Impact of COVID-19 on total excess mortality and geographic disparities in Europe, 2020–2023: a spatio-temporal analysis

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Summary

Background COVID-19 dramatically reshaped mortality across Europe. This study aimed to assess its impact on total mortality in European countries taking into consideration the relationship with selected country-level socioeconomic indicators, non-pharmaceutical interventions, and vaccine uptake.

Methods We obtained weekly mortality data from 2010 to 2023 from the Short-term Mortality Fluctuations data series, the annual population data from the United Nations archives, selected sociodemographic and economic indicators from the World Bank's database, the stringency index and the percentage of the population fully vaccinated from Our World in Data. A quasi-Poisson regression model trained on pre-pandemic years was used to estimate expected number of deaths in 2020–2023 in 29 European countries. Excess mortality was estimated using three different metrics: excess deaths (number), relative excess mortality (% different from expected deaths) and age-standardized excess death rate per 10,000 population. The relationship between socioeconomic indicators and excess mortality was evaluated using linear regression models, which included both linear and quadratic terms for the predictors to account for possible non-linear relationships.

Findings We estimated 1,642,586 excess deaths (95% confidence interval, CI: 1,607,161–1,678,010) across all countries over the four years (+8.0% compared to the expected number of deaths). Excess mortality was mainly concentrated in 2020–2022 (0.52 million excess deaths in 2020, 0.57 million in 2021 and 0.44 million in 2022), with no substantial excess (0.11 million) estimated for 2023. Over the period 2020–23, the highest number of excess deaths was estimated for Italy (227,736 deaths, +8.7%), Poland (223,735 deaths, +13.7%), and Germany (218,111 deaths, +5.6%), while the highest excesses in relative terms were in Bulgaria (72,328 deaths, +17.2%), Lithuania (23,813 deaths, +16.1%), and Slovakia (31,984 deaths, +14.9%). The age-standardised death rates ranged from 1.8 per 10,000 population in Sweden to 24.7 in Bulgaria. The percentage of the population living below the poverty line and the Gini index were significantly associated with an increased excess death rate, with *p*-values for the linear and quadratic terms being 0.003 and 0.003 for the Gini index, and 0.024 and 0.017 for the population living below the poverty line. Conversely, gross domestic product per capita (*p*-values for the linear and quadratic terms: <0.001, 0.003), health expenditure (0.001, 0.273) and the percentage of people fully vaccinated by the end of 2021 (<0.001, 0.989) or 2022 (0.001, 0.890) were inversely associated with excess death rate. No significant association was observed with population density and stringency index.

Interpretation The observed geographic disparities in total mortality excess across Europe can be related to differences in socioeconomic contexts, as well as to suboptimal vaccine uptakes in some countries.

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Abbreviations: AUT, Austria; BEL, Belgium; BGR, Bulgaria; CHE, Switzerland; CZE, The Czech Republic; DEU, Germany; DNK, Denmark; ESP, Spain; EST, Estonia; FIN, Finland; FRA, France; GBR-ENW, England and Wales; GBR-NIR, Northern Ireland; GBR-SCO, Scotland; GRC, Greece; HRV, Croatia; HUN, Hungary; ISL, Iceland; ITA, Italy; LTU, Lithuania; LUX, Luxembourg; LVA, Latvia; NLD, The Netherlands; NOR, Norway; POL, Poland; PRT, Portugal; SVK, Slovakia; SVN, Slovenia; SWE, Sweden

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Research in context

Evidence before this study

We conducted a comprehensive search on PubMed for studies evaluating disparities in excess mortality across Europe from 2020 to 2023, without language restriction, including all studies published from January 2020 to April 2024. We used the following search terms in titles and abstracts: "excess deaths", "excess mortality" and "COVID-19". Of the 1184 studies identified through the electronic search, none provided a comprehensive and updated evaluation of the disparities in excess mortality within Europe.

Since the onset of the pandemic, international organizations and independent research groups have been tracking and estimating excess deaths to provide insights into the overall effect of the pandemic. While there has been consistency in reporting total excess deaths across many countries, a significant variation in the magnitude of these excesses was observed. Throughout different phases of the pandemic, the patterns of excess deaths have also varied, reflecting changes in the spread of SARS-CoV-2, the implementation of mitigation measures, and the efficacy of vaccination campaigns. Socioeconomic indicators, non-pharmaceutical interventions, and vaccination coverage have been hypothesized as possible determinants of disparities in excess mortality across countries.

Added value of this study

This study provides a comprehensive assessment of the impact of COVID-19 on overall mortality in Europe from 2020 to 2023. The results are based on weekly death counts spanning from 2010 to 2023, obtained from the Short-term Mortality Fluctuations data series, and population data from the United Nations archive. Estimates were provided for each country, European regions and all countries combined. The study estimated over 1.6 million excess deaths (+8.0% compared to the expected number of deaths) across all countries throughout the four-year study period. About half a million excess deaths occurred in each of the first three pandemic years, while only a modest excess was observed in 2023. The excess was notably higher in Eastern European countries (+13.2%) compared to Western (+6.3%), Northern (+7.0%) and Southern Europe (+7.8%). An elevated poverty level and unequal income distribution were associated with high excess mortality, while gross domestic product per capita, health expenditure and vaccine uptake were associated with reduced excess mortality.

Implications of all the available evidence

While the pandemic has consistently shaped mortality excesses throughout its initial three years, its impact was modest in 2023, indicating a trend towards pre-pandemic levels. Our spatio-temporal analysis provides additional evidence that can be interpreted within the specific socioeconomic contexts of European countries and the public health measures implemented in Europe during the COVID-19 pandemic.

Introduction

The Coronavirus Disease 2019 (COVID-19) outbreak originated in China and rapidly disseminated to Europe, with Northern Italy serving as the first epicentre for its transmission.[1] Despite its global transmission, the impact of the pandemic varied substantially across European countries. In 2020, the statistical office of the European Union (Eurostat), which receives data from the European Union Member States, reported mortality rates from RT-PCR-confirmed COVID-19 deaths ranging from less than 10 deaths per 100,000 in some Northern European countries such as Finland and Norway to over 140 per 100,000 in Slovenia and Belgium.[2] Subsequent estimates provided by different research groups showed that regional differences persisted in the following years of the pandemic.[3,4]

The causes of these disparities are multidimensional and can be related to variations in the timing of the pandemic's outbreak, the stringency of containment measures, the preparedness of healthcare systems, the age distribution of populations, as well as the timing and efficacy of vaccine delivery, particularly within vulnerable groups.[5,6] Another important factor contributing to regional differences lies in the variability of case identification, surveillance, monitoring, and readiness to act.

Indeed, while the number of COVID-19 deaths has served as a primary epidemiological indicator throughout the pandemic, it is important to acknowledge its limitations. During the initial waves, COVID-19 deaths were under-reported in several countries. In later waves, countries with intensive testing and high sensitization for COVID-19 diagnosis likely experienced overcounting.[7]

For these reasons, excess total mortality serves as a reliable indicator for evaluating the overall impact of the pandemic. This metric accounts for the under-reporting of COVID-19 cases and overdiagnosis in cases where COVID-19 was not the primary cause of death. It also encompasses the indirect effects of the pandemic on the management of other health conditions serving as a better comparative measure across countries with different health systems, resources and vaccination rates.[8,9]

On May 5, 2023, the WHO Director-General declared the end of the pandemic, and thus a transition from emergency mode to managing COVID-19 alongside other infectious diseases.[10] This declaration followed favourable trends in epidemiological indicators and increasing population immunity, although deaths from COVID-19 continued to be reported throughout 2023.

This study aims to evaluate the overall impact of COVID-19 on total excess mortality in Europe during the period 2020–2023 and to assess geographic disparities. As a secondary aim, we evaluate the relationship between excess mortality and selected countries' socioeconomic indicators, vaccine uptake, and the strength of non-pharmaceutical interventions implemented by countries.

Methods

Mortality data

The weekly death count from 2010 to 2023, disaggregated by country, sex and age groups (0–14, 15–64, 65–74, 75–84 and ≥85 years) was obtained from the Short-term Mortality Fluctuations (STMF@HMD) data series, released on April 15th, 2024. This international database provides open-access, harmonized, uniform, and fully documented data on all-cause mortality.[11,12] Deaths were recorded in the STMF data series based on their date of occurrence, except for England, Wales, Scotland and Northern Ireland, where they were recorded by registration date.

The STMF data are sourced from official statistics provided by national statistical institutes and have been used by various research groups to estimate excess mortality during the pandemic. However, to verify the validity of these data, we compared them with those available from the exceptional data collection on total weekly deaths established by Eurostat in April 2020.[13] For most countries and calendar years, the number of deaths from the two sources is identical, with the exception of France, where deaths from overseas territories were not included in the STMF data series (Supplementary Table S1).

Population data

Annual population data as of 1st July were obtained from the United Nations (UN) archives from 2010 to 2023,[14] except for the UK countries. The UN does not provide separate population estimates for England, Wales, Scotland, and Northern Ireland. Consequently, these data were directly downloaded from the website of the Office for National Statistics.[15] UN population estimates rely on census data and official intercensal estimates from national statistical offices and closely align with those reported by the Eurostat. In a comparison between sources, we found that the differences between UN and Eurostat mid-year population ranged from −2.9% for Lithuania in 2022 to +3.9% for Slovakia in 2022, with most falling within the range of ± 1%. The findings of this comparison are detailed in Supplementary Table S2.

Excess mortality

Excess deaths were computed as the difference between observed and the expected number of deaths based on pre-pandemic trends in mortality rates and changes in population size and age structure over the study period.

The number of expected deaths for each country was predicted using the following quasi-Poisson regression model fitted on mortality and population data of a reference pre-pandemic period:

$$\begin{aligned} \ln\left[E\left(deaths_{i,j,k,l}\right)\right] = \alpha + \beta_1 \times sex_i + \beta_2 \times age_j + \beta_3 \times \left(sex \times age_{i,j}\right) \\ + \beta_4 \times ns\left(week_k, df\right) \\ + \beta_5 \times year_l + \ln\left(pop_{i,j}\right) + \varepsilon_{i,j,k,l} \end{aligned}$$

The model included sex, age group, a sex-by-age group interaction term, a natural spline function (ns) with eight degrees of freedom (df) applied to weeks within a year, a linear term for year as predictors and the natural logarithm of the population size as offset term. The offset term allowed for the control of differences in population size and age distribution over time.

The reference pre-pandemic period used to predict the number of expected deaths spanned from 2010 to 2019. The only exceptions were Italy, Greece, and Northern Ireland, for which data were available from the 1st week of 2011, the 1st week of 2015 and the 2nd week of 2015, respectively. Mortality data were completed for all the weeks during which excess deaths were estimated (i.e., from the first week of 2020 to the last week of 2023). For England and Wales, Scotland, and Northern Ireland, the final week of 2023 was excluded due to delays in registering deaths that occurred at the end of the year, likely registered in the first week of 2024.

Empirical 95% confidence intervals (CI) for the point estimate of excess deaths were derived via Monte Carlo simulation. We generated 1000 realizations of the regression coefficients from a multivariate normal distribution using their point estimates and the variance-covariance matrix. For each realization, we calculated the difference between observed and expected deaths and obtained the 95% CI using the normal approximation.

Relative excess mortality was calculated as (observed deaths - expected deaths)/expected deaths * 100. To facilitate comparison across countries with varying population sizes and age distributions, excess deaths were also presented as age-standardized excess death rates per

10,000 population. The calculation was based on the revised European Standard Population – 2013 Edition.[16]

Estimates were provided for each country, as well as for all countries combined. Additionally, estimates were calculated for European regions using the classification adopted by the Statistics Division of the United Nations to group countries.[17] Accordingly, countries were grouped in Northern Europe (Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden, England and Wales, Scotland, Northern Ireland), Eastern Europe (Bulgaria, the Czech Republic, Hungary, Poland and Slovakia), Southern Europe (Croatia, Greece, Italy, Portugal, Slovenia and Spain) and Western Europe (Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland). To derive estimates for European regions, we summed up the estimates obtained for each individual country.

As a sensitivity analysis, we used the above-described model to estimate the differences between observed and expected deaths in 2019, using 2010–2018 mortality data, to estimate the regression coefficients. This additional analysis was conducted to verify that the model did not detect any important excess mortality in a pre-pandemic year.

Country-level indicators and excess mortality

Socio-economic indicators, including population density (people per km^2 of land area), population aged 65 and above (% of total population), population aged 25 and above with at least completed bachelor's degree (% of total population), population living below the national povery line (% of total population), gross domestic product (GDP) per capita (current US$), Gini index (an inequality measure on a scale from 0 to 100, with higher values indicating higher inequality), and current health expenditure (% of the GDP), were obtained from the DataBank of the World Bank.[18] For this analysis, we used the data recorded for 2020 (the first year of the pandemic). If not available, we used the data reported for 2019 or 2018.

Additionally, the stringency index, a metric reflecting the strength of non-pharmaceutical interventions implemented by countries during the pandemic, and the percentage of the population fully vaccinated according to the initial vaccination protocol (% of the total population) by the end of 2021 and 2022 were sourced from Our World in Data.[19] This public online repository gathers data from government sources, international institutions, statistical agencies, research articles, and specialized institutes across a range of topics.

The relationship between the aforementioned indicators and excess mortality was assessed using linear regression models. These models included the age-standardized excess death rate per 10,000 population as the response variable and one of the indicators as the predictor. To accommodate potential nonlinear relationships between the predictor and the response variable, a quadratic term for the predictor was also included in the regression models.

Role of the funding source

The funding source had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

Results

The study included 29 European countries with mortality data available until the final week of 2023. From 2020 to 2023, a total of 22,254,542 deaths were registered in the 29 European countries (5,720,658 deaths in 2020, 5,663,838 in 2021, 5,580,807 in 2022, and 5,289,239 in 2023).

Excess mortality was estimated as the absolute number of excess deaths (Table 1), relative excess deaths (expressed as the % difference from expected deaths) (Table 2) or age-standardized excess death rate per 10,000 population (Table 3).

We estimated 1,642,586 excess deaths (+8.0% compared to the expected number of deaths) across all countries over the four-year period (2020–2023). Important excesses were estimated in 2020 (521,889 deaths, +10.0%), 2021 (568,186 deaths, +11.2%) and 2022 (443,883 deaths, +8.6%), while a smaller excess was estimated for 2023 (108,629 deaths, +2.1%). Throughout 2020–2023, the countries with the highest number of excess deaths were Italy (227,736 deaths), Poland (223,735 deaths) and Germany (218,111 deaths). In relative terms, the countries with the highest excess were Bulgaria (+17.2%), Lithuania (+16.1%) and Slovakia (+14.9%). These countries also had the highest age-standardized excess death rates: Bulgaria (24.7 deaths per 10,000 population), Lithuania (19.9 deaths per 10,000 population) and Slovakia (17.6 deaths per 10,000 population). Eastern Europe was the region with the highest excess mortality (+13.2% over the entire 2020–2023 period, compared to 6.3 to 7.8% estimated for other regions). This was particularly evident in 2021, when excess mortality reached +29% in Eastern Europe, while remaining around 6–8% in other regions. Fig. 1 shows the full ranking of countries based on all three measures of excess mortality considered during the period 2020–2023.

Detailed estimates of excess mortality for each country and across different weeks over the whole period are shown in Supplementary Figs. S1–S4 (S1 Northern Europe, S2 Eastern Europe, S3 Southern Europe, S4 Western Europe).

Fig. 2 presents a choropleth map in which countries are coloured differently according to the relative excess mortality estimated for the whole 2020–2023 period and by calendar year. In 2020, Austria, Belgium, Bulgaria, Switzerland, the Czech Republic, Spain, England and

Country	2020	2021	2022	2023	2020–2023
AUT	8842 (8299; 9384)	9542 (8937; 10,146)	11,586 (10,903; 12,268)	7504 (6737; 8270)	37,472 (34,881; 40,062)
BEL	17,192 (16,533; 17,850)	3315 (2576; 4053)	6814 (5973; 7654)	1154 (208; 2099)	28,473 (25,296; 31,649)
BGR	15,973 (15,343; 16,602)	42,485 (41,785; 43,184)	14,745 (13,970; 15,519)	−873 (−1720; −25)	72,328 (69,382; 75,273)
CHE	7897 (7444; 8349)	2369 (1856; 2881)	4941 (4353; 5528)	1469 (803; 2134)	16,675 (14,460; 18,889)
CZE	18,227 (17,579; 18,874)	28,771 (28,049; 29,492)	9924 (9112; 10,735)	2093 (1186; 2999)	59,014 (55,933; 62,094)
DEU	25,952 (22,018; 29,885)	56,672 (52,236; 61,107)	95,035 (89,980; 100,089)	40,452 (34,728; 46,175)	218,111 (199,007; 237,214)
DNK	163 (−225; 551)	2392 (1951; 2832)	4101 (3597; 4604)	2227 (1657; 2796)	8882 (6982; 10,781)
ESP	61,437 (59,362; 63,511)	17,690 (15,352; 20,027)	27,176 (24,518; 29,833)	−740 (−3718; 2238)	105,561 (95,531; 115,590)
EST	684 (504; 863)	3539 (3340; 3737)	2421 (2198; 2643)	1364 (1114; 1613)	8006 (7156; 8855)
FIN	981 (617; 1344)	3027 (2615; 3438)	7986 (7515; 8456)	5180 (4647; 5712)	17,172 (15,397; 18,946)
FRA	53,443 (50,993; 55,892)	42,109 (39,348; 44,869)	51,188 (48,026; 54,349)	9772 (6190; 13,353)	156,511 (144,584; 168,437)
GBR-ENW	62,358 (59,516; 65,199)	45,839 (42,664; 49,013)	27,337 (23,674; 30,999)	22,866 (18,712; 27,019)	158,399 (144,618; 172,179)
GBR-NIR	1674 (1373; 1974)	1583 (1202; 1963)	1159 (689; 1628)	1167 (609; 1724)	5582 (3883; 7280)
GBR-SCO	5103 (4680; 5525)	4430 (3951; 4908)	3085 (2535; 3634)	2732 (2114; 3349)	15,348 (13,286; 17,409)
GRC	6047 (4896; 7197)	18,585 (17,142; 20,027)	14,105 (12,323; 15,886)	−572 (−2719; 1575)	38,164 (31,661; 44,666)
HRV	5122 (4740; 5503)	11,489 (11,065; 11,912)	6077 (5600; 6553)	428 (−103; 959)	23,115 (21,304; 24,925)
HUN	10,853 (10,119; 11,586)	26,557 (25,742; 27,371)	7383 (6460; 8305)	−1467 (−2500; −433)	43,325 (39,828; 46,821)
ISL	−57 (−121; 7)	−51 (−125; 23)	268 (182; 353)	105 (7; 202)	263 (−58; 584)
ITA	99,415 (96,263; 102,566)	62,526 (58,947; 66,104)	62,913 (58,795; 67,030)	2884 (−1806; 7574)	227,736 (212,227; 243,244)
LTU	5262 (4961; 5562)	10,199 (9873; 10,524)	6172 (5816; 6527)	2181 (1791; 2570)	23,813 (22,444; 25,181)
LUX	354 (259; 448)	238 (131; 344)	134 (12; 255)	71 (−66; 208)	795 (336; 1253)
LVA	1301 (1055; 1546)	7553 (7283; 7822)	3749 (3448; 4049)	1196 (862; 1529)	13,797 (12,649; 14,944)
NLD	13,887 (13,088; 14,685)	14,648 (13,743; 15,552)	10,795 (9751; 11,838)	7170 (5977; 8362)	46,498 (42,567; 50,428)
NOR	−325 (−640; −9)	1030 (674; 1385)	4348 (3943; 4752)	1918 (1461; 2374)	6970 (5440; 8499)
POL	73,742 (71,995; 75,488)	117,525 (115,579; 119,470)	39,683 (37,446; 41,919)	−7213 (−9762; −4663)	223,735 (215,272; 232,197)
PRT	10,658 (9885; 11,430)	11,552 (10,683; 12,420)	11,009 (10,020; 11,997)	4092 (2978; 5205)	37,310 (33,573; 41,046)
SVK	5597 (5214; 5979)	19,905 (19,477; 20,332)	6172 (5687; 6656)	311 (−235; 857)	31,984 (30,145; 33,822)
SVN	3604 (3390; 3817)	2897 (2659; 3134)	2193 (1923; 2462)	1014 (710; 1317)	9706 (8684; 10,727)
SWE	6520 (6008; 7031)	−216 (−789; 357)	1397 (743; 2050)	157 (−577; 891)	7857 (5388; 10,325)
Eastern Europe	129,510 (127,348; 131,671)	246,729 (244,313; 249,144)	83,983 (81,221; 86,744)	−6723 (−9851; −3594)	453,498 (443,052; 463,943)
Northern Europe	83,658 (80,660; 86,655)	79,320 (75,961; 82,678)	62,019 (58,145; 65,892)	41,088 (36,700; 45,475)	266,083 (251,519; 280,646)
Southern Europe	181,159 (177,157; 185,160)	113,248 (108,675; 117,820)	117,393 (112,104; 122,681)	6677 (634; 12,719)	418,475 (398,616; 438,333)
Western Europe	127,564 (122,699; 132,428)	128,890 (123,419; 134,360)	180,491 (174,260; 186,721)	67,589 (60,544; 74,633)	504,531 (480,972; 528,089)
All countries	521,889 (514,642; 529,135)	568,186 (560,008; 576,363)	443,883 (434,486; 453,279)	108,629 (97,931; 119,326)	1,642,586 (1,607,161; 1,678,010)

Country Abbreviations: AUT (Austria), BEL (Belgium), BGR (Bulgaria), CHE (Switzerland), CZE (the Czech Republic), DEU (Germany), DNK (Denmark), ESP (Spain), EST (Estonia), FIN (Finland), FRA (France), GBR-ENW (England and Wales), GBR-NIR (Northern Ireland), GBR-SCO (Scotland), GRC (Greece), HRV (Croatia), HUN (Hungary), ISL (Iceland), ITA (Italy), LTU (Lithuania), LUX (Luxembourg), LVA (Latvia), NLD (The Netherlands), NOR (Norway), POL (Poland), PRT (Portugal), SVK (Slovakia), SVN (Slovenia), SWE (Sweden). **European regions:** Eastern Europe (BGR, CZE, HUN, POL, SVK), Northern Europe (DNK, EST, FIN, GBR–ENW, GBR–NIR, GBR–SCO, ISL, LVA, LTU, NOR, SWE), Southern Europe (GRC, HRV, ITA, PRT, SVN, ESP), Western Europe (AUT, BEL, FRA, DEU, LUX, NLD, CHE).

Table 1: **Excess deaths (number) in the years 2020–2023 and for the 2020–2023 period, by country and European region and in all countries combined.**

Wales, Northern Ireland, Italy, Lithuania, Poland, Slovakia and Slovenia had excess mortality exceeding 10%. In 2021, several countries, including Bulgaria, the Czech Republic, Croatia, Hungary, Poland, Slovakia, and the Baltic Republics, experienced higher excesses, with Bulgaria reaching a peak of +40%. In 2022, excess mortality exceeding 10% persisted in Austria, Bulgaria, Finland, Greece, Croatia, Iceland, Norway, Slovakia, Slovenia, and the Baltic Republics. However, by 2023, no country exhibited excesses ≥10%.

Fig. 3 shows the relationship between the socioeconomic indicators, the stringency index, vaccination uptake, and age-standardized excess death rate. The percentage of the population living in poverty and the Gini index were significantly associated with an increased excess death rate. Conversely, GDP per capita, health expenditure and the percentage of people fully vaccinated by the end of 2021 or 2022 were associated with a decreased excess death rate. No significant associations were found for the remaining indicators considered. The results of the regression models used to draw the lines and confidence bands of the figure are presented in Supplementary Table S3.

When we applied the model used in the main analysis to estimate the difference between the observed deaths in the year preceding the COVID-19 pandemic (i.e., 2019) and those expected according to our model, we did not observe any substantial deviation from the expected mortality (Supplementary Figs. S5 and S6). The estimations of CI directly from the variance of

Country	2020	2021	2022	2023	2020–2023
AUT	10.7 (10.0; 11.5)	11.9 (11.1; 12.8)	14.5 (13.5; 15.5)	9.3 (8.3; 10.4)	11.6 (10.7; 12.5)
BEL	15.5 (14.8; 16.1)	3.1 (2.4; 3.8)	6.2 (5.4; 7.1)	1.0 (0.2; 1.9)	6.5 (5.7; 7.3)
BGR	14.5 (13.9; 15.2)	40.0 (39.1; 40.9)	14.2 (13.4; 15.1)	−0.9 (−1.7; 0.0)	17.2 (16.4; 18)
CHE	11.4 (10.6; 12.1)	3.5 (2.7; 4.2)	7.1 (6.2; 8.1)	2.1 (1.1; 3.1)	6.0 (5.2; 6.9)
CZE	16.1 (15.4; 16.8)	26.1 (25.2; 26.9)	9.0 (8.2; 9.8)	1.9 (1.1; 2.8)	13.3 (12.5; 14.1)
DEU	2.7 (2.2; 3.1)	5.9 (5.4; 6.4)	9.8 (9.2; 10.4)	4.1 (3.5; 4.7)	5.6 (5.1; 6.1)
DNK	0.3 (−0.4; 1.0)	4.4 (3.5; 5.2)	7.4 (6.5; 8.4)	4.0 (2.9; 5.1)	4.0 (3.1; 4.9)
ESP	14.0 (13.5; 14.6)	4.1 (3.6; 4.7)	6.3 (5.6; 6.9)	−0.2 (−0.8; 0.5)	6.1 (5.5; 6.7)
EST	4.4 (3.2; 5.7)	23.8 (22.2; 25.5)	16.4 (14.7; 18.2)	9.2 (7.4; 11.1)	13.4 (11.8; 15)
FIN	1.8 (1.1; 2.4)	5.5 (4.8; 6.4)	14.5 (13.5; 15.5)	9.3 (8.3; 10.4)	7.8 (6.9; 8.7)
FRA	8.7 (8.3; 9.2)	7.0 (6.5; 7.5)	8.5 (7.9; 9.0)	1.6 (1.0; 2.2)	6.4 (5.9; 7.0)
GBR-ENW	11.3 (10.7; 11.9)	8.5 (7.9; 9.2)	5.0 (4.3; 5.7)	4.2 (3.4; 4.9)	7.2 (6.6; 7.9)
GBR-NIR	10.4 (8.4; 12.5)	9.9 (7.4; 12.6)	7.2 (4.2; 10.5)	7.3 (3.7; 11.2)	8.7 (5.9; 11.7)
GBR-SCO	8.5 (7.8; 9.3)	7.5 (6.6; 8.4)	5.2 (4.2; 6.1)	4.6 (3.5; 5.7)	6.4 (5.5; 7.4)
GRC	4.8 (3.8; 5.7)	14.9 (13.5; 16.2)	11.2 (9.6; 12.8)	−0.4 (−2.1; 1.3)	7.5 (6.2; 8.9)
HRV	9.7 (8.9; 10.5)	22.5 (21.5; 23.5)	11.9 (10.9; 13.0)	0.8 (−0.2; 1.9)	11.2 (10.3; 12.2)
HUN	8.2 (7.6; 8.8)	20.7 (19.9; 21.4)	5.7 (5.0; 6.5)	−1.1 (−1.9; −0.3)	8.4 (7.6; 9.1)
ISL	−2.4 (−4.9; 0.3)	−2.1 (−5.1; 1)	11.1 (7.3; 15.1)	4.3 (0.3; 8.6)	2.7 (−0.6; 6.2)
ITA	15.1 (14.6; 15.7)	9.7 (9.1; 10.3)	9.7 (9.0; 10.4)	0.4 (−0.3; 1.2)	8.7 (8.1; 9.4)
LTU	13.5 (12.6; 14.4)	27.4 (26.3; 28.5)	17.0 (15.9; 18.2)	6.1 (5.0; 7.3)	16.1 (15.0; 17.2)
LUX	8.2 (5.9; 10.6)	5.6 (3.0; 8.3)	3.1 (0.3; 6.1)	1.6 (−1.5; 4.9)	4.6 (1.9; 7.5)
LVA	4.6 (3.7; 5.6)	28.1 (26.8; 29.4)	14.1 (12.9; 15.4)	4.5 (3.2; 5.9)	12.8 (11.6; 14.0)
NLD	8.8 (8.3; 9.4)	9.4 (8.8; 10.1)	6.8 (6.1; 7.5)	4.4 (3.7; 5.2)	7.3 (6.7; 8.0)
NOR	−0.8 (−1.5; 0.0)	2.5 (1.6; 3.4)	10.5 (9.5; 11.6)	4.6 (3.5; 5.8)	4.2 (3.3; 5.2)
POL	17.9 (17.4; 18.4)	29.3 (28.7; 29.9)	9.7 (9.1; 10.3)	−1.7 (−2.3; −1.1)	13.7 (13.1; 14.3)
PRT	9.3 (8.5; 10.0)	10.2 (9.4; 11.1)	9.7 (8.7; 10.7)	3.6 (2.6; 4.6)	8.2 (7.3; 9.1)
SVK	10.2 (9.5; 11.0)	37.5 (36.4; 38.6)	11.6 (10.6; 12.6)	0.6 (−0.4; 1.6)	14.9 (13.9; 15.9)
SVN	17.3 (16.1; 18.5)	14.3 (13.0; 15.7)	10.8 (9.4; 12.3)	5.0 (3.4; 6.6)	11.9 (10.5; 13.3)
SWE	7.2 (6.6; 7.8)	−0.2 (−0.9; 0.4)	1.6 (0.8; 2.3)	0.2 (−0.6; 1.0)	2.2 (1.5; 2.9)
Eastern Europe	14.8 (14.5; 15.1)	29.0 (28.6; 29.4)	9.8 (9.5; 10.2)	−0.8 (−1.1; −0.4)	13.2 (12.8; 13.5)
Northern Europe	8.8 (8.4; 9.1)	8.5 (8.1; 8.9)	6.6 (6.1; 7.0)	4.3 (3.8; 4.8)	7.0 (6.6; 7.4)
Southern Europe	13.3 (13.0; 13.7)	8.5 (8.1; 8.9)	8.7 (8.3; 9.2)	0.5 (0.0; 0.9)	7.8 (7.4; 8.2)
Western Europe	6.3 (6.1; 6.6)	6.5 (6.2; 6.8)	9.0 (8.7; 9.4)	3.3 (3.0; 3.7)	6.3 (6.0; 6.6)
All countries	10.0 (9.9; 10.2)	11.2 (11.0; 11.3)	8.6 (8.4; 8.8)	2.1 (1.9; 2.3)	8.0 (7.8; 8.2)

Country Abbreviations: AUT (Austria), BEL (Belgium), BGR (Bulgaria), CHE (Switzerland), CZE (the Czech Republic), DEU (Germany), DNK (Denmark), ESP (Spain), EST (Estonia), FIN (Finland), FRA (France), GBR-ENW (England and Wales), GBR-NIR (Northern Ireland), GBR-SCO (Scotland), GRC (Greece), HRV (Croatia), HUN (Hungary), ISL (Iceland), ITA (Italy), LTU (Lithuania), LUX (Luxembourg), LVA (Latvia), NLD (The Netherlands), NOR (Norway), POL (Poland), PRT (Portugal), SVK (Slovakia), SVN (Slovenia), SWE (Sweden). **European regions:** Eastern Europe (BGR, CZE, HUN, POL, SVK), Northern Europe (DNK, EST, FIN, GBR–ENW, GBR–NIR, GBR–SCO, ISL, LVA, LTU, NOR, SWE), Southern Europe (GRC, HRV, ITA, PRT, SVN, ESP), Western Europe (AUT, BEL, FRA, DEU, LUX, NLD, CHE).

***Table 2:* Relative excess deaths (% difference from expected deaths) in the years 2020–2023 and for the 2020–2023 period by country and European region and in all countries combined.**

model prediction of the expected deaths were generally narrower compared to the ones estimated through Monte Carlo simulation (Supplementary Figs. S7).

Discussion

This study estimated over 1.6 million excess deaths (+8.0%), during the period from 2020 to 2023 in 29 European countries with approximately half a million excess deaths occurring in each of the first three pandemic years, and only a modest excess in 2023. It also highlighted important disparities across Europe, showing a greater impact of COVID-19 in Eastern Europe and the Baltic Republics compared to other European regions. Additionally, our study revealed an increased excess in countries with high poverty levels and income inequality, while also indicating an inverse relationship between a country's wealth and its health expenditure, vaccination uptake, and excess mortality.

In managing the COVID-19 pandemic, European countries implemented varying strategies, each tailored to their available resources and the spatio-temporal spread of SARS-CoV-2 within the country. During the initial months of the pandemic in Europe in early Spring 2020, there was relatively uniform enforcement of stringent non-pharmaceutical measures across all European countries. These measures included restrictions of internal movements and gatherings,

Country	2020	2021	2022	2023	2020–2023
AUT	9.75 (9.15; 10.35)	10.52 (9.86; 11.19)	12.57 (11.83; 13.31)	7.92 (7.10; 8.73)	10.18 (9.47; 10.89)
BEL	13.98 (13.43; 14.54)	2.82 (2.20; 3.43)	5.20 (4.51; 5.88)	0.63 (−0.13; 1.38)	5.57 (4.92; 6.22)
BGR	21.39 (20.53; 22.24)	57.11 (56.15; 58.08)	20.54 (19.45; 21.63)	−1.03 (−2.24; 0.18)	24.73 (23.70; 25.75)
CHE	8.86 (8.35; 9.38)	2.67 (2.10; 3.25)	5.30 (4.66; 5.95)	1.47 (0.76; 2.19)	4.52 (3.91; 5.14)
CZE	19.35 (18.69; 20.01)	28.61 (27.87; 29.34)	10.72 (9.90; 11.53)	2.72 (1.82; 3.61)	15.24 (14.46; 16.02)
DEU	2.69 (2.29; 3.10)	6.11 (5.66; 6.56)	9.77 (9.26; 10.27)	4.65 (4.09; 5.21)	5.78 (5.30; 6.26)
DNK	0.64 (−0.05; 1.32)	4.58 (3.82; 5.34)	7.26 (6.42; 8.11)	3.89 (2.95; 4.82)	4.13 (3.33; 4.94)
ESP	11.32 (10.93; 11.71)	3.40 (2.96; 3.83)	4.64 (4.15; 5.13)	−0.19 (−0.73; 0.35)	4.72 (4.26; 5.19)
EST	4.91 (3.60; 6.21)	25.33 (23.89; 26.76)	17.04 (15.45; 18.62)	9.65 (7.91; 11.39)	14.19 (12.67; 15.7)
FIN	1.43 (0.83; 2.04)	4.66 (3.99; 5.33)	12.3 (11.56; 13.05)	7.75 (6.93; 8.57)	6.62 (5.91; 7.33)
FRA	6.69 (6.36; 7.03)	4.96 (4.58; 5.33)	5.82 (5.40; 6.24)	0.63 (0.16; 1.10)	4.46 (4.06; 4.86)
GBR-ENW	10.71 (10.22; 11.20)	7.87 (7.32; 8.42)	4.64 (4.03; 5.26)	3.79 (3.10; 4.47)	6.69 (6.11; 7.27)
GBR-NIR	10.08 (8.27; 11.89)	9.13 (6.89; 11.37)	6.7 (3.99; 9.41)	6.60 (3.44; 9.76)	8.09 (5.61; 10.57)
GBR-SCO	9.61 (8.81; 10.40)	8.12 (7.23; 9.00)	5.72 (4.72; 6.72)	4.98 (3.87; 6.09)	7.05 (6.11; 8.00)
GRC	4.92 (3.99; 5.85)	15.28 (14.13; 16.44)	11.02 (9.60; 12.43)	−0.22 (−1.89; 1.44)	7.71 (6.42; 9.00)
HRV	11.8 (10.92; 12.68)	26.34 (25.36; 27.32)	13.82 (12.73; 14.91)	0.90 (−0.31; 2.10)	13.16 (12.12; 14.20)
HUN	11.47 (10.69; 12.25)	27.10 (26.23; 27.97)	7.61 (6.64; 8.58)	−1.69 (−2.77; −0.62)	11.01 (10.09; 11.93)
ISL	−2.52 (−4.89; −0.16)	−2.32 (−4.96; 0.32)	9.34 (6.36; 12.32)	3.1 (−0.21; 6.42)	1.95 (−0.88; 4.77)
ITA	12.82 (12.40; 13.23)	8.38 (7.91; 8.84)	7.78 (7.25; 8.30)	0.54 (−0.04; 1.13)	7.30 (6.80; 7.80)
LTU	17.50 (16.51; 18.49)	33.98 (32.9; 35.07)	20.49 (19.29; 21.69)	7.33 (6.01; 8.64)	19.85 (18.71; 20.99)
LUX	7.40 (5.51; 9.29)	4.75 (2.67; 6.83)	2.5 (0.19; 4.81)	1.27 (−1.28; 3.81)	3.9 (1.69; 6.11)
LVA	6.20 (5.00; 7.40)	37.16 (35.83; 38.48)	18.51 (17.03; 19.99)	6.11 (4.48; 7.75)	16.96 (15.55; 18.37)
NLD	8.55 (8.07; 9.04)	8.74 (8.21; 9.28)	6.45 (5.85; 7.06)	4.20 (3.53; 4.87)	6.92 (6.34; 7.49)
NOR	−0.68 (−1.33; −0.02)	2.23 (1.51; 2.95)	8.88 (8.08; 9.68)	3.89 (3.01; 4.77)	3.64 (2.88; 4.41)
POL	21.56 (21.06; 22.07)	33.55 (32.99; 34.11)	11.36 (10.74; 11.99)	−1.67 (−2.36; −0.97)	15.90 (15.30; 16.49)
PRT	8.68 (8.04; 9.33)	9.37 (8.66; 10.09)	8.68 (7.88; 9.47)	3.27 (2.39; 4.16)	7.47 (6.71; 8.23)
SVK	12.81 (11.93; 13.69)	43.4 (42.43; 44.37)	14.22 (13.14; 15.31)	0.82 (−0.37; 2.01)	17.60 (16.57; 18.63)
SVN	16.82 (15.83; 17.82)	13.32 (12.22; 14.42)	9.85 (8.63; 11.08)	4.37 (3.02; 5.72)	11.01 (9.84; 12.17)
SWE	6.13 (5.64; 6.61)	−0.13 (−0.66; 0.40)	1.29 (0.70; 1.88)	0.17 (−0.48; 0.81)	1.82 (1.26; 2.39)
Eastern Europe	18.66 (18.35; 18.97)	34.56 (34.21; 34.90)	11.98 (11.59; 12.37)	−0.79 (−1.22; −0.36)	15.92 (15.56; 16.29)
Northern Europe	8.45 (8.14; 8.75)	7.97 (7.64; 8.31)	6.16 (5.78; 6.54)	3.99 (3.56; 4.41)	6.60 (6.24; 6.96)
Southern Europe	11.42 (11.17; 11.68)	7.4 (7.11; 7.69)	7.11 (6.78; 7.44)	0.53 (0.16; 0.90)	6.55 (6.24; 6.86)
Western Europe	5.72 (5.50; 5.94)	5.91 (5.66; 6.16)	7.94 (7.66; 8.21)	3.04 (2.74; 3.35)	5.63 (5.37; 5.90)
All countries	9.55 (9.42; 9.68)	10.54 (10.39; 10.69)	7.88 (7.71; 8.05)	1.91 (1.72; 2.10)	7.42 (7.26; 7.58)

Country Abbreviations: AUT (Austria), BEL (Belgium), BGR (Bulgaria), CHE (Switzerland), CZE (the Czech Republic), DEU (Germany), DNK (Denmark), ESP (Spain), EST (Estonia), FIN (Finland), FRA (France), GBR-ENW (England and Wales), GBR-NIR (Northern Ireland), GBR-SCO (Scotland), GRC (Greece), HRV (Croatia), HUN (Hungary), ISL (Iceland), ITA (Italy), LTU (Lithuania), LUX (Luxembourg), LVA (Latvia), NLD (The Netherlands), NOR (Norway), POL (Poland), PRT (Portugal), SVK (Slovakia), SVN (Slovenia), SWE (Sweden). **European regions:** Eastern Europe (BGR, CZE, HUN, POL, SVK), Northern Europe (DNK, EST, FIN, GBR–ENW, GBR–NIR, GBR–SCO, ISL, LVA, LTU, NOR, SWE), Southern Europe (GRC, HRV, ITA, PRT, SVN, ESP), Western Europe (AUT, BEL, FRA, DEU, LUX, NLD, CHE).

Table 3: **Age-standardized excess death rates (per 10,000 population) in the years 2020–2023 and for the 2020–2023 period by country and European region and in all countries combined.**

physical distancing, remote working and mandating mask-wearing, all aimed at containing the spread and impact of the virus. The Northern/Eastern areas, where the extensive spread of COVID-19 started later, highly benefited from the timely implementation of these public health measures.[20] Conversely, countries that experienced the earliest circulation of COVID-19 (e.g., Italy and Spain) had to face medical equipment shortages, including protective masks, intensive care hospital beds and respiratory ventilators, as well as a lack of safety protocols for infectious disease control, resulting in the highest number of causalities.[21,22] Consistently, during this initial phase of the pandemic, the mortality excesses in Southern and Western countries ranged from 30 to 40%, while they were smaller in Eastern and Northern Europe, apart from Sweden. In Sweden, the excess mortality registered in the country has been attributed to the less intense government restrictions implemented at the beginning of the outbreak.[23]

Interestingly, our analysis failed to identify a significant relationship between the stringency of non-pharmaceutical interventions implemented by European countries and excess mortality. For this analysis, we employed a composite index based on nine interventions, such as school closures, workplace shutdowns, cancellation of public events, restrictions on

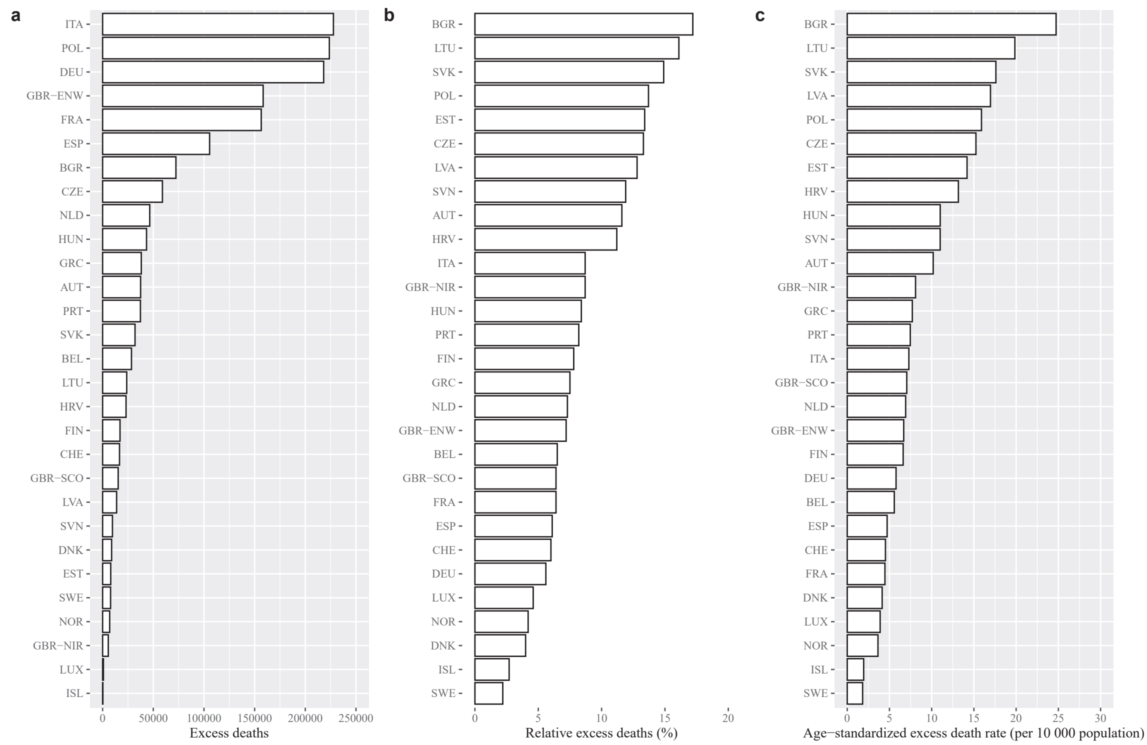

Fig. 1: Ranking of countries by excess deaths (number) (Panel a), relative excess deaths (% difference from expected deaths) (Panel b) and age-standardized excess death rate per 10,000 population (Panel c), estimated during the period 2020–2023.

gatherings, public transport closures, stay-at-home mandates, public awareness campaigns, limitations on domestic travel, and international travel restrictions.

As the summer of 2020 approached, the limited number of documented cases and deaths led to a widespread easing of the internal restrictions and the reopening of the borders, motivated by political and economic factors. However, in early autumn 2020, most European countries faced a second wave of the pandemic, prompting the quick reinstatement of stricter measures. During this pandemic phase, there was a significant shift in the geographic patterns of mortality excesses. By the last quarter of the year, Central and Eastern European countries surpassed the numbers recorded in the countries where the pandemic first started. This East/West gradient in mortality excess was likely related to poorer compliance of the population with the authorities' recommendations in Eastern countries, coupled with a higher vulnerability of their health infrastructures and logistics. In the Northern countries, the observed low mortality excess was attributed not only to the timely application of containment measures but also to the lower population density, although we did not find any relationship between population density and excess mortality.

The COVID-19 vaccination campaigns followed a similar timeline in the European countries. In the first half of 2021, vaccine administration prioritized selected high-risk categories, such as healthcare workers, the elderly, and immunocompromised individuals. From the second half of that year onwards and throughout the pandemic, vaccines were freely available to the general population. By the end of 2021, approximately 60% of the population in most European countries completed the initial COVID-19 vaccination protocol.[24] However, some Central and Southern European countries showed lower coverage rates, while in the Eastern Bloc, levels remained considerably lower, with Romania and Bulgaria showing the lowest levels of vaccination uptake (26% and 18%, respectively).[25] In countries with low vaccination rates, mortality excess remained consistently high throughout the pandemic, with periodic peaks observed, particularly in the midseason.

The European Union coordinated the COVID-19 response in the Member States, providing financial and logistical resources for vaccine production, purchase, and distribution. This centralized approach ensured uniform access to vaccines, implying that disparities in vaccination coverage cannot be attributed to variations in supply. Rather, reluctance towards vaccination among certain populations, related to underlying socioeconomic and cultural factors such as low confidence in healthcare systems, logistical constraints, and resistance to government regulations, likely contributed

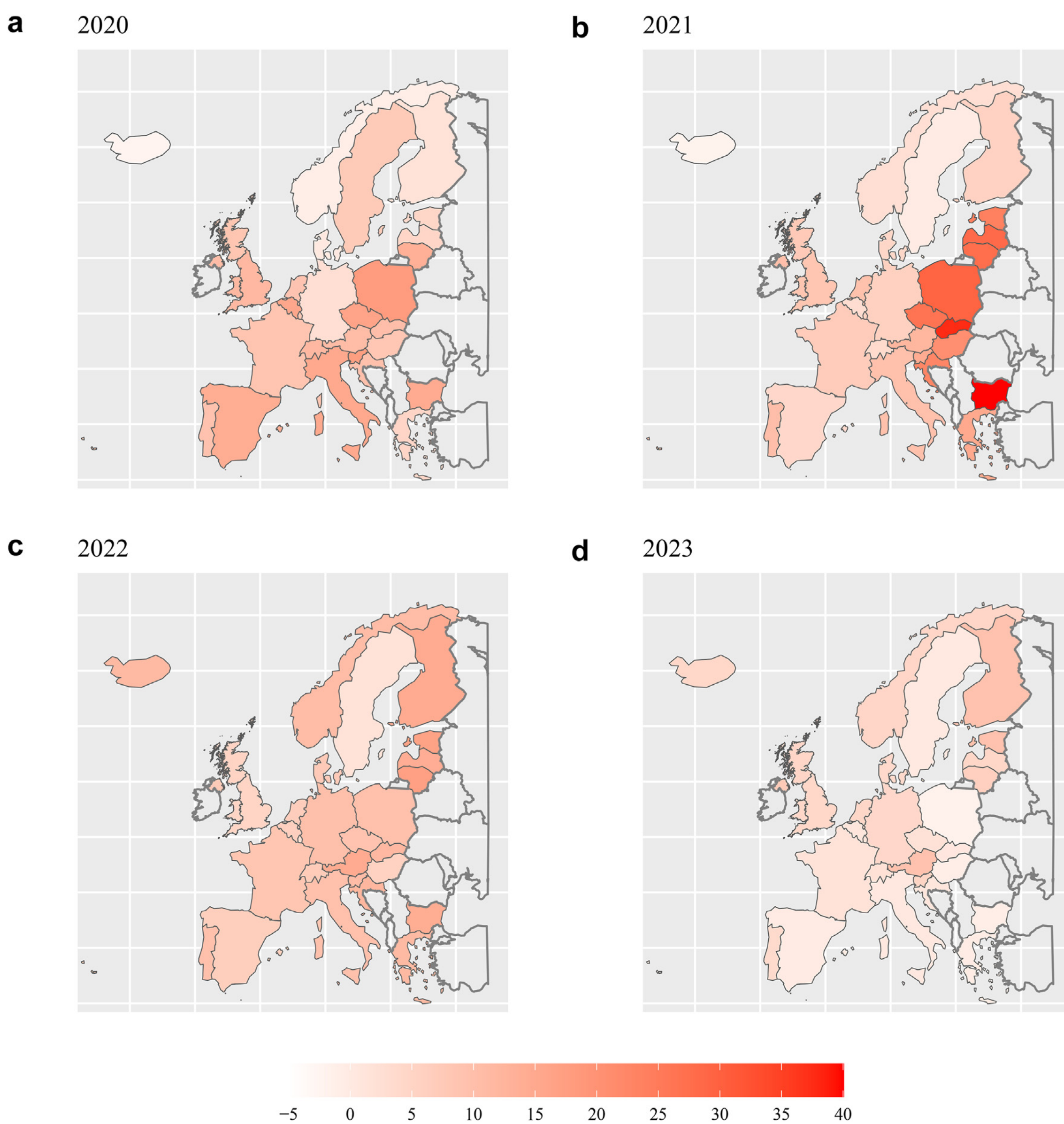

Fig. 2: Relative excess deaths (% difference from expected deaths) across European countries from 2020 to 2023.

to lower uptake rates.[21,26] By the end of 2021, the implementation of the European COVID-19 Digital Certificate, which was compulsory for entering public places or travelling, incentivised individuals to get fully vaccinated. However, vaccination rates by the end of 2021 varied from 28% in Bulgaria to 83% in Portugal, and by the end of 2022, they remained below 50% in Bulgaria and Slovakia. Our analysis confirms the inverse association between vaccine uptake and excess mortality. Lagging vaccination campaigns and delayed booster administration have been linked to higher excess mortality rates, whereas high vaccination rates have been associated with reduced virus-associated mortality.[27]

In the latter half of the pandemic, governments had more opportunities than during the initial phase to develop comprehensive strategies and adapt to the challenges posed by the pandemic. Despite the diverse resources and national characteristics of the healthcare systems in various countries, our findings suggest that the discrepancy in healthcare spending across European regions is an important determinant of the observed disparity in excess mortality during the pandemic. The pandemic underscored the critical importance of having a well-structured and organized network of healthcare infrastructures. Countries with well-funded healthcare systems exhibited a more robust ability to navigate the

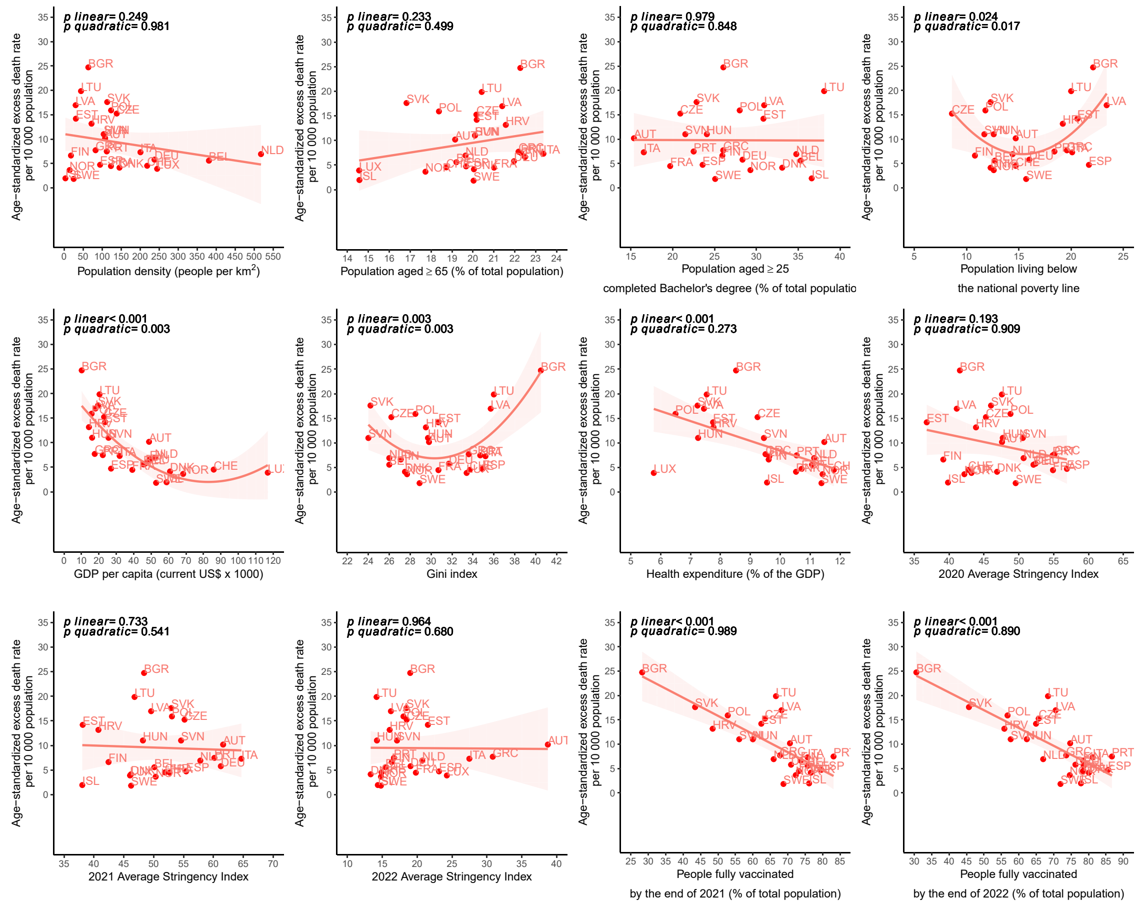

Fig. 3: Country-level socioeconomic indicators, stringency of non-pharmaceutical interventions to control the pandemic, vaccination uptake, and excess mortality. The regression lines and the 95% confidence bands were derived from linear regression models, with the age-standardized excess death rate (per 10,000 population) as the response variable, and linear and quadratic terms for one of the indicators as predictors. When the quadratic term was not significant, the model was simplified by removing it. The reported *p*-value in the figure for the linear term corresponds to that of the simplified model.

crisis, being better equipped to handle the challenges posed by the pandemic.[28]

In our analysis, as in previous studies, countries with high GDP per capita experienced reduced excess mortality.[29,30] This underscores the difficulties faced by limited-resource systems, characterized by inadequate workforce capacity and outdated infrastructure, to cope with the escalating costs associated with the long-term management of the pandemic. Additionally, poverty rates and the Gini index, an indicator of the wealth distribution within a population, resulted as important determinants of disparities across countries. Public health measures may have been less effective among communities with higher levels of inequality and socioeconomic vulnerability.[29]

The contagiousness of the SARS-CoV-2 virus and the severity of infection have varied during the pandemic period with the emergence of new variants. The Omicron variants, which have been prevalent across Europe since early 2022, have exhibited reduced clinical severity, resulting in milder symptoms and lower mortality compared to earlier strains. With fewer severe cases, healthcare systems succeed in better managing patient care and allocating resources effectively. Additionally, advances in understanding the clinical presentation of COVID-19, risk factors, and treatment options have enabled more effective diagnosis and treatment of cases. The overall intensity of the pandemic appreciably declined from the second quarter of 2022, leading to a reduction of the mortality excesses registered across European countries in the previous period. The causes behind the excess mortality observed in 2022, even in countries with high vaccine uptake are difficult to explain and may be partly related to the effects of COVID-19 on other conditions.[9] Moreover, the early onset of seasonal influenza across Europe in November–December 2022 partly contributed to the excess mortality in that year and likely resulted in a mortality deficit in early 2023.[31] Therefore, the 2% excess deaths in 2023 may be somewhat underestimated. In this regard, causes of death data will be useful in providing possible explanations.

When interpreting our results, some factors deserve consideration. First, we decided to use 10 years preceding the outbreak of the COVID-19 pandemic in Europe to capture long-term trends in all-cause mortality in each country. However, alternative timeframes may have yielded different estimates.[32] Second, data for the last weeks of a year and all weeks of the most recent year may be incomplete due to delayed registration of deaths. Statistical offices may subsequently revise this information in the course of the next data releases. Third, weekly estimates for the UK countries are affected by delays in death registration. Unlike other countries, deaths in the UK were recorded by the date of registration rather than the date of occurrence. However, since the majority of deaths not registered in a given week are then registered in the subsequent week, this may have only marginally affected the estimates for the whole year.[33] Fourth, each year in the STMF data files includes weeks of seven days, encompassing the first and the last of the year. This week's arrangement follows the ISO 8601-2004 standard. According to this standard, days from preceding years and corresponding deaths are accounted for in either the first week (if January 1st fell on Tuesday, Wednesday, or Thursday) or in the last calendar week (if December 31st fell on Thursday, Friday, or Saturday). Finally, we used a linear term to model the long-term trends in mortality rate and five age groups to account for age differences in mortality rates and changes in population age structures during the study period. Alternative choices might have led to different estimates.[34] These factors may be among the reasons for the difference between the estimates of excess mortality provided in the present study and those previously published by other research groups or international institutions.[3,4,35,36]

The main strength of our study lies in the provision of a comprehensive and updated assessment of excess mortality in Europe attributable to the direct and indirect effects of the COVID-19 pandemic over the period 2020–2023. Furthermore, these estimates are based on the STMF data series which contain objective and internationally comparable mortality data that were built with the specific aim of monitoring the effects of temporary hazards such as influenza epidemics, temperature extremes, as well as man-made or natural disasters on short-term mortality fluctuations. The database includes only data provided by high-quality statistical systems, i.e., those where the census and vital registration system cover close to 100 per cent of the population.

In conclusion, this study provides a comprehensive analysis of the effect of the COVID-19 pandemic on excess mortality in Europe from 2020 to 2023, estimating approximately 1.6 million excess deaths. Our study also highlights important geographic disparities that can be partly explained by differences in socioeconomic context and vaccine uptake across European countries.

Contributors
Margherita Pizzato: Conceptualization, Visualization, Writing - original draft. Alberto Giovanni Gerli: Conceptualization, Data curation, Visualization, Writing - review & editing. Carlo La Vecchia: Writing - review & editing, Project administration, Funding acquisition. Gianfranco Alicandro: Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing - original draft, Supervision. All authors had full access to the data in the study, verified them, and accepted responsibility for submitting the manuscript for publication.

Data sharing statement
All data used in this study are publicly available.

Editor note
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Declaration of interests
The authors have no conflict of interest related to this work.

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Appendix A. Supplementary data
Supplementary data related to this article can be found at https://doi.org/10.1016/j.lanepe.2024.100996.

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