Spatiotemporal inequalities of excess mortality in Europe during the first two years of the Covid-19 pandemic

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The coronavirus pandemic has severely affected Europe, but not equally. The aims of this study were to present the methodological issues of using pandemic indicators and to analyse the regional excess mortality data to show which regions and countries in Europe were the most and least affected by Covid-19 in each period of the pandemic, with a particular focus on the geographical reasons behind the differences. The study found that there were significant spatial inequalities and a strong centre-periphery differences in the excess mortality in Europe Although the centres (metropolitan and urban regions, Western and Southern Europe) were the most affected during the first wave, from the second wave, the main negative effects of the pandemic were shifted to the peripheries: rural regions and East-Central Europe (especially Bulgaria). However, the geographically isolated peripheries (sparsely populated areas and islands) had low excess mortality throughout the entire period.

Keywords:
Covid-19,
excess mortality,
pandemic geography,
health inequalities,
Europe

Introduction

The Covid-19 pandemic has hit Europe severely, but different countries and regions have been affected at different times and by different measures. The question of which countries and regions have been more or less affected by the pandemic (and the possible reasons behind this) is still a matter of debate. One of the elements of this dispute is that the impact of the pandemic can be interpreted along many dimensions using several indicators, and there is no single indicator that clearly identifies which regions have been more or less affected. However, the use of different indicators raises various methodological issues that may lead to misunderstanding.

This study analysed the impact of Covid-19 on human lives based on regional excess mortality data to show which regions and countries in Europe were the most and least affected by Covid-19 in each period of the pandemic, with a particular focus on the geographical reasons behind the differences. However, it should be realised that the Covid-19 pandemic is a complex phenomenon, and it does not only have an impact in terms of mortality, but also has complex environmental (Shakil et al. 2020, Thakur–Das 2022), economic (Dániel et al. 2021, Nyikos et al. 2021, Dijkstra et al. 2022), labour market (Czirfusz 2021, Dijkstra et al. 2022, Kapás 2022, Varga 2022), social (Gao et al. 2020, Karácsonyi et al. 2021, Szirmai 2021, Dijkstra et al. 2022, ESPON 2022) and health impacts (Kovács–Uzzoli 2020, Xie et al. 2022) (which may of course have their own impact in terms of additional human lives).

The aim of this study was to identify the main geographical characteristics underlying the spatiotemporal inequalities in excess mortality in Europe. This can be used to compare how countries and regions were affected by the pandemic and better understand the spatial patterns of Covid-19 and the role of geographical characteristics.

This article is divided into four parts. First, it explores the main characteristics and challenges of indicators related to the Covid-19 pandemic, particularly the indicator of excess mortality. Second, it presents the methodology of this study: the spatial and temporal frame, the calculation method of excess mortality, the definition of the studied sub-periods, and the methodology of data analysis. Third, it analyses the spatiotemporal inequalities and geographical characteristics of regional excess mortality in Europe at different territorial levels (macro-regional, national, and regional). This chapter also presents the results of the hierarchical cluster analysis of regional excess mortality data, which aimed to group the regions of Europe according to the temporal pattern of excess mortality. Finally, the paper discusses the conclusions and compares them with other results of scientific dialogues on the spatiality of Covid-19.

Methodological issues of Covid-19-related territorial pandemic data

To explore the impact of the Covid-19 pandemic on human lives, it is necessary to identify pandemic indicators and the limitations of their usage. In most countries, the following Covid-19 related data have been published through official Covid-19 webpages/databases:

- Reported number of Covid-19 cases: number and (daily, weekly) changes, and other connected indicators; for example, the incidence rate, morbidity, and cases by variants.
- Reported Covid-19-related deaths: number and changes, and other connected indicators, such as mortality rate and case fatality rate.

- Number of recovered cases: number and changes, and other connected indicators; for example, recovery rate.
- Number of active cases: the current number and any changes.
- Number of serious/critical cases: Several indicators can be used. In most cases, the number of people hospitalised in intensive care units (ICU) or ventilators is used.
- Number of tests: Number of tests used (PCR and/or antigen) and percentage of positive tests. The latter indicator refers to the extent to which the country can track the spread of Covid-19 and the reliability of the published pandemic data.
- \+ (Vaccination-related indicators are also usually represented on these webpages.)

Although a large amount of up-to-date pandemic data are available from European countries, there are many challenges in using them. First, in many cases, the coronavirus causes no or only mild symptoms; therefore, many cases may remain hidden from official statistics. For this reason, the capacities of the healthcare system and disease control are of particular importance for monitoring the pandemic. The number of reported cases, the number of recoveries and active cases, as well as the number of reported Covid-19 deaths, are all affected by the number of tests performed and the effectiveness of contact tracing (Kiss 2020, Verity et al. 2020, Igari 2021a). For the number of serious cases, the capacity of the healthcare system (number of health personnel and number of available hospital beds, intensive care beds, and ventilators) can also strongly influence pandemic data both among and within countries.[1]

At the same time, the spatial heterogeneity of the methodologies used could also hamper the interpretation of the data; different countries record the number of reported cases in different ways, depending on the type of tests performed and the place of registration. Recording the number of recoveries also varies among countries (its methodology is the most diverse and, therefore, the most difficult to interpret), which has a major impact on the number of active cases. Furthermore, different countries reported the number of Covid-19 deaths in different ways: some counted as victims of the pandemic those who died specifically from the coronavirus, some counted those who tested positive for coronavirus but may not have died from it, while others used a different methodology. Causal classification is more difficult because many people have multiple causes of death (Kiss 2020, Ferenci 2021, Igari

[1] The importance of health personnel and the infrastructure of the healthcare system varies across time and countries. While during the first wave in the main hotspots both the number of ventilators and nurses was an important factor, in later periods, the number of nurses was crucial: in Germany, the maximum number of patients per nurse in intensive care units was set at 2 during the day and 3 at night (2.5 and 3.5 respectively by 31 January 2022) (BMG 2022); above this number, the mortality rate increases significantly. However, the maximum number of patients per nurse was fixed at a higher level in East-Central Europe: e.g. in Hungary, the maximum number was set at 5 in November 2021 (Portfolio 2021b). In Romania, the number of ICU patients reached the upper limit of ICU capacity in October 2021 and patients were transferred to Hungary, Austria, and Poland (Portfolio 2021a).

2021a). There are also variations among countries in how different types of severe case are recorded. Finally, the spatial details of data publication also vary from country to country, and have changed many times over the last two years.

Overall, many methodological issues can arise when using officially available pandemic data. Inaccurate data can lead to incorrect conclusions regarding the severity of the pandemic in each country and region. To avoid this, the indicator of excess mortality is increasingly used in Covid-19-related scientific literature (Félix-Cardoso et al. 2020, Kontis et al. 2020, Bogos et al. 2021, Igari 2021a, Natale et al. 2021, Rodríguez-Pose–Burlina 2021, Díaz Ramírez et al. 2022) and in statistical analyses by national offices and international organisations (CSO 2021, Tóth 2021, Destatis 2022, Dijkstra et al. 2022, OHID 2022).

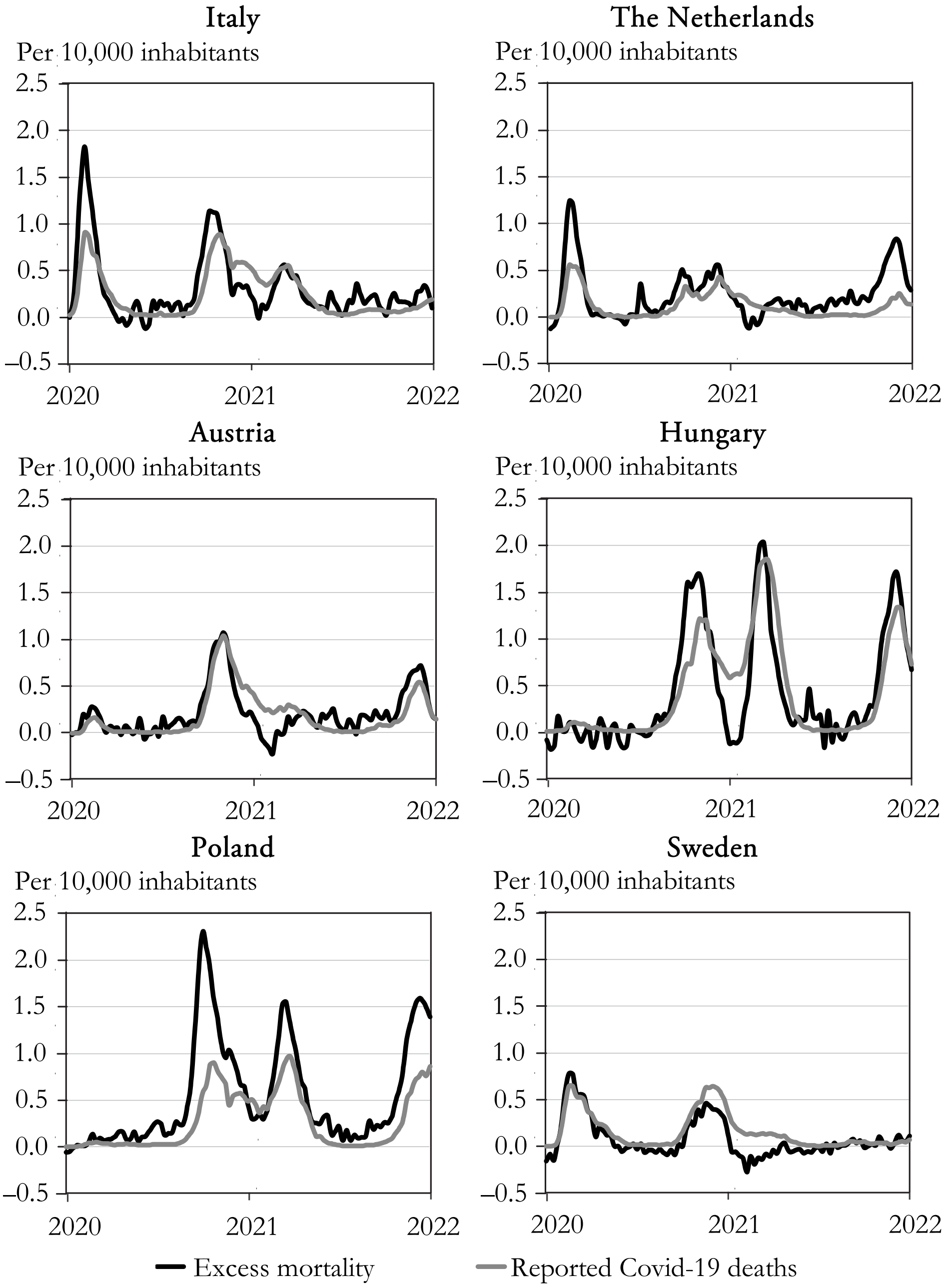
Excess mortality could be described as 'An unusual mortality increase during a specific period, in a given population' (Eurostat 2021). It is calculated by measuring the number of deaths from all causes reported in a specific period with the expected number of deaths based on the mortality statistics of previous years. Its main advantage over reported Covid-19 deaths is that the value of excess mortality does not depend on testing capacities or on the causal classification of deaths. Because of its flexibility, excess mortality is also used to estimate deaths caused by many other phenomena (e.g. influenza [Nielsen et al. 2019, Rosano et al. 2019, Wong et al. 2019] and heat waves [Weinberger et al. 2020, Yang et al. 2021]).

The difference between reported Covid-19 deaths and excess mortality refers to the reliability of the reported Covid death statistics in different countries. As Figure 1 shows, national pandemic offices have not always been able to track mortality, as the number of reported Covid-19 deaths is far below the excess mortality near the peak of pandemic waves in many countries.

There are several ways to calculate excess mortality; first, current mortality values can be correlated to the deaths in the year before the crisis (2019), but in this case, the uncertainty is increased by estimating the result based on only one year. A more precise method is to use an average over a five-year period as the basis of the calculation. The reference period values can be further 'smoothed' using a multiweek moving average value. In these cases, potential outliers in a single year have little effect on the analysis. Of course, there are many ways to further refine the model: the spatially heterogeneous effects of long-term mortality trends and aging of the population on mortality, the dependence of mortality on age structure and other factors (obesity, smoking, etc.), the exclusion of seasonal flu epidemics from studies, etc., can modify the values of excess mortality (Kanieff et al. 2010, Wéber 2014, Bonanad et al. 2020, Acosta–Irizarry 2020, CSO 2021, Ferenci 2021, Hou et al. 2021, Poly et al. 2021, Varga 2021, EuroMOMO 2022, Ferenci–Tóth 2022).

Figure 1

Weekly excess mortality and weekly reported Covid-19 deaths per 10,000 inhabitants in six European countries, 1 January



However, the use of excess mortality poses additional challenges. On the one hand, since it indicates deaths from all causes, it is not possible to distinguish whether a person died from coronavirus or from other causes, which means that the value of the indicator can be affected by many other phenomena. For example, the number of deaths due to road accidents has decreased as a result of lockdowns, but the number of suicides has increased (Ferenci 2021, ESPON 2022, Ferenci–Tóth 2022). Furthermore, the number of deaths has increased because of the overwhelmed healthcare system (Kalanj et al. 2021, Eckford et al. 2022, Kovács–Vántus 2022): e.g. long-term cardiovascular deaths have also increased significantly since the onset of the Covid pandemic (Xie et al. 2022). On the other hand, deaths related to other airborne diseases decreased due to closures and mask use; in Hungary, there was no seasonal flu epidemic during the winter of 2020–2021 (NNK 2021). In addition, events unrelated to the pandemic, such as deaths due to heatwaves, can also affect the value of excess mortality. Separating all these different causes that can affect excess mortality is therefore not possible in this case, so the excess mortality indicator should be used as a summation of the impact on human lives in a given period – in this case, the period of Covid-19 – rather than as a 'real' indicator of the mortality from coronavirus.

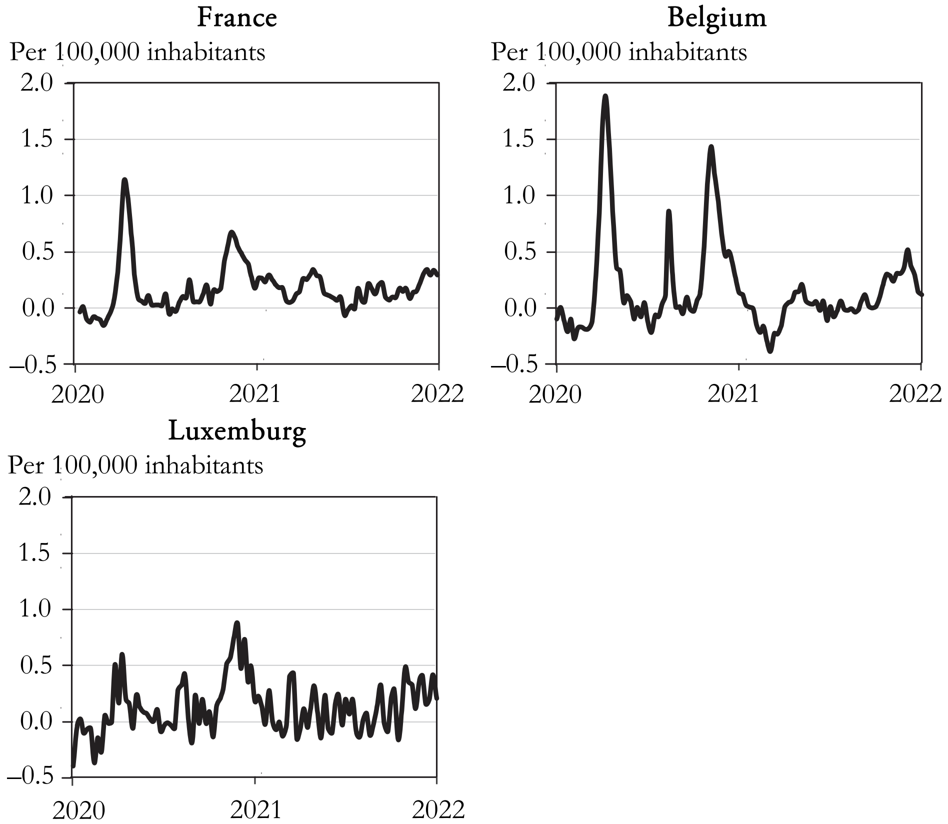
Other challenges occur when analysing timely and spatially changing excess mortality data. First, there may be a mortality deficit in certain periods, both for the reasons described above (e.g. no flu season) and because it is common to see decreased mortality after the peak of pandemic waves (CSO 2021). This is because the pandemic also causes the death of people who would otherwise have lived only a few weeks or months, which occurs slightly earlier than expected. Second, for areas with smaller populations, the data may be much more volatile, while in countries with larger populations, local variations are masked by the aggregate data (Figure 2 shows these two effects: mortality deficit and different curves for different countries with varying population sizes).

Another issue is related to the availability of basic data on excess mortality. As the number of deaths is entered into the databases with a delay of a few weeks, the time lags vary between countries, and ex-post data corrections are common and differ among countries. Also related to the availability of the data is that data are available at different territorial levels among countries and that there may be data gaps (data and methodological issues with this paper are discussed in the next chapter).

Altogether, there are many issues and challenges raised not only in using official Covid-19 data but also in using excess mortality, in terms of methodology, data availability, and usability. However, it seems that the indicator of excess mortality can provide the most accurate comparison of the effect of the pandemic in different countries and regions.

Figure 2

Weekly excess mortality per 10,000 inhabitants in France, Belgium, and Luxemburg, 1 January



Spatial and time frame and the methodology of this paper

For the analysis, weekly mortality data (from all causes) was downloaded from 2015 until the beginning of 2022, from the 'Deaths by week, sex, 5-year age group and NUTS 3 region' data table in Eurostat, where data is available mostly at the NUTS 3 level. The exceptions were Germany (NUTS 1 level), Croatia, Estonia, Ireland, Malta, and Slovenia (country level). Furthermore, data disclosure from the UK ended in 2020, presumably as a consequence of Brexit, so I supplemented it with data from national databases. Furthermore, data from Ireland are only available in the Eurostat from the second half of 2019, so data from earlier years were obtained from the national database [1–5]. A *simple model* was used to calculate excess mortality: the 2020–2022 weekly number of deaths was compared with the five-week moving-average of average death numbers for the same weeks of 2015–2019 (in Germany and

Ireland: 2016–2019). To compare the different territories, I calculated the values per 10,000 inhabitants (excess mortality rate). While the model could have been further refined, the aim of this model was to explore the differences in crude excess mortality rates among regions. These values are influenced by factors such as the vulnerability/resilience of the population and age-specific mortality rates. Nevertheless, I used the simple model above as it allowed me to highlight the basic differences in vulnerability among regions, but these factors will also need to be considered when assessing the results.

The territorial scope of the research was Europe, including the 27 member states of the European Union, the United Kingdom, Switzerland, Liechtenstein, Iceland, and Norway. Considering that the Covid-19 pandemic appeared in Europe in January 2020 and the first deaths were reported at the end of February, the time frame of the study was from the beginning of the Covid-19 pandemic until the end of the fourth wave.

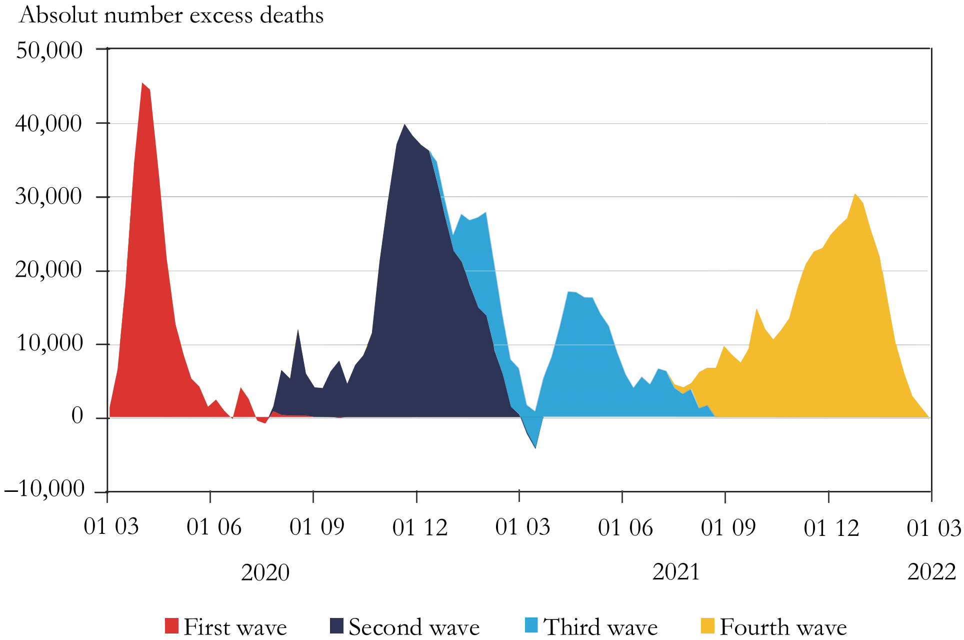
An important issue was the separation of the subperiods to be studied. Given the sensitivity of excess mortality to temporal and spatial factors, it is not advisable to select periods that are too short. Therefore, the four pandemic waves formed the basis for this separation. Of course, excess mortality, based on its methodology, is not necessarily aligned with the pandemic waves, but in most cases, the effects of each pandemic wave can be separated. However, the separation of each period raises further issues. First, the pandemic situation varied from country to country, with peaks in some countries occurring several months apart. To compensate for this, the start and end dates of each wave were estimated separately for each country, based on the excess mortality, the reported Covid-19 cases (taking into account the several weeks' lag between the date of the report of the case numbers and deaths [Ferenci 2021, Igari 2021a, Uzzoli et al. 2021, Ferenci–Tóth 2022]), and the reported Covid-19 deaths. On the other hand, periods of mortality deficit between each wave were also included in the analysis (usually related to the preceding pandemic wave), as these are also part of the pandemic period effects.

It was easy to determine the start date of the first wave, which was the 10–14th week of 2020, in each country. Because the first wave was followed by a so-called inter-wave period, the important question in separating the first and second waves was, to which period (first or second wave) should I assign the data from this calmer period for each country? The decisive factor here was as follows: as long as the excess mortality did not show the effect of the second wave starting in August–September, I assigned it to the first wave. The biggest challenge was to separate the second and third waves; in some countries, the second wave only peaked in November–December 2020, while in the UK, the third wave of the pandemic peaked in December 2020–January 2021. Furthermore, several Western European countries had a significant mortality deficit in March 2021, and in some countries, the excess mortality of the two waves overlapped, while the third wave peaked in East-Central

Europe only in March–April 2021. In separating the third and fourth waves, I followed an approach similar to the separation of the first and second waves. The fourth wave ended between the 51st week of 2021 and the 4th week of 2022, depending on the country (see Figure 3).

Figure 3

Weekly number of excess deaths in Europe by the first four pandemic waves



After overcoming the above-mentioned methodological issues, I analysed the excess mortality data using three main methods. First, I inspected the spatial heterogeneity (macro-region[2], country, and regional typologies[3]) of the time trends of excess mortality over the examined period in Europe. Second, I examined the regional pattern of the pandemic for the period as a whole and in waves. Finally, hierarchical cluster analysis was used to group regions according to the excess mortality values they had in each subperiod.

To perform the cluster analysis, I fed the excess mortality rates of each region per wave and the combined value of the second and third waves as separate indicators into the JASP program. These datasets were subjected to hierarchical cluster analysis in two

[2] Used macroregional classification: *North*: Denmark, Finland, Sweden, Iceland, Norway. *West*: Belgium, France, Luxemburg, Netherlands. *British Isles*: Ireland, United Kingdom. *South*: Cyprus, Greece, Italy, Malta, Portugal, Spain. *West-Central*: Austria, Germany, Liechtenstein, Switzerland. *East-Central*: Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia.

[3] Used regional typologies for NUTS3-level regions: Predominantly urban, Intermediate, Predominantly rural, Metropolitan, Coastal, Island, Border, Mountainous, Sparsely populated. Based on Eurostat 2019.

ways: first, I clustered the results of the four separate waves (1st model), and second, I replaced the separate data of the second and third waves with their combined data (2nd model), thus reducing the uncertainties in the separation of the periods. Furthermore, because the high values may have skewed the results (overestimating the differences between high values), I also calculated the square root values of the excess mortality per population (and assigned 0 values for mortality deficits) and analysed these values in a similar way to the original excess mortality rates (3rd and 4th models). In each case, hierarchical cluster analysis was used, and the final cluster number was determined using the elbow method; however, I also examined the dendrograms in each case to inspect the relationships among the clusters.

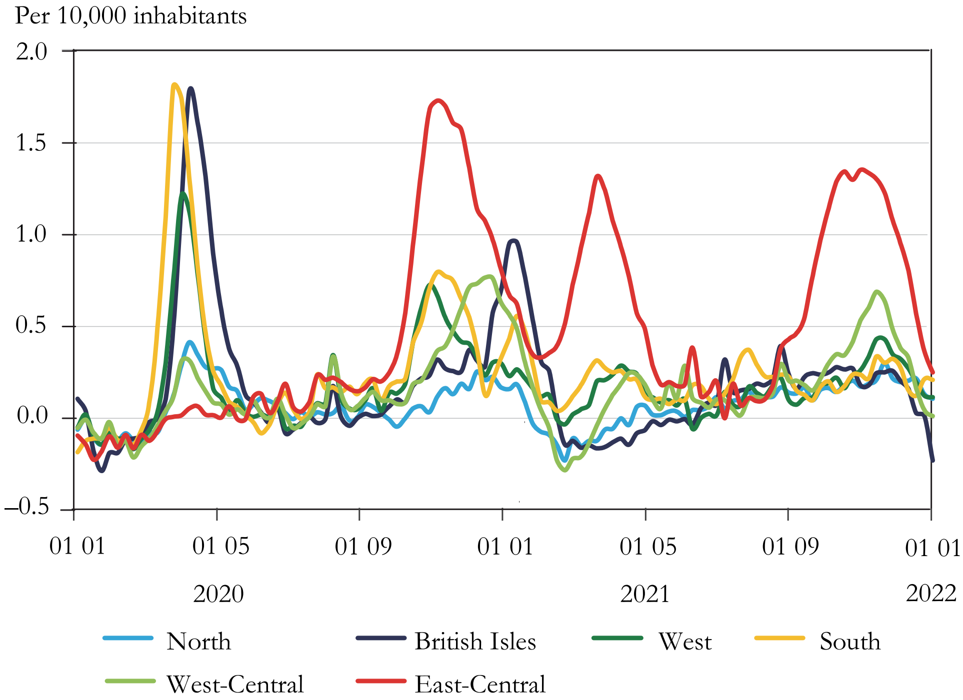
Regional inequalities in excess mortality in Europe

To the best of our knowledge, the Covid-19 pandemic in Spain appeared in Europe in January 2020. Within a few weeks, it appeared in all countries of Southern and Western Europe, and in late February–March in Northern and East-Central European countries. The initial spread of the Covid-19 pandemic followed the hierarchical type of diffusion: it appeared first in the major cities strongly connected to global transport networks, from where it spread to macro-regional centres, other cities, and then to rural areas. Some tourist areas also played a key role in the spread of the pandemic; ski resorts and sporting events became early hotspots. At the same time, the virus started to spread from cities to neighbouring agglomerations and from there to their neighbourhoods, which is known as contiguous-type diffusion (Amdaoud et al. 2021, Bourdin et al. 2021, Brockmann–Helbing 2020, Kiss 2020, Kincses–Tóth 2020, Igari 2021a, Kovalcsik et al. 2021, Lennert 2021, Szirmai 2021, Uzzoli et al. 2021, ESPON 2022).

The pandemic spread across Europe as a spatiotemporal wave, which also manifested in excess mortality a few weeks later. As shown in Figure 4, the pandemic waves hit macro-regions at different times. The excess mortality value was positive in March and early April in European countries: in Southern Europe in early March; in the British Isles, in Western and West-Central Europe in mid-March; and in Northern and East-Central Europe in the second half of March and early April. The first wave was most severe in the British Isles, Southern Europe, and Western Europe, whereas moderate excess mortality was observed in West-Central, Northern, and East-Central Europe.

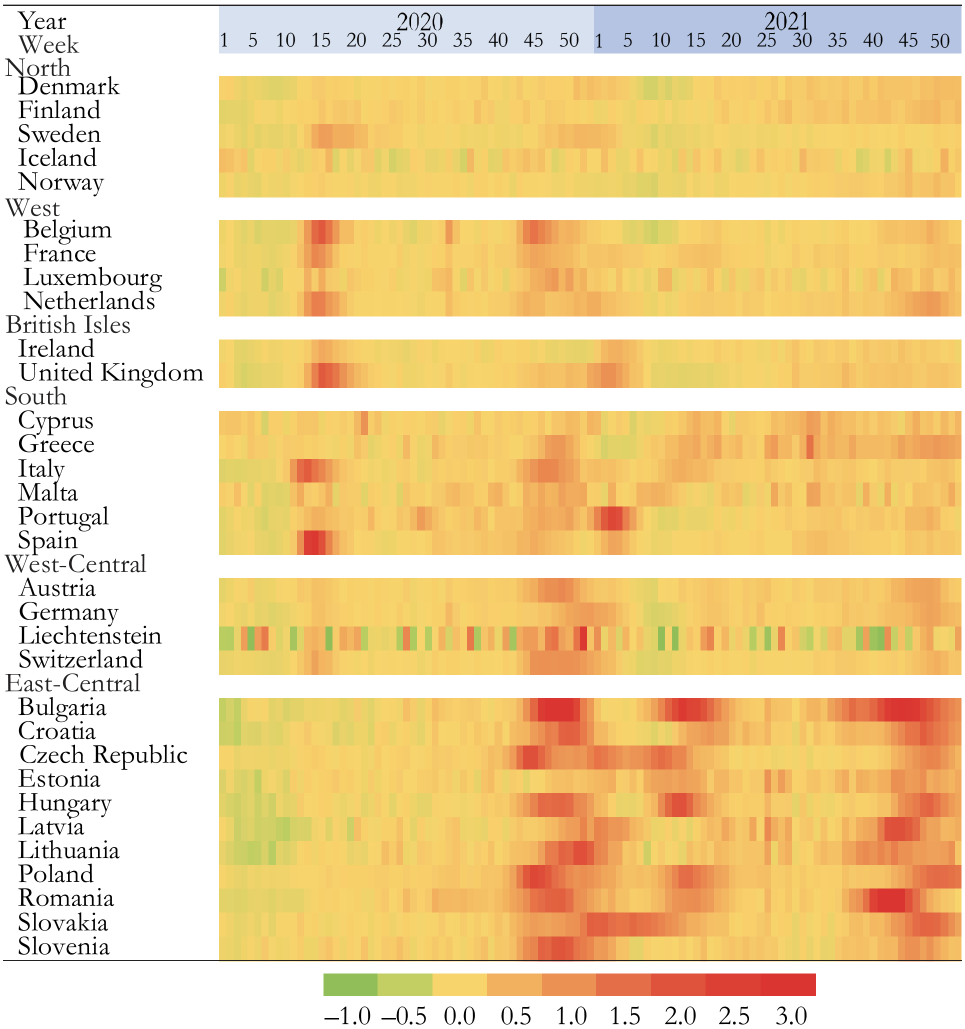
Figure 4

Weekly excess mortality per 10,000 inhabitants by main macro-regions



The first wave was followed by a calmer period during the summer of 2020. In August–September 2020, the second wave of the pandemic started, with a major impact on excess mortality in October. This wave mainly affected East-Central Europe, but all macro-regions (except Northern Europe) experienced significant excess mortality. In the United Kingdom, the number of cases started to decline in November 2020, and restrictions were eased, together with the emergence of new variants (Alpha, Beta), triggering the third wave of Covid-19. It hit the United Kingdom and East-Central Europe hard, but caused only moderate excess mortality or mortality deficit in major regions of Europe (partly for methodological reasons). This was again followed by a calmer period in summer 2021, but then a new (fourth) wave of the pandemic hit Europe in autumn 2021, again causing significant excess mortality predominantly in East-Central Europe (see Figure 4). Similar excess mortality curves were observed within each macro-region, although there were some outliers (e.g. Sweden, Portugal, Czech Republic, and Slovakia) (see Figure 5).

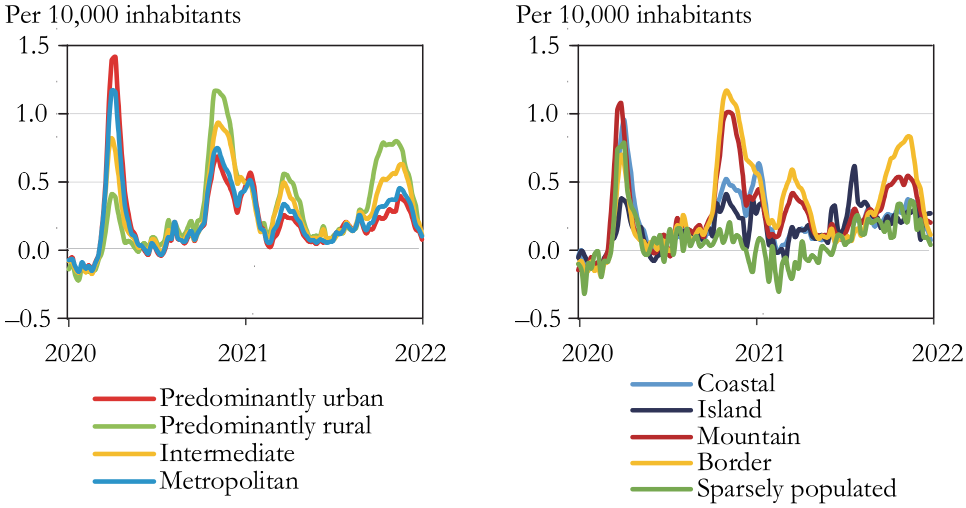
Figure 5
Heatmap of weekly excess mortality per 10,000 inhabitants by country



Furthermore, the spatiotemporal heterogeneity of excess mortality can be interpreted among *the regional typologies*. While the first wave of the pandemic affected urban and metropolitan areas in Europe much more severely (Natale et al. 2021, Szirmai 2021, ESPON 2022), the latter affected rural regions much more heavily (see Figure 6). In 2020 and 2021, the average values per inhabitant of urban and metropolitan regions were lower than those of rural and intermediate regions. This means that after the significant disparities of the first wave, the urban-rural gap in excess mortality in Europe turned contrary during the subsequent waves.

Figure 6

Excess mortality per 10,000 inhabitants by regional typologies,* 1 January



* Without data from Croatia, Estonia, Germany, Slovenia, and Ireland (except island regional typology).

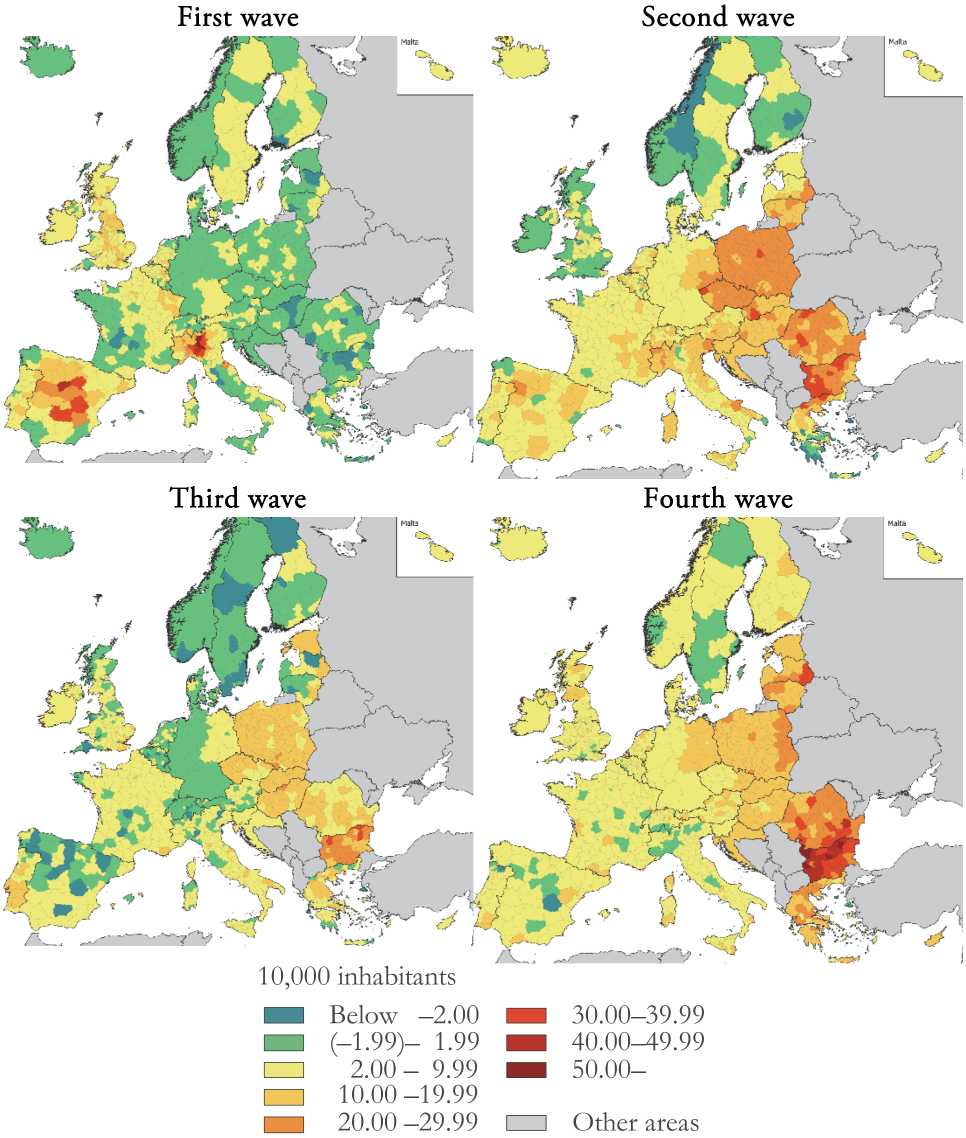
Differences were also observed in other regional typologies. The coastal, border, and mountain regions' excess mortality varied over time, but with similar excess mortality throughout the period, and two geographically peripheral regions had significantly low excess mortality rates: islands and sparsely populated regions. For islands, the Mediterranean, northern, and British Isles[4] had low values (with a few exceptions), but even lower excess mortality values were found in sparsely populated regions (mainly in Northern Europe), which were not severely affected by any of the waves (only a few sparsely populated Spanish regions were affected by the first wave) (see Figure 6). In summary, I found that the spatial pattern of excess mortality fundamentally changed in the first two years of the Covid-19 pandemic. Shifting to the temporally changing *regional pattern of excess mortality*, as Figure 7 shows, the first wave caused outstanding excess mortality in Spanish and Northern Italian (mainly metropolitan) regions, and high rates in British and Western European regions, whereas in Northern and East-Central Europe, there was no significant excess mortality. This is due to the fact that the diffusion patterns mentioned above prevailed during the first wave (i.e. the central areas of Europe were hit earlier than the peripheral areas), which was stopped in the early phase through timely and strict measures (e.g. closures and lockdowns). Thus, the virus did not spread evenly in Europe: the first wave of Covid-19 caused only a minimal number of reported cases

[4] Regions of the main British island do not count as island regions under the typology, as the Channel Tunnel is a direct link to the continent. Thus, the island regions of the British Isles include the Isle of Ireland and the smaller archipelagos surrounding Britain.

in Northern and East-Central Europe, so deaths and excess mortality remained low in these areas (Amdaoud et al. 2021, Dániel et al. 2021, Igari 2021a, Kovalcsik et al. 2021, ESPON 2022).

Figure 7

Excess mortality per 10,000 inhabitants of the European regions

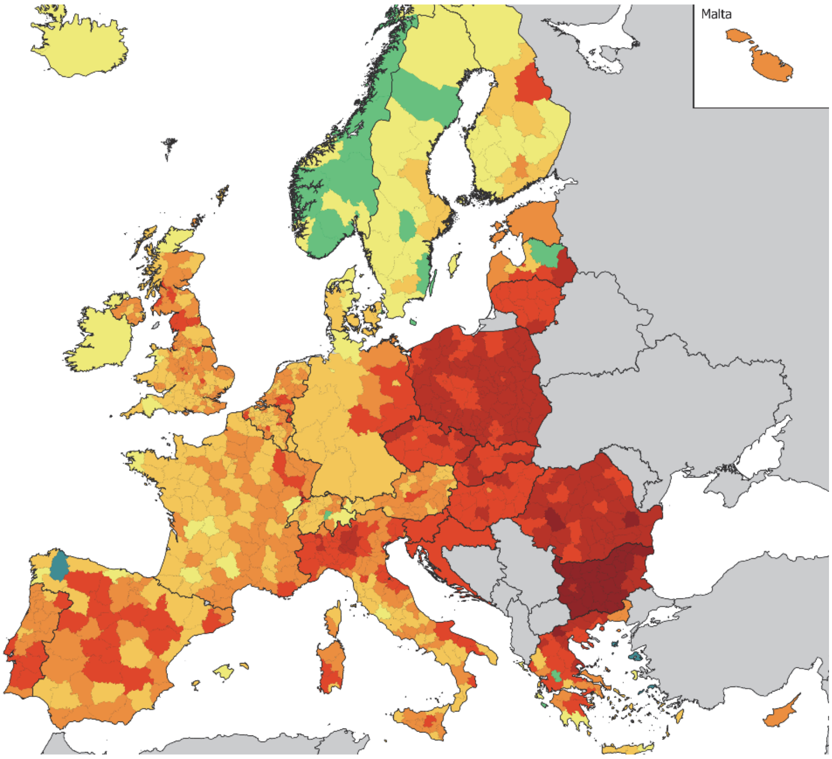


By the second wave, this had fundamentally changed; significant excess mortality was observed almost everywhere (except in the northern regions, other geographical peripheries, and in the hotspots of the first wave), with outstanding rates in East-

Central Europe. This was due to the fact that the virus caused a similar number of cases throughout Europe (because, although the hierarchical pattern of diffusion prevailed again in the initial phase of the wave, the measures were delayed and less strict than during the first wave), so the role of other factors increased. In the third wave, East-Central Europe (and Bulgaria within it) became the most affected macro-region of Europe, while the western, northern, and southern parts of Europe had low excess mortality rates or a mortality deficit. Finally, the excess mortality of the fourth wave again highlighted (north)west–(south)east inequality, with the highest values in Bulgaria and Romania, while the rest of Europe showed only moderate excess mortality (Figure 7).

Figure 8

Excess mortality rate since the beginning of the Covid-19 pandemic in Europe until the end of the fourth wave



10,000 inhabitants

Below –2.00
(–1.99)– 1.99
2.00 – 9.99
10.00 –19.99
20.00 –29.99
30.00–49.99
50.00–74.99
75.00–
Other areas

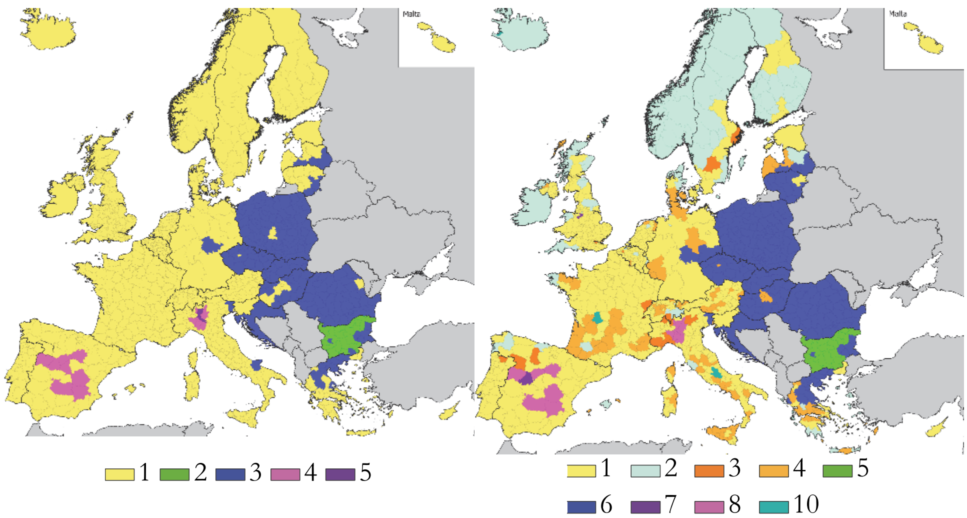
Summing up the values for each period, I found that during the first four waves of the pandemic, significant geographical disparities in excess mortality emerged in Europe, with low excess mortality in the northern periphery of Europe and on some islands, and mostly below average mortality in Western and West-Central Europe. Above average values were recorded in the hotspots of the first wave in Southern Europe and in the main parts of East-Central Europe. Finally, Bulgaria had the highest excess mortality rate: 10 Bulgarian regions had an excess mortality rate of over 100 per 10,000 inhabitants. The West-East difference was also observed within some countries (e.g. between the former West and East Germany), while urban-rural differences also emerged in East-Central Europe: the regions of Budapest, Prague, Bratislava, and Sofia, had the (or one of the) lowest excess mortality rates in their countries (see Figure 8).

The excess mortality values for each pandemic wave were then analysed using *cluster analysis*. As presented above I used several methods but obtained similar results for different models. Most European regions were grouped into a common cluster. From this, three main clusters were distinguished: the 'East-Central European', 'Bulgarian', and 'early hotspot' clusters. These three clusters were fundamentally different from the average European cluster.

Figure 9

Clusters based on the 1st and 4th models of the hierarchical cluster analysis

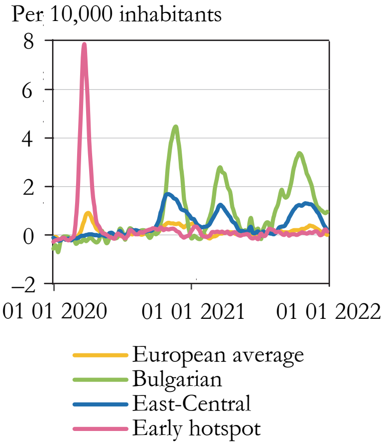
Model 1 **Model 4**



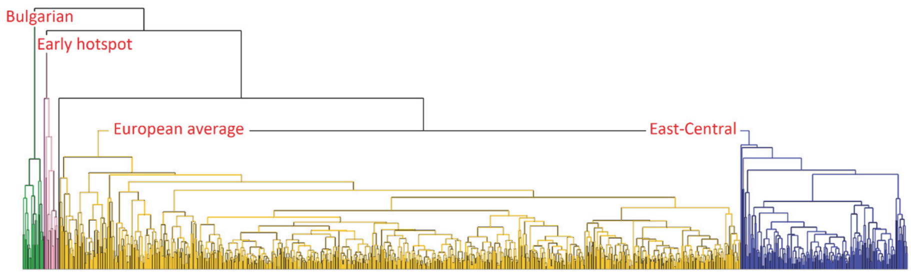
Depending on the model used, minor differences emerged: some outlier regions were separated, and the above-mentioned clusters could split further (e.g. the Bulgarian and early hotspot clusters were split in several cases). Furthermore, in the 3^{rd} and 4^{th} models, several other clusters of regions were separated from the average European cluster because the role of the differences between outstanding values was less important (since I used square root values in these models). On the one hand, some regions of Western Europe, which were affected above-average by the first and second waves (clusters 3 and 4 in the 4th model), and on the other hand, the peripheral regions (cluster 2 in the 4th model) were affected below-average by Covid-19: regions of the northern and western periphery of the continent, and some Greek regions (see Figure 9).

Figure 10

Outcomes of the 1st model of the hierarchical cluster analysis: Excess mortality per 10,000 inhabitants by main clusters (graph and table), and the dendrogram of the cluster analysis



Name (cl. number)	1st	2nd	3rd	4th	All
	wave				
European average (1)	4.7	6.4	3.4	5.7	20.1
Bulgarian (2)	–1.5	29.9	23.2	42.0	93.7
Early hotspots (4, 5)	32.2	4.4	2.6	2.6	41.9
Bergamo-type (4)	56.6	–0.9	1.9	1.9	59.5
Other hotspots (5)	29.2	5.1	2.7	2.7	39.7
East-Central (3)	1.0	21.4	12.1	18.0	52.5



All things considered, *there were four clusters that were distinct in each model: the 'European average', 'Bulgarian', 'East-Central European', and 'early hotspot' clusters.* However, the excess mortality curves were completely different. The regions of the 'early hotspot' cluster had elevated excess mortality during the first wave (it was extremely high in the case of the 'Bergamo-type' sub-cluster) but since then they had about a zero excess mortality rate. The 'Bulgarian' and 'East-Central' clusters had high excess mortality in the second, third, and fourth waves: the regions of the 'Bulgarian' cluster had much higher values than the latter. Finally, the regions in the so-called European average cluster had only a moderate average excess mortality, with a slight increase in the excess mortality curve during each wave (Figure 10). Although this did not occur in the 1st model, the peripheral cluster separated in the 3rd and 4th models differed from the other clusters because the regions belonging to this cluster had a near-zero excess mortality rate during the entire Covid-19 period.

Overall, the European regions differed significantly in terms of excess mortality during the Covid-19 pandemic. Most regions of Europe had relatively favourable values, with no outstanding excess mortality during any of the pandemic waves. This differed markedly from the values of the regions in the other clusters, which were geographically concentrated. There was a sharp difference between the western and eastern parts of Europe, while Bulgaria and the peripheries were also separated. Another interesting geographical phenomenon was observable in East-Central Europe: some capital city regions had more favourable values than other regions. In several model variations of hierarchical clustering, these capital city regions were in a different cluster than in other regions of their countries (e.g. Prague, Budapest, and Sofia).

Discussion and conclusion

As the analysis showed, the excess mortality rates in Europe's regions differed substantially, but these differences followed more or less clear spatial patterns. On the one hand, the spatiotemporal variation in excess mortality illustrates the spatial pattern of the spread of pandemic waves: each wave first affected the central areas most connected to international transport networks (large cities, tourist regions, and the western part of Europe) and then moved to more peripheral areas: rural regions, islands, sparsely populated areas, and the peripheries of the continent (East-Central Europe and Northern Europe). On the other hand, there was also a gradual shift from west to east and from urban to rural regions during the period of the Covid pandemic: while the first wave mainly hit the metropolitan regions of Southern and Western Europe, from the second wave onwards, the rural areas and the East-Central European countries and regions of Europe were increasingly affected.

The West-East and urban-rural differences can be interpreted in terms of a kind of centre-periphery relationship, where the peripheries have the advantage of being hit later by pandemic waves. This initial centre-periphery inequality (associated with the hierarchical-type spatial diffusion model) has also been observed in the early spread of many previous epidemics (Shannon–Pyle 1989, Golub et al. 1993, Gould 1993, Welford 2018). All these differences are due to the fact that the diffusion of human-to-human epidemics is strongly connected to human mobility patterns and the urban hierarchy; the hubs of these transportation (and social) networks are concentrated in the central areas (Morrill et al. 1988, Haggett 2006, Nemes Nagy 2009, Zdanowska et al. 2021). The impact of these networks on epidemic diffusion has also been widely studied (Barabási 2003, Balcan et al. 2010, Bertuzzo et al. 2010, Brockmann–Helbing 2013, Childs et al. 2015).

This is also reflected in the excess mortality rates of the Covid-19 pandemic in Europe. During the first wave, few hotspots were severely affected by Covid-19 because of the timely and rigorous government actions (Amdaoud et al. 2021, Bourdin et al. 2021, Dániel et al. 2021, Igari 2021a, ESPON 2022). However, in later waves, the pandemic had spread across the continent (thanks to delayed closures), so another aspect of the centre-periphery relationship became more important. Some less developed, peripheral countries have the disadvantage of their healthcare systems being less developed and more difficult to access, and the health status of their populations is generally worse; therefore, the resilience of these regions is presumably lower (Kovács–Uzzoli 2020, Uzzoli et al. 2020, 2021, Pál et al. 2021, ESPON 2022, Kovács–Vántus 2022). The lag was further compounded by lower vaccination rates in East-Central Europe (especially in rural and peripheral regions), which may have contributed to higher mortality rates during the third and fourth waves (Igari 2021b, Dijkstra et al. 2022, Oroszi et al. 2022, Rydland et al. 2022). These inequalities often correlate with socioeconomic development.

However, there were peripheral regions that were not as severely affected; the geographically isolated peripheries in Northern and Western Europe had low excess mortality rates throughout the last two years. This may be due to several factors; on the one hand, peripheral regions had the advantage of a later arrival of the virus, while on the other hand, they had a good-quality healthcare system and high social resilience. Another positive factor may be the low population density of sparsely populated regions (ESPON 2020, 2022, Karácsonyi et al. 2021, Sigler et al. 2021).

All things considered, the study presented the challenges and methodological issues of using pandemic indicators and then analysed excess mortality in regions of Europe. There were significant spatial inequalities and a strong centre-periphery relationship in the excess mortality, although the centres (metropolitan and urban regions of Western and Southern Europe) were the most affected during the first wave. From the second wave, the main negative effects of the pandemic shifted to the peripheries: rural regions and the eastern and south-eastern parts of Europe. However, the geographically isolated peripheries (northern sparsely populated areas and islands), which have good healthcare systems, had low excess mortality throughout the study period. The reasons for the differences in excess mortality in Europe may be more complex, and further research is required to analyse them.

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