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# Seasonal mortality and its impact on spatial inequality in life expectancy across Italy

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## Declarations

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**Authors' contributions:** IM, DAJ and FJ conceived and designed the study. IM conducted the statistical analysis and drafted the manuscript. DAJ and FJ provided critical input and revisions to the draft manuscript. DJ, MN and provided scientific advice for the interpretation and framing of the analysis. All authors revised the final draft and approved the final version of the manuscript.

## Abstract

Seasonal mortality fluctuations significantly affect national life expectancy, yet their role in regional inequalities remains underexplored. Understanding this is crucial for targeted health policies aimed at reducing spatial mortality differences. We quantify the impact of seasonal excess mortality on regional life expectancy levels ($e_0$) and inequalities in Italy. Using monthly mortality data from the Italian National Statistical Institute by region (N = 20), sex and age between 2005-2019, we assessed $e_0$ losses due to seasonality by comparing observed mortality with minimum achievable levels. Seasonal effects on inequalities in $e_0$ were quantified by comparing standard deviations with and without excess seasonal mortality and examined regional contributions using decomposition analysis. Eliminating seasonal excess mortality reduced regional $e_0$ differences by 1.4 years (1.36-1.70) on average for both sexes. This effect was most pronounced in southern and insular regions (Campania and Sicilia), especially for winter-related excess mortality. Overall, removing winter excess mortality led to an average of 0.6 years (7.5%) decline in regional inequality. However, during the years with high mortality burdens (2005 and 2015), seasonality contributed to spatial mortality inequality by 10% and 5.2%, respectively. The regional contributions to $e_0$ inequality revealed that Campania and Sicilia also had the strongest role in increasing spatial mortality variation throughout the period. The pronounced regional inequalities in $e_0$ losses due to seasonal excess mortality contributed significantly to shaping regional $e_0$ variation in Italy, mostly due to different impacts of winter mortality within the country.

# 1 Introduction

Short-term events, such as intra-annual mortality fluctuations due to seasonal variations, can substantially affect annual life expectancy levels (Ballester et al., 2019; Rau, 2006). These seasonal mortality impacts on life expectancy have been observed to be relatively heterogeneous within Europe (Ballester et al., 2011; Marinetti et al., 2024), varying not only between countries but also by subpopulations (Bennett et al., 2014; Burkart et al., 2014; Hajat & Kosatky, 2009; Lerch & Oris, 2018). Indeed, inequalities in vulnerability (Füssel, 2010; Islam & Winkel, 2017) contribute to diverse patterns of extreme temperature effects on mortality, even within the same country (Kovats & Hajat, 2008; Lerch & Oris, 2018).

Nevertheless, most research on seasonal mortality focuses on the national level, while the subnational dimension remains understudied, with only some exceptions (Ballester et al., 2011; Martínez-Solanas et al., 2021). These studies found that not only will the impact of temperature-attributable mortality most likely increase, especially in the Mediterranean area, but also its heterogeneity within those countries. Understanding how and to what extent seasonal mortality shapes spatial inequalities in life expectancy is fundamental for targeted health policies and allocating resources to areas which are majorly affected by these mortality fluctuations. To our knowledge, no previous study has systematically examined how seasonal mortality influences mortality inequality within countries and how those seasonal regional differences thereby shape mortality patterns.

Italy provides an interesting case for investigating these patterns. Firstly, it is among the European countries most affected by heat waves and flu epidemics (Kovats & Kristie, 2006; Michelozzi et al., 2009, 2010). Secondly, the country's pronounced regional meteorological differentials (Di Giuseppe et al., 2013) and the decentralisation of healthcare to regional authorities (Tediosi et al., 2009) have led to uneven excess mortality patterns across Italian regions during heatwaves, flu epidemics and cold spells (Conti et al., 2005; Kosatsky, 2005;

Meijer et al., 2006; Michelozzi et al., 2016; Rosano et al., 2019). Thirdly, regional disparities in life expectancy still persist in the country, with life expectancy in the South and North-West lagging behind the North-East and Centre by around 3 years (Italian National Statistical Institute (ISTAT), 2023; Iuzzolino et al., 2011) and seem to be increasing in recent years (Sauerberg et al., 2024).

Although it is highly likely that the spatial differences in seasonal mortality in Italy contribute significantly to the observed regional inequalities in life expectancy, comprehensive analyses of the effects of seasonal mortality on overall mortality and life expectancy levels – and how they shape regional inequalities in Italy - are scarce. A study by Rizzo and colleagues (Rizzo et al., 2007) assessed age-specific patterns of influenza-related deaths between 1969 and 2001, although they didn't find any variations in influenza-related mortality when dividing the country into North, Centre, and South regions. Moreover, research on specific high-mortality periods, such as heatwaves, flu epidemics and extreme cold events, found heterogeneous impacts on mortality within the country (Conti et al., 2005; Michelozzi et al., 2005; Michelozzi et al., 2016).

In this study, we assess the impact of seasonal excess mortality on subnational life expectancy levels and measure how seasonal excess mortality has affected regional life expectancy inequalities in Italy. Through the analysis of monthly death counts by region by a modified decomposition method, we integrate the exploration of regional disparities in mortality, offering new insights into the broader dynamics of mortality with the influence of external shocks on demographic patterns.

# 2 Data and Methods

## 2.1 Data

We employed data from the Italian National Statistical Istitute (ISTAT) database. We used monthly death counts by 5-year age groups for 20 Italian regions at NUTS 2 level and weekly death counts by 5-year age groups for 5 Italian NUTS1 group of regions. We also employed yearly population estimates on the 1$^{st}$ of January for each region and group of regions. A map of the regions and groups of regions is included in Supplementary Information, Figure S1. Valle d'Aosta and Molise were not considered in interpreting or analysing the results due to their small population size (around 125 thousand and 303 thousand inhabitants, respectively). All the analyses were carried out separately by Italian region and group of regions, sex, and period (both single-year, 5-year period 2005-2009, 2010-2014, 2015-2019 and all years together). To compute the 5-year and the overall period (2005-2019) analyses, we have aggregated mortality and population counts for the years considered.

## 2.2 Methods

To measure the impact of seasonal mortality fluctuations on annual $e_0$ by NUTS2 region, we first computed the region-specific annual and seasonal $e_0$ employing standard demographic life table techniques (Preston et al., 2001) to the respective age-specific mortality rates. We then computed the *ideal* level of $e_0$ using mortality rates of three months with the lowest death counts in a year, [sentence eliminated to ensure double-blind review], and as explained below. The constructed *ideal* $e_0$ can be interpreted as the lowest mortality scenario theoretically achievable in each region each year. The difference between the *ideal* and the observed (and season-specific) $e_0$ is the loss in life expectancy at birth due to excess seasonal mortality.

### *2.2.1 Mortality rates in the absence of excess seasonal mortality (ideal $m_x$)*

As explained above, we used the lowest quartile of monthly death counts (i.e. within-year baseline mortality based on 3 months with the lowest death counts across all ages within the year) to estimate the seasonal excess mortality by region. We computed the *ideal* mortality as:

$$m_{x,t,r}^{lowest,month} = \frac{4 \cdot D_{x,t,r}^{lowest,month}}{P_{x,t,r}} \quad (1)$$

where $P_{x,t,r}$ are the population exposures for respective age group, year, and region; $D_{x,t,r}^{lowest,month}$ represents the deaths sum of the 3 months with the lowest death counts for age *x*, year *t* and region *r* and where estimated as:

$$D_{t,r}^{lowest,month} = \min_{M3 \subset \{1,2,\ldots,12\}; |M3|=3} \sum_{m \in M3} \sum_{x} D_{x,t,r}^{m} \quad (2)$$

However, considering death counts by month might not produce precise estimates of the minimum mortality theoretically achievable in a year. Hence, we used the weekly mortality information from the NUTS1 group of regions, dataset to adjust our estimates of *ideal* mortality.

### *2.2.2 Correction factor*

To adjust our *ideal* life expectancy estimates, we computed a correction factor based on the information given by the weekly death counts at group of regions level. This adjustment allowed us to integrate in the monthly regional dataset a more granular dataset that has information on weekly mortality. Therefore, to construct the correction factor (*c*) we first computed the within-year baseline mortality based on 13 weeks with the lowest mortality within the year (i.e. the lowest quartile of weekly death counts) using the weekly deaths data by group of regions. For each group of regions, year, and sex separately, death counts of 13 weeks with the lowest death counts were summed up to estimate the lowest mortality scenario in a specific year as:

$$m_{x,t,g}^{lowest,week} = \frac{D_{x,t,g}^{lowest,week}}{j_t P_{x,t,g}} \quad (3)$$

where $D_{x,t,g}^{lowest,week}$ represents the sum of the 13 weeks with the lowest death counts for all ages, year *t* and group of regions *g*, considering all ages, and $P_{x,t,g}$ the population exposures for age *x*, year *t* and group of regions *g*; *j* is the coefficient to make years with different number of weeks comparable, is equal to $k_t/4$ ($k_t = \frac{52*7}{365}$ when the year t has 52 weeks, and $k_t = \frac{53*7}{365}$ in case of 53 weeks, according to ISO 8601). Subsequently, using the same weekly data as in (2), we constructed a monthly dataset by groups of regions. We then computed the within-year baseline mortality based on 3 months with the lowest mortality within the year. For each group of regions, year, and sex separately, death counts of 3 months with the lowest death counts were summed up to estimate the lowest mortality scenario in a specific year as:

$$m_{x,t,g}^{lowest,month} = \frac{D_{x,t,g}^{lowest,month} \cdot 4}{P_{x,t,g}} \quad (4)$$

where $D_{x,t,g}^{lowest,month}$ represents the deaths sum of the 3 months with the lowest death counts for age *x*, year *t* and group of regions *g*, considering all ages, and $P_{x,t,g}$ the population exposures for age *x*, year *t* and group of regions *g*. We calculated the correction factor as a ratio between the within-year baseline using weekly and monthly data (based on the same group of regions dataset) for each group of regions:

$$c_{x,t,g} = \frac{m_{x,t,g}^{lowest,week}}{m_{x,t,g}^{lowest,month}} \quad (5)$$

Where $m_{x,t,g}^{lowest,week}$ and $m_{x,t,g}^{lowest,month}$ are computed as in (3) and (4). Therefore, the adjusted *ideal* mortality estimates were computed multiplying (1) by the correction factor ($c_{x,t,g}$), calculated as in (5):

$$m_{x,t,r}^{lowest,month} = \frac{D_{x,t,r}^{lowest,month}}{P_{x,t,r}} \cdot c_{x,t,g} \quad (6)$$

Where $c_{x,t,g}$ is the correction factor that add the weekly information at group of regions level as explained in (5), and region *r* belongs to group of regions *g* as in Figure S1, Supplementary Information.

### *2.2.3 Spatial variation*

To evaluate the seasonal impact on $e_0$ and the spatial variation under various mortality scenarios (eliminating overall seasonal and season-specific excess mortality), we have compared the standard deviations (SD) between Italian regions of the observed $e_0$, *ideal* $e_0$ and $e_0$ in the absence of season-specific excess mortality. To measure the latter, we used as mortality rates:

$$m_{x,t}^{-season} = \frac{D_{x,t}^{-season}}{P_{x,t}} \quad (7)$$

where $D_{x,t}^{-season}$ are the age- and year-specific death counts, after the elimination of excess deaths of a specific season and $P_{x,t}$ the population exposures for age x, and year t. The elimination of season-specific excess deaths was performed by replacing season-specific deaths with those based on death counts in the lowest mortality quartile. [sentence eliminated to ensure double-blind review].

### *2.2.4 Decomposition of seasonal mortality by regions*

Lastly, to assess the region-specific contribution of seasonality in spatial inequality in life expectancy, we decomposed the difference between observed and ideal $e_0$ standard deviations by regions, separately by each season, and overall. We applied a modified version of the stepwise decomposition method by age and cause of death (Andreev et al., 2002), using region-specific death counts instead of cause-specific death counts ([sentence eliminated to ensure double-blind review]).

We decomposed the difference between the variation of the observed and *ideal* $e_0$ by season and age as follows:

$$SD(e_{0,t}{}^{observed}) - SD(e_{0,t}^{upper}) = \Delta SD(e_{0,t}) = \sum_{x=0}^{100+} \sum_{region} \Delta SD(e_{x,t}^{region})$$

where $\Delta SD(e_{x,t}^{region})$ are age-, year- and region-specific contributions of the variations in excess deaths. The analysis was conducted using the statistical software R (version 4.2.3).

# 3 Results

## 3.1 Life expectancy losses due to seasonality in Italian regions

Life expectancy at birth ($e_0$) in Italy increased from 81.2 years (regional range: 79.8-82.2 years) to 82.8 years (regional range: 81.2-83.8 years) between 2005 and 2019 (Figure 1). Life expectancy at birth shows a pronounced spatial gradient, with central and north-eastern regions (such as Marche and Trentino-Alto Adige) having more than a 2-year advantage in life expectancy than the South and Islands (particularly Campania and Sicilia). The maximal average regional differences during 2005-2019 were slightly more pronounced for females (2.7 years) than for males (2.5 years) (Figure S2 and Figure S3, Supplementary Information). The losses in life expectancy due to excess seasonal mortality revealed a heterogeneous regional pattern. Overall, we observed the total average of 1.42-year life expectancy loss at the national level and the losses across the regions varying from 1.36 to 1.70 years (1.34-1.74 years for males and 1.35-1.72 years for females) (Figure 1, Figure S2 and Figure S3, Supplementary Information). The largest losses in $e_0$ were experienced in 2005-2009 with a 1.51-year loss (regional range: 1.33-1.80 years) at the national level (1.30-1.74 years loss for males, 1.33-1.86 years loss for females). Generally, the highest impact of excess seasonal mortality throughout all the years was observed in insular and southern regions, 1.6-1.7 years for Sardegna, Sicilia, Campania, and Calabria (sex-specific findings in Figure S2, Figure S3 and Table S1 in Supplementary Information; losses across time are presented in Figure S4). When analysing season-specific losses in $e_0$ (Figure S2 and S3 in Supplementary Information), we found that winter excess mortality is the main driver of the overall seasonal excess mortality impact with 2.2 years loss (regional range: 1.82-2.66) on average in the analysed period (males: 2.1 (1.70-2.66), females: 2.2 (1.87-2.56), Figure S5, S6, Table S2, Supplementary Information).

## 3.2 Analysis of life expectancy losses in extreme mortality burden years

The annual-specific analysis revealed that two years (2005 and 2015) were particularly affected by high mortality losses. First, the year 2005 was characterised by a severe winter, with snowing episodes throughout the whole country (D'Errico et al., 2020), while the flu epidemic of 2015 and the combined effect of a heatwave (Michelozzi et al., 2016) significantly increased mortality nationwide throughout the year. The larger at-risk population group also aggravated the high burden of mortality in 2015 due to the unusually lower mortality in the summer of 2014 (Michelozzi et al., 2016). Therefore, to better understand spatial patterns in seasonal excess mortality in the context of mortality shocks, we are also providing the results for these years.

We found that the overall life expectancy at birth ($e_0$) was 80.7 years (regional range 81.8-79.2 years) in 2005 and 82.3 years (regional range 80.5-83.3 years) in 2015 (Figure 2). The losses in $e_0$ due to excess seasonal mortality were, on average, 1.8 years (regional range 1.6-2.2 years) in 2005 and 1.5 years (regional range 1.3-2.1 years) in 2015. The most significantly affected regions included the Italian islands, especially in 2005 (Sardegna, 2.6 years loss, and Sicilia, 2.15 years loss), southern regions (Basilicata, 2.4 years loss, Campania, 2.3 years loss) and the centre of Italy (Umbria, 2.3 years loss). The sex-specific analysis (Supplementary Information Figure S7 and S8) revealed a similar regional pattern. However, the female population overall was slightly more affected showing 1.9 years loss (regional range: 1.7-2.5 years) in 2005 and 1.5 years loss (regional range: 1.3-2.15 years) in 2015 than the male population (1.7 years loss in 2005, regional range: 1.5-2.7 years and 1.4 in 2015, regional range: 1.3-2.1 years).

**Figure 1** Regional life expectancy at birth, regional life expectancy at birth due to excess seasonal mortality and the related losses, Italian average and the regional standard deviation (SD), Italian regions, total population, 2005-2009, 2010-2014, 2015-2019

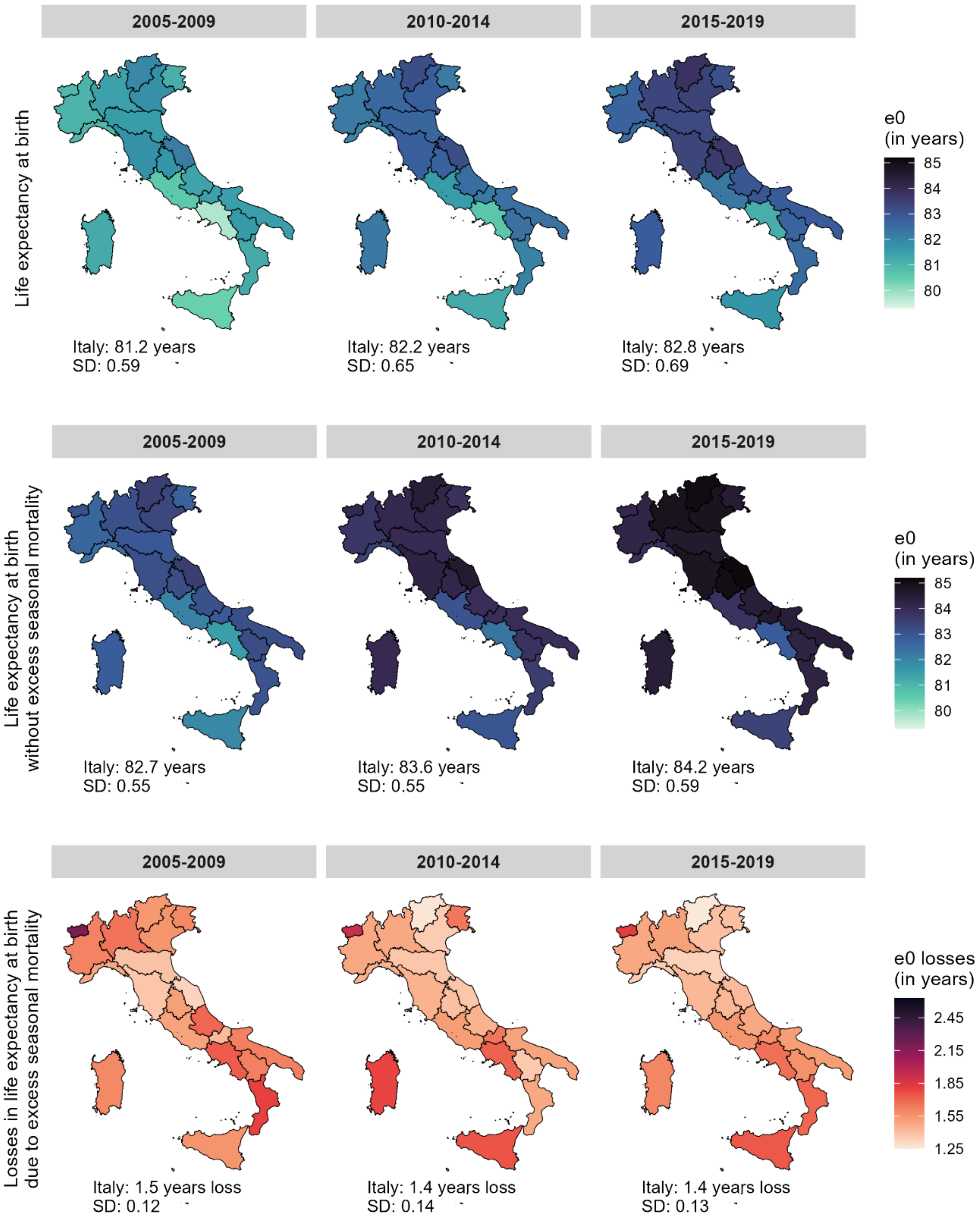
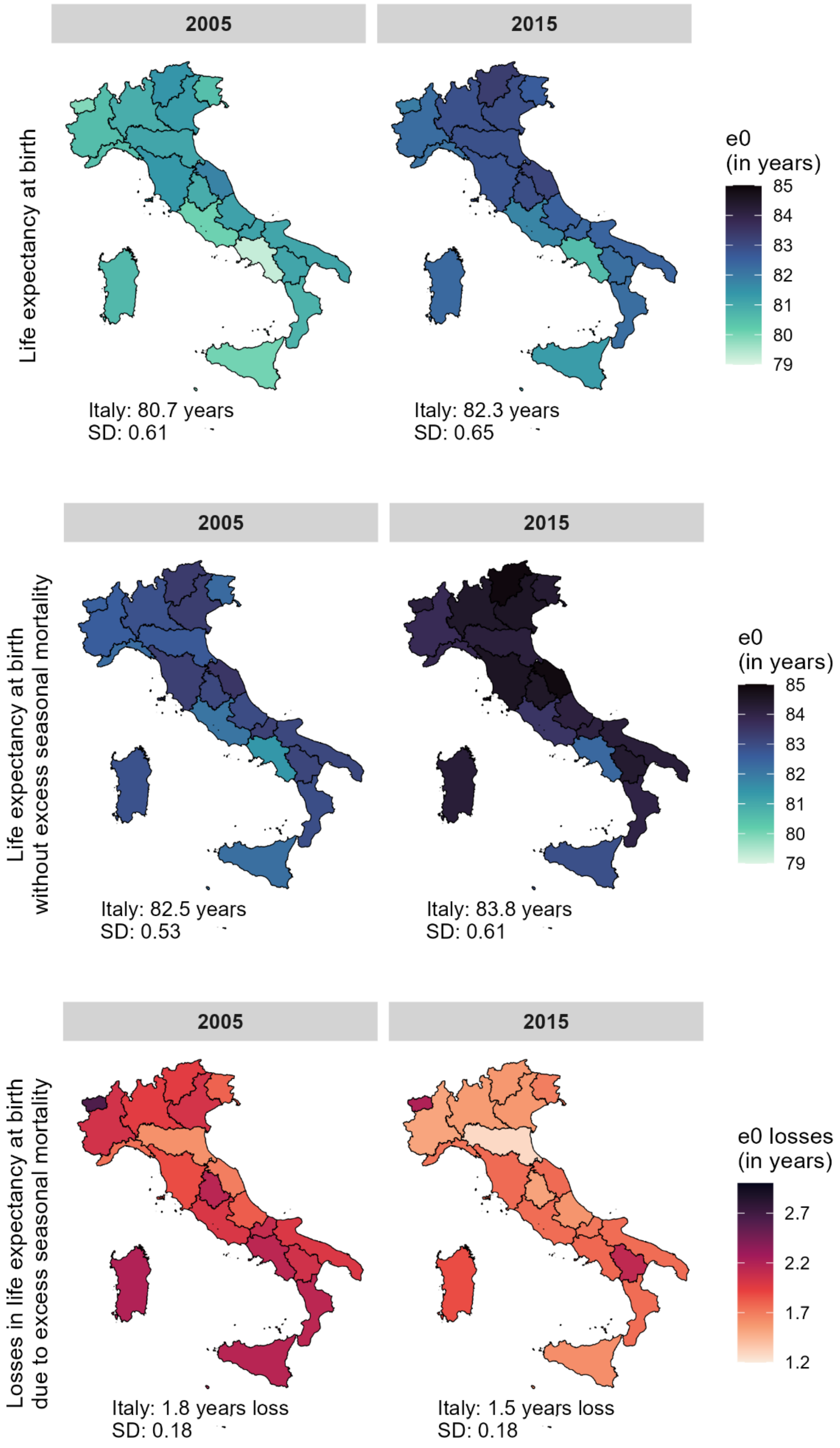


**Figure 2** Regional life expectancy at birth, regional life expectancy at birth due to excess seasonal mortality and the related losses, the Italian average and the regional standard deviation (SD), Italian regions, total population, 2005 and 2015



## 3.3 Spatial inequality in life expectancy at birth due to seasonality in Italian regions

As already observed in Figures 1 and 2, life expectancy inequality in Italy reflects a persistent spatial divide from 2005 to 2019, with north-eastern and central regions generally experiencing lower mortality rates compared to the southern and insular regions. To better understand how seasonal excess mortality affected spatial mortality inequality within the country, we provide a spatial analysis of the life expectancy values observed without seasonal excess mortality and without season-specific excess mortality.

We found that removing excess seasonal mortality would have decreased spatial variation on average by 11.2% in the analysed years (Table 1). These results are mainly attributable to eliminating excess winter mortality (-7.5%), and they most likely correspond to the flu epidemic years. In particular, male life expectancy difference showed a bigger reduction than the corresponding difference among females (respectively, -13.8% and -9.1%), again mostly due to the elimination of excess mortality during winter months (respectively, -8.4% and -6%). Generally, male $e_0$ showed a higher effect of removing excess seasonal mortality on reducing the regional life expectancy gap. Interestingly, during extreme mortality burden years (2005 and 2015), the elimination of excess seasonal mortality led to varying results. Under this scenario, the regional difference in e0 would decline by 10% in 2005 and only by 5.2% in 2015. This finding suggests that almost all the Italian regions suffered quite similar burdens during 2015, but it was not the case in 2005 (see also Table S3, S4 and S5 in Supplementary Information for the period (2005-2009, 2010-2014, 2015-2019) specific results).

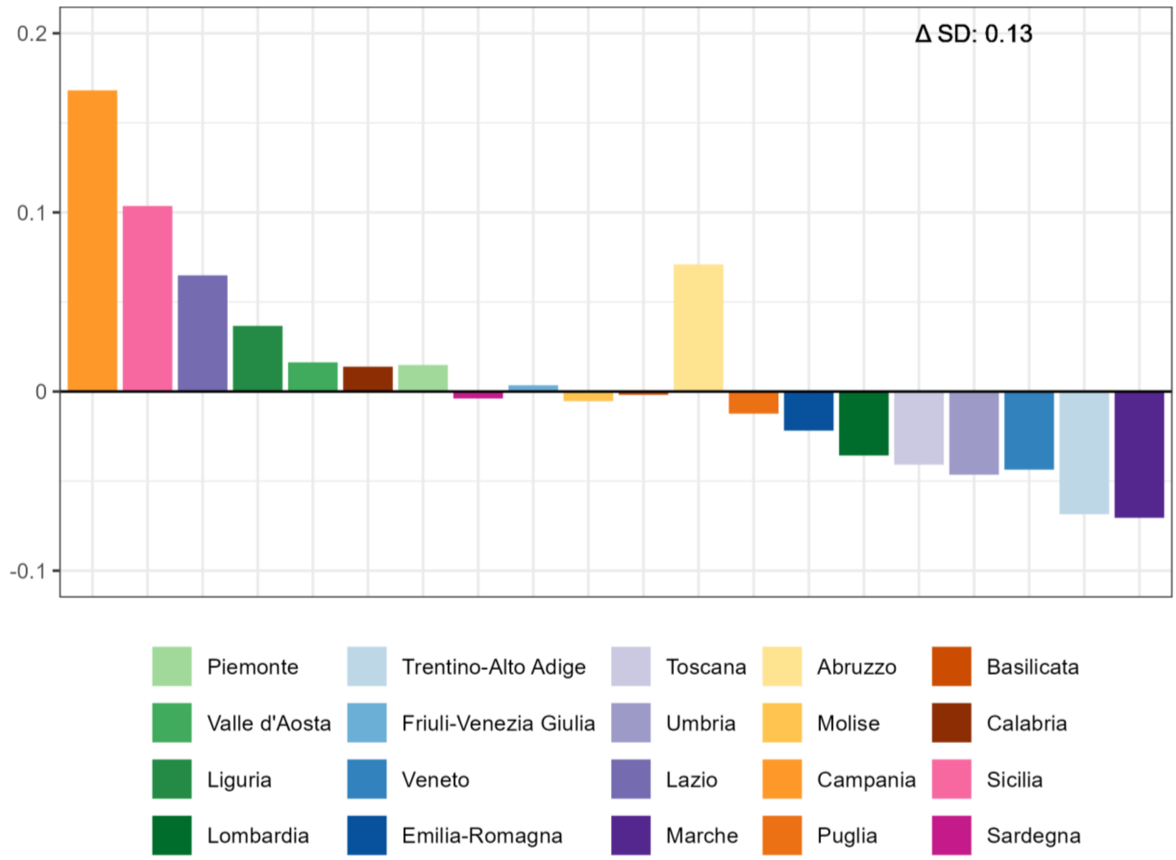
**Table 1** Standard deviations in life expectancy at birth among Italian regions by sex (observed, without overall seasonal excess mortality, without season-specific excess mortality) and percentage difference with the observed standard deviation (%Δ), 2005-2019, 2005 and 2015

| **SD** | **2005-2019** | | | | | | **2005** | | **2015** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | %Δ | Female | %Δ | Male | %Δ | Total | %Δ | Total | %Δ |
| **Observed** | 0.64 | - | 0.69 | - | 0.62 | - | 0.60 | - | 0.68 | - |
| **Without Seasonality** | 0.57 | *-11.2%* | 0.63 | *-10.1%* | 0.54 | *-14.4%* | 0.54 | *-10%* | 0.64 | *-5.2%* |
| **Without Winter** | 0.59 | *-7.5%* | 0.65 | *-6.2%* | 0.57 | *-9.2%* | 0.54 | *-10.4%* | 0.64 | *-5.9%* |
| **Without Spring** | 0.62 | *-3.3%* | 0.67 | *-2.8%* | 0.61 | *-3.3%* | 0.59 | *-2%* | 0.66 | *-2.3%* |
| **Without Summer** | 0.65 | *1%* | 0.69 | *0.3%* | 0.63 | *1.3%* | 0.60 | *0.9%* | 0.68 | *0%* |
| **Without Autumn** | 0.64 | *0.5%* | 0.7 | *1%* | 0.62 | *-0.6%* | 0.62 | *3.6%* | 0.69 | *1.4%* |

## 3.4 Regional contributions to spatial inequality in Italy due to seasonal excess mortality

The contributions of Italian regions to the changes in spatial standard deviations in $e_0$ provided insight into regional drivers of spatial inequality due to excess seasonal mortality (Figure 3). We have decomposed the difference in standard deviations by region for the overall difference in observed and removing excess seasonal mortality standard deviations (Figure 3) and by each season independently (Figure S9 Supplementary Information). In the plot, a positive value means that a specific region contributes to increasing the seasonal impact on life expectancy, while a negative value reduces it. The regions are ordered based on the overall observed region-specific life expectancy, from the lowest to the highest. Campania (South) consistently emerged as the region that contributed the most to increasing spatial inequality due to excess seasonal mortality seasonality, with the highest contribution observed in the winter of 2010-2014 and 2015-2019 (0.24, Figure S9 Supplementary Information). One of the two Italian islands, Sicilia, also displayed positive contributions over the whole period, peaking in wintertime 2015-2019 (0.14, Figure S9 Supplementary Infomration). Conversely, Marche (Centre), Trentino-Alto Adige and Veneto (North-East) consistently contributed to reducing spatial inequality, particularly in 2005 (with a total average of 0.6). Analysing the results for each season independently, it is evident that there was a seasonal gradient, with autumn and summer showing the lowest inequality levels in life expectancy (Figure 9, Supplementary Information).

**Figure 3** Contributions of Italian regions[1] to the difference in spatial inequality (Δ SD) between $e_0$ observed and without excess seasonal mortality, ordered by the observed $e_0$ in the region, total population, 2005-2019




*[1]Regions are colour-coded by NUTS1: North-West: green, North-East: blue, Centre: purple, South: orange/red, Insular: pink*

# 4 Discussion

## 4.1 Main findings

Our study revealed systematic regional variation in the impact of seasonal excess mortality in Italy. Seasonal mortality reduced regional $e_0$ by an average of 1.4 years (regional range: 1.36 - 1.70) for both males and females in Italy over the years 2005-2019. The largest losses in $e_0$ were observed in the South and Islands of the country, especially during the winters of 2005 and 2015. Our analysis showed that spatial inequality in $e_0$ would have been reduced on average by 11.2% by eliminating excess seasonal mortality, mostly due to excess winter mortality (-7.5). Campania (South) and Sicilia (Insular) consistently emerged as the biggest seasonal contributors to the overall spatial inequality in $e_0$ throughout the period. These findings highlight not only the persisting regional disparities in the impact of seasonal excess mortality on $e_0$ but also point to the uneven and changing contributions of regions to the seasonal spatial inequality in $e_0$ over time.

## 4.2 Explanation of the findings

Seasonal excess mortality contributed to a stable loss of about 1.4 years in life expectancy in Italy from 2005 to 2019. This effect was not only constant over time but also relatively consistent between sexes, indicating similarities in vulnerability to seasonal mortality shocks. Winter mortality emerged as the main driver of seasonal excess mortality and its spatial inequality, accounting for most of the life expectancy losses across Italian regions. This finding aligns with previous studies, which highlighted the key role of winter-related mortality in shaping life expectancy and mortality levels (Gasparrini et al., 2015; Marinetti et al., 2024) due to the epidemiological processes (cardiovascular and respiratory diseases) that underlie cold-related mortality (Von Klot et al., 2012).

Moreover, we identified substantial spatial variation in the distribution of seasonal losses in mortality. Specifically, the spatial inequality was driven by the larger impacts on southern and insular regions, which emerged more vulnerable to seasonal excess mortality, particularly during winter. The observed regional variation in the impact of seasonal mortality on $e_0$ in Italy has the same gradient as healthcare and socioeconomic factors. Southern and insular Italy - where the largest losses in $e_0$ due to excess seasonal mortality were observed - has faced significant challenges in healthcare provision. These regions have fewer healthcare facilities, limited access to advanced treatments, and longer waiting times compared to the northern and central regions (Carboni et al., 2024). Such healthcare disparities are further heightened by persistent socioeconomic inequalities, including lower educational and occupational levels in the South and Islands (Lenzi et al., 2013). Consequently, these regions may face challenges in responding effectively to external health stresses, such as seasonal epidemics or extreme temperature events. The inadequate implementation of preventive measures, such as influenza vaccination campaigns, may further reduce population adaptability to seasonal risk factors. Vaccination uptake rates, which are also influenced by socioeconomic status and trust in their efficacy (Bonanni et al., 2015; Giacomelli et al., 2022), may also contribute to these disparities, as lower trust and access can lead to insufficient coverage and reduced population resilience during epidemic seasons. Additionally, the already existent lower socioeconomic status of individuals in these areas could limit their capacity to respond optimally to health risks, even if healthcare systems were equally well set up across regions. Furthermore, the geographic differences might also be partly driven by disparities in the management of preventive health screening, which is strongly associated with socioeconomic status (Petrelli et al., 2018). These systemic shortcomings have increased mortality rates during periods of severe health stress, such as seasonal epidemics or extreme temperature events, highlighting the interplay between healthcare inequalities and mortality shocks.

We found that, on average, seasonal excess mortality accounts for approximately 11% of the overall regional variation (measured by the standard deviation) in life expectancy in Italy. Compared to other external factors, the observed seasonal impact is rather substantial. For example, smoking has been found to reduce regional mortality inequality in Italy by only 8% among the male population during the first decade of the 21st century (Federico et al., 2013). In the European context, it has been found that the contribution of smoking to European countries' differences in $e_0$ was higher than 20% between 1985 and 2014 for both sexes (Janssen, 2021) and a study on German regions revealed that eliminating smoking-related mortality would reduce the East-West mortality gap by about 25% (Grigoriev et al., 2022). On the other hand, alcohol-related mortality contributed between 10% to 20% of the life expectancy differences between Western and Central and Eastern Europe among males and below 10% among females (Trias-Llimós et al., 2018). In this context, behavioural factors contribute to regional health inequalities by influencing long-term mortality trends, whereas seasonal excess mortality captures critical disparities caused by short-term risk factors.

Analysis of the contribution of seasonality on $e_0$ in high mortality burden years (2005 and 2015) revealed two distinct patterns. While in 2005, the high contribution of seasonality on $e_0$ (around 10%) was mainly explained by a concentration of winter excess mortality in the first weeks of the year, we observed only halved contributions in 2015. This result was most likely due to a prolonged flu epidemic season in winter alongside intense heatwave weeks during the summer (Michelozzi et al., 2016), which increased mortality almost homogeneously within the country. The different duration of the high mortality burden events of the two years might be the reason for the observed unequal contribution of seasonal excess mortality on $e_0$, however, further research is needed to clarify the causal relationship between the length of health stressors and the influence on spatial mortality inequality.

We observed consistent patterns in the impact of seasonal excess mortality on life expectancy for both sexes. However, during specific high-burden years, such as 2005 and 2015, the female population experienced a slightly greater absolute impact from seasonal excess mortality. This difference might be due to sex-specific vulnerabilities to prolonged mortality shocks, potentially driven by differences in healthcare access and use, as well as the higher representation of women in healthcare occupations, which could increase their exposure to health risks. On the other hand, males showed a higher contribution of seasonality on spatial mortality inequalities, suggesting that reducing seasonal excess mortality would lead to a greater decrease in regional mortality inequality for males compared to females. This effect may be attributed to the fact that excess seasonal mortality among males primarily occurred in regions with a typically lower life expectancy, hence contributing more substantially to regional inequality.

## 4.3 Strengths and limitations

To our knowledge, this is the first paper that assessed and quantified the impact of seasonal excess mortality across regions in Italy. Moreover, we have integrated the information of monthly mortality data by region and weekly mortality data by group of regions, and analysed these data for the first time to obtain a more reliable estimation of the minimum possible achievable level of mortality within a year. The data used were provided by the National Statistical Institute (ISTAT), which provides high-quality official statistics based on Eurostat guidelines. Nevertheless, our study has some limitations. First, two Italian regions, Valle d'Aosta and Molise, have small population sizes, and their estimates could be biased by random fluctuations in mortality. Although the outcomes did not significantly change, to avoid their misinterpretations, we are not considering them in the interpretations and analysis of the results. Second, the overall estimation of the impact of seasonality on $e_0$ is a challenging task due to the counterbalancing effects of the different seasons. Moreover, estimates depend on the choice of the baseline mortality level. [sentence eliminated to ensure double-blind review] Sensitivity analyses on the computation of the excess mortality baseline and found that the method proposed was the best choice to overcome stochastic fluctuations of mortality without losing intra-annual mortality information.

### 4.4 Conclusions

Seasonal fluctuations in mortality had substantial effects on both the life expectancy levels and regional differences, with southern and insular Italian regions emerging as the most affected. These regions face greater challenges due to structural weaknesses in healthcare systems, which leave them less prepared to handle seasonal health crises.

Timely and region-specific data are essential for monitoring health losses linked to seasonality and for informing targeted public health interventions. Policies should prioritise strengthening healthcare preparedness, particularly in the South and Islands of the country, by implementing early warning systems and proactive measures tailored to local seasonal vulnerabilities. More evidence and research are needed to understand and mitigate the consequences of climate change-related risks, which would help to reduce the increasing threats related to the seasonal mortality burden.

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