pandey, B., Gu, J., Ramaswami, A.: Characterizing COVID-19 waves in urban and rural districts of India. npj Urban Sustain. **2**, 26 (2022). https://doi.org/10.1038/s42949-022-00071-z
Pilyasov, A.N., Zamyatina, N.Y., Kotov, E.A.: The Spread of the COVID-19 Pandemic in Russian Regions in 2020: Models and Reality. Ekonomika regiona [Economy of regions]. 17(4), 1079–1095 (2021). https://doi.org/10.17059/ekon.reg.2021-4-3
Rodríguez-Pose, A., Burlina, C.: Institutions and the uneven geography of the first wave of the COVID-19 pandemic. J. Reg. Sci. **64**(4), 728–752 (2021). https://doi.org/10.1111/jors.12541
Shoshin, A.A.: Fundamentals of medical geography. M.-L. Publishing House of the Academy of Sciences of the USSR.147p. (1962). (In Russian)
Tarkhov, S.A., SUSTAINABILITY: Spatial Features of COVID-2019 Diffusion in Russian Regions: the View of the Transport Geographer. GEOGRAPHY, ENVIRONMENT,. 15(1),87–101(2022). https://doi.org/10.24057/2071-9388-2021-107
Wang, H., Paulson, K., Pease, S., Watson, S., et al.: Estimating excess mortality due to the COVID-19 pandemic: a systematic analysis of COVID-19-related mortality, 2020–21, The Lancet. Vol. 399. no. 10334. P. 1513–1536. (2022)
Zamyatina, N., Goncharov, R., Poturaeva, A., Pelyasov, A.: The sandwich of russian space: How different spaces differentiate themes in regional science. Reg. Sci. Policy Pract. **12**(4), 559–577 (2020). https://doi.org/10.1111/rsp3.12272

Zemtsov, S.P., Baburin, V.L.: COVID-19: Spatial Dynamics and Diffusion factors across russian regions. Reg. Res. Russ. **10**, 273–290 (2020). https://doi.org/10.1134/S2079970520030156