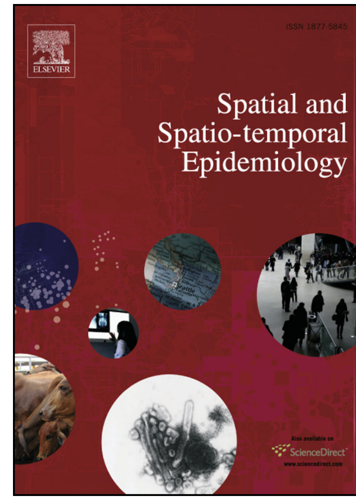


Real geographies and virtual landscapes: Exploring the influence on place and space on mortality Lexis surfaces using shaded contour maps

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# Title Page Information

## Title

**Real geographies and virtual landscapes: Exploring the influence on place and space on mortality Lexis surfaces using shaded contour maps**

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## Abstract

This paper describes how shaded contour plots, applied to mortality data from the Human Mortality Database, can be used to compare between nations, and start to tease out some of the ways that place and space matters. A number of shaded contour plots are presented, in order to describe the age, period and cohort effects which are apparent within them. They show variations between different subpopulations within the same nation, over time, and between nations. In illustrating these intra- and international variations in the patterns, we hope to encourage the development of hypotheses about the influence of such factors on mortality rates. We conclude with a brief discussion about how such hypotheses might be developed into statistical models, allowing for more rigourous testing of hypotheses and projection across time, place and space.

## Highlights

- Shaded contour maps are a way of showing how something varies over a two dimensional surface.
- A two dimensional surface where the dimensions are age and year is known as a Lexis surface.
- A Lexis surface where the outcome variable is mortality is known as a mortality surface.
- Mortality surfaces for around 100 populations from 37 nations have been produced.
- These surfaces can show how place and space influences health and longevity.

## Key words

- Demography
- Mortality
- Data visualization
- International variation
- Maps

## Acknowledgements

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# 1. Introduction

Spatiotemporal research can benefit from the interplay between data visualisation and formal statistical modelling. Data visualisation makes it easier for the human brain to turn tables of numbers into theories. In the case of demographic data these are theories about how the way we live and die has changed over the long-term, how it differed, and how it may continue to differ over space and place. Data visualisation also helps us to avoid being fooled, by over-reliance on statistical summary measures, into thinking that different relationships between variables are really equivalent. (Anscombe 1973) Conversely, formal statistical modelling, in which alternate theories are rendered as alternative algebraic formulations, allows for the theories developed through visually exploring the data to be tested. They allow for alternative hypotheses to be tested with each other and, importantly given the tendency of the human brain to see faces in clouds, against the null hypothesis.

Within a recent paper, we described two types of enhancements to existing methods for visualising demographic data. (Minton et al. 2013) These methods were applied to the full range of data from the Human Mortality database, including observations dating back to the late 19$^{th}$ century for almost forty distinct nations. The focus of the previous paper was on introducing these visualisations and how best to read them. The breadth of the data visualised, 48 populations based in 37 nations, means they offer important opportunities for spatial analysis. This paper will focus on the more complex of the two visual methods described in the previous paper, shaded contour plots. The purpose of this paper is to encourage the use of shaded contour plots by researchers interested in long-term trends in longevity, and how this varies by country.

## 1.1. Aims and structure of the paper

This paper aims to encourage interplay between informal pattern-seeking through graphical inspection of the data, and formal statistical model building and testing. The structure of the paper is as follows. Firstly, it will discuss the source of the many datasets used, the Human Mortality Database (HMD). Then it will introduce shaded contour plots as a method for visualising these demographic data. The bulk of the article will focus on discussing first the age, then the period, then the cohort effects apparent in the visualisations, with accompanying figures which illustrate these effects in general, and how they may differ spatially. The discussion section will describe, verbally, how the visual intuitions which are implemented by the human brain when making sense of the patterns shown in the contour maps could be used as a starting point for more formal statistical modelling of these patterns and estimation of effect magnitudes; it will also discuss some other sources of data to which shaded contour plots may usefully be applied.

## 1.2. The Human Mortality Database

Records of births and deaths have been collected by some states for hundreds of years. Although records of what happens to people between these events is more patchy, simply knowing these two facts about individuals can be very informative. As with other variables, some variation in how births and deaths have been defined and recorded over time and between countries is inevitable. For example, the definitions of live births and still births are not universally agreed, and have varied over time. Despite this, records of births and deaths can be expected to be more consistent and comparable between time and place than almost any other variable. Information about how old people are, though more uncertain, is inferable from previous records of births – subject to very little uncertainty – and previous and current records of inflows and outflows – subject to somewhat more uncertainty. Unlike life expectancies, which are based on projections, crude death rates – deaths divided by population size - are based on records of what has actually taken place. Both numerator and denominator are known with less uncertainty and for more of the population than most other variables.

All of the visualisations presented here used data from the HMD. The HMD contains demographic data in a standardised format for thirty seven separate nations. It is managed by the Department of Demography at the University of California, Berkley, in collaboration with the Max Planck Institute for Demography Research, under the directorship of John Wilmoth and Vladimir Sckolnikov. The great advantage of this database from an operational perspective is the consistency of the formatting of the records, which allowed for maps to be produced for all of the datasets available using a simple R script, available from the corresponding author. This is what opens up the opportunity to make large scale spatial comparisons. The resolution of the data available is one year by one year of age.

Figure 1 shows for which countries there are records on the HMD, and for how long these records go back. Data are not available on the HMD for unshaded countries, and are available for countries shaded grey. For shaded countries, the darkness of the shade indicates for how long the records go back, with darker shades indicating records which go back further.

As the figure indicates, the data are available for almost all European nations, as well as for nations founded by European empires such as New Zealand, the United States of America, and Canada. Additional countries for which some data are available include Chile, Israel, Taiwan and Japan. The broad availability of data for European nations, together with the known spatial proximity of the nations to each other, means they perhaps offer the greatest scope for spatiotemporal inferences to be drawn.

All of the data are presented separately for males and females. This separate reporting can help with testing certain hypotheses about the possible causes of effects. For example, in times of war males are more likely to have experienced front line service and so be exposed to additional mortality risks than females of the same age. Conversely, in times of peace, adult females – post menarche and pre menopause - have always experienced additional mortality risks relative to age matched males due to childbirth. Comparison between male and female mortality maps can help to get a sense of the magnitude of the additional mortality effects resulting from exposure to events where exposure is differentiated by gender. However, inferences based on these data will always be open to interpretation as there are likely to also be differences in the broader age, period and cohort effects experienced by males and females. In particular, it is known that males tend to experience a higher risk of infant mortality than females, and that females have a tendency towards greater longevity conditional on reaching adulthood.

For a number of the nations, separate datasets are presented for sub-regions or sub-populations. For example, data for Germany is presented separately for East and West Germany; data for New Zealand is presented separately for Maori and Non-Maori populations; and data for the United Kingdom is presented separately for England & Wales, Scotland and Northern Ireland. Within England & Wales (treated as one 'nation'), and France, the data are subdivided into total population and civilian population. Because of this there are a total of 48 datasets from the 37 countries, but not all datasets are mutually exclusive spatially.

The separation of civilian from total populations for England & Wales, and France, allows the size and mortality rates of the military sub-populations within these nations to be identified, so providing an estimate of how exposure to military service during times of peace and war may have affected mortality risk. However, there should still be caution in interpretation because civilian and military populations may differ in ways other than exposure to additional risks of warfare.

Datasets for Germany are presented for the entire nation after reunification, and separately for East Germany and West Germany following their formation. This provided a form of natural experiment, because prior to the formation of East and West Germany both populations were exposed to broadly similar national events and policies, but after formation records about the population and mortality structures of the nations were recorded by separate administrations. We made use of this natural experiment to test, informally, whether an apparent cohort effect could be an artefact of changes in the methods of data collection. (Minton et al. 2013) Observing the same effect in two nations which partly shared the same population but were too ideologically disinclined to wish to collaborate with each other with regard to administrative procedures strongly suggests the effect in question (described later) is unlikely to be an artefact. (Minton et al. 2013)

The New Zealand data are presented separately for the indigenous Maori population, who have substantially higher mortality and morbidity rates than the population at large. Because of these differences, the Maori population have been of much interest to demographers and public health researchers (Malcolm and Salmond 1993; Brown 1999; Hetzel 2000; Blakely et al. 2002, 2005; Ellison-Loschmann et al. 2002; Carter et al. 2006; Ellison-Loschmann and Pearce 2006; Hill et al. 2007, 2010; Jatrana and Blakely 2008; Sandiford et al. 2012).

## 1.1. Lexis Surfaces and Contour Plots

There are a number of ways of presenting how a third variable, z, varies as a function of two others, x and y. One approach is simply to present the values of z as an array, x values along the row, y values along the column. Z values at each x-y configuration can be read off. There are two major disadvantages of this approach. Firstly, when there are many values to be presented, the data becomes unwieldy and hard to read. For example, in the case of the England and Wales datasets which were the primary object of discussion in the IJE article, there were over 13,000 values. Presenting each of these values becomes both cognitively and physically unwieldy. Secondly, though the method is intuitive to understand, its interpretation is not, and does not facilitate accurate at-a-glance comparison. Better, faster, more intuitive methods, which make it easier to see the wood for the trees, are needed.

The pseudospatial quality of the data is our ally in moving to more intuitive forms of visualisation. Z becomes a surface, and x and y its dimensions. The value of z at each x-y coordinate along this surface can therefore be thought of as surface 'height'. A simple way of representing these heights becomes by converting each height to a monochrome shade. In the greyscale case this tends towards white (or black) with increasing (or decreasing) values. So long as the gradation of monochrome varies in proportion with the value of z, then our capacity to see subtle variations in shades can allow us to compare many values at once. An example of this form of visualisation is shown in Figure 2.

Two things about this visualisation should be mentioned. Firstly, the spatial resolution of the x-y values at which the z value is available (one year by one year) is evident through the pixellated quality of the image. Each cell is a continuous block of colour, and all cells are contiguous. As an alternative to this, we might wish to turn each z value into a point floating in the centre of the cell space. However, our perception of the values of z are then likely to be dominated by the colour of the background medium in which the z values 'swim'. Pixellation, in the context of death rate data, can be slightly misleading in suggesting that the phenomena being visualised – when people die – is discrete when in fact it is continuous. People do not just die on their birthday or at the start of the year. Applying some form of spatial smoothing to these data, for example a two dimensional kernel density filter, may help to ameliorate this problem. Kernel density filters smooth data by making the predicted value at a point dependent on weighted averages of nearby values, with nearer values weighted more strongly than more distant values. However, the output they produce is affected by the bandwidth parameter used by the filter, and so what the visualisation looks like depends partly on how the filter has been applied. (Altman 1992)

A second and more serious problem with this form of visualisation is that local variations in values can make objective global comparisons more difficult. This is due to the human propensity to judge light and dark in relative rather than absolute terms, leading to the same shade of grey to appear either light grey or dark grey depending on the shades of grey which surround it. This gives rise to the famous Checkerboard Illusion reproduced as Figure 3 (Adelson 1995). In terms of visualising demographic data, it means that our intuitions, although fast, can be unreliable, thinking that a given mortality rate is either high or low depending on neighbouring values. Without the numeric values alongside the shades of grey, these potentially false inferences might not be identified as such.

A common approach is to coarsen the z values into a much smaller number of categories, such as quintiles or deciles, as in Figure 1. Instead of there being as many shades of grey as there are unique values of z, only (say) five or ten different values are displayed. These shades are more distinctive from each other, and so easier to distinguish between. However, a lot of information has been discarded in this approach, and so more subtle patterns may be hidden. The visualisation produced also depends on how the data have been coarsened, which colours have been selected to represent which categories, and what threshold values have been selected to demarcate between categories.

The solution arrived at in our previous paper was to use contour plots, where each contour was labelled with the value of the associated death rate. (Minton et al. 2013) The contour lines provide an intuitive sense of how the death rate varies as a function of person age and year; the numeric labelling allows this intuitive sense of the relationship to be checked and where necessary corrected through quantitative comparison. At the suggestion of a peer reviewer shading was added to the contour plots, in order to allow viewers to distinguish between 'high' and 'low' areas on the surface at a glance, without needing to compare values of lines. The contour labels are relatively small due to the large number of contours drawn, and so are best viewed in high resolution, zoomed in on the screen, or printed on an A4 or even A3 sheet. However, for the purposes of this paper smaller images are adequate, as the aim is to introduce comparisons within and between datasets. Readers are then invited to explore the full images in more detail later.

After our paper was accepted, the lead author shared the manuscript with a demographer, Tim Riffe, who kindly explained that our shaded contour plots are a reinvention. The same approach had been developed by the demographer James Vaupel and colleagues. While writing this paper, we also discovered a 1992 article in *Teaching Sociology* describing the use of 'contour surfaces', and providing a clear graphical illustration of how contour lines correspond to virtual three dimensional surfaces. (Ploch and Hastings 1992) This search was not systematic, and so there may be more antecedents waiting to be discovered. As we noted in our previous paper, and as Vaupel et al had noted previously, the use of ad hoc contour lines to group together clusters of values in demographic data was used in an article published in 1934 by Kermack, McKendrick and McKinley, which was more recently republished in 2001. (Vaupel et al. 1987; Kermack 2001; Smith 2001)

Despite the more limited computing power of the time, and greater barriers in accessing data, Vaupel produced a monograph in 1987 containing around one hundred shaded contour plots, and variations of the plots which were not considered in our paper. (Vaupel et al. 1987) This was followed by a book published in 1997. (Vaupel et al. 1997) Readers interested in this technique are strongly encouraged to read these sources, in addition to our previous paper and its online appendices, which contain the full series of contour plots at a high resolution. (Minton et al. 2013)

Our approach differed from the approach used in the majority of the shaded contour plots produced by Vaupel and colleagues in two ways. Firstly, our plots show mortality rates, rather than the log mortality rates they used. Secondly, our contour lines are interpolated, and so provide estimates of where on the continuous age-year surface a given death rate occurs. By contrast the majority of the plots by Vaupel are non-interpolated, defining boundaries between rectangular clusters of values.

There are both advantages and disadvantages to these differences. Using log mortality rates rather than mortality rates can underplay some of the substantive changes which have occurred to mortality trends over the last hundred years, in particular with regard to child mortality rates. (Minton) However, using logged values can make other patterns more apparent. Some shaded contour plots of log mortality surfaces will be presented in this paper alongside unlogged mortality surfaces for this reason.

Not interpolating the contour lines means that the lines have a jagged appearance, and so as described above perhaps over emphasise the resolution of the data. However, the use of interpolation necessarily involves relying on an interpolation algorithm, and so the precise position of these lines may vary as a result of the assumptions built into the algorithm used.

Vaupel and colleagues describe plots where the horizontal and vertical axes are age and year as Lexis surfaces, after Willhelm Lexis. (Lexis 1875; Vaupel et al. 1997) We will use this term too. Where the z axis - the contours and shading – relates to mortality, then the plots show a particular type of a Lexis surface known as a mortality surface. The z axis could be any of a range of other outcomes, including morbidity outcomes such as prevalence of heart disease or type two diabetes, and would still be types of Lexis surface so long as the other axes are age and year. Although we encourage the development of these alternative uses of shaded contour plots, our paper will focus entirely on shaded contour plots of mortality surfaces.

# 1. Adding 'Area' to Age, Period and Cohort Effects

Having introduced shaded contour plots as an approach to visualising Lexis surfaces, we will now discuss how to use them to identify age, period and cohort effects within the data they present, and to make comparisons between subpopulations within a nation, such as males and females, and between nations. This section of the paper will discuss each of the three effect types in turn, and present a number of shaded contour plots within each subsection by way of illustration. However, as there are multiple pieces of information and interpretations which can be drawn from a shaded contour plot, readers are invited to consider all of the shaded contour plots from the perspective of each of the effect types, as well as to search through the appendix to our previous paper which contains visualisations for each of the 48 data series available on the HMD. Exploration is strongly encouraged.

A formal mathematical treatment of the effects and trends which these maps illustrate will not be presented, as the focus is on developing hypotheses about these effects and effect modifiers informally. The treatment of these issues will therefore be exploratory rather than confirmatory. We do not aim to prove that any of the effects described are statistically significantly different from those which might be expected under a null hypothesis, but hope that future research, which models these effects and modifiers appropriately, will be able do this.

The distinction between age, period and cohort effects in demographic data is long established. (Gompertz 1825; Kermack 2001; Smith 2001; Barker 2004) Age effects are variations in mortality rates as a function of age, and period effects are variation in mortality rates as a function of year. In the shaded contour plots, with age along the vertical axis and year across the horizontal axis, age effects can therefore be thought of in terms of how the density and values of the contours change while looking across vertical sections of the maps; and period effects can be thought of as variations in the contours observed while looking across the maps, slicing it into horizontal sections.

Given only one alternative, people age one year per year.(Vonnegut 2005) A cohort therefore experiences their own biological age increasing (the age value) by the same amount as the value of the year increases (the period value), meaning the influence of both age and period effects increases for individuals in a cohort as they age. Cohort effects might be thought of either as interaction effects between age and period, or alternatively as a kind of differential residual: something which still remains even when age effects and period effects are accounted for. Though age, period and cohort effects are difficult to partition out mathematically, due to issues like colinearity between variables, they are easy to identify and distinguish between visually within our shaded contour plots.

Even though the formal statistical modelling of age, period and cohort effects is non-trivial, the contour maps make it relatively straightforward to identify and distinguish between the effects through informal visual analysis. The labelling of contour lines with the mortality risk which they correspond to means that maps from different datasets can be compared, and differences in effect magnitude between datasets can be estimated without any additional computation.

Researchers interested in making comparative inferences between datasets should note, however, that the degree of shading of cells in the contour maps is relative only to the distribution of values observed in the specific data used in its construction, and so the same shade will correspond to different values in different maps. It would be relatively straightforward, however, to produce additional contour maps in which a common shading scale is used for all visualisations. These may be more useful, for example, when comparing a large number of nations over the same period of time.

The informal visual comparison between maps - corresponding to different genders, populations within nations, and different nations – helps to develop ideas about the influence of such factors on the effects observed. This can help guide the development of additional contour maps, such as maps of log mortality and of differences between males and females, as are presented here for the first time. In addition, it can help researchers think about how best to incorporate these factors as explanatory variables in statistical models.

## 1.1. Age Effects

Age effects show how the mortality risk varies as people age. Historically, this relationship has been characterised as 'bathtub shaped': high in infancy, then low until early middle age, and then exponentially increasing in older age. (Gompertz 1825; Makeham 1860; Minton 2013a; see also figure 5 of this paper) However, looking at the contour plots, and other statistics which can be derived from the same data, shows that the shape of this 'bathtub' has changed substantially over the course of the twentieth century. Additionally, careful analysis of visualisations for a number of countries, and over the log scale, reveals that a substantially better model fit might be achieved using a slightly more complex model which incorporates two additional features. These features are referred to below as the coming-of-age effect and the coming-of-ageing effect, although other terms may exist.

### 1.1.1. Infant Mortality

Newborn babies are very vulnerable, and childbirth is hazardous for both mother and baby. Although in relative terms the first few years carry a much higher mortality risk than the years that follow, the size of this risk has reduced by some orders of magnitude over the course of the twentieth century across the world. This is illustrated for England & Wales in Figure 4, which shows how probability of dying within the first five years of life changed over the period for which the data are available. In 1850, the mortality risk was around one-in-three; by 2000 it had reduced to less than one-in-150. Despite heavy involvement and adult losses in two world wars, the majority of this improvement in infant mortality occurred within around two generations, between 1900 and 1950.

Comparing similar metrics between nations can help to identify which nations were the 'leaders' and which were the 'followers' in this revolution towards historically low levels of child mortality. In addition to the large number of European nations included in the HMD, the inclusion of more recently industrialised nations like Japan will help to identify whether other non-European nations have been able to make a transition to low child mortality in a shorter period.

### 1.1.2. Mortality in adulthood and older age

The right side of the bathtub represents mortality risk due to ageing. After a certain age has been reached the relationship between age and mortality risk is approximately log-linear. However, this side of the bathtub has been increasingly 'flattened' over time, meaning that any given ageing-related mortality risk which people used to face at a particular age is now faced a few years later. This is clearest to see by focusing on a single contour line, associated with early middle age in the late nineteenth or early twentieth century, and seeing how it has receded into much older years by the start of the twenty-first century. For an illustration of this see Minton (2013a).

There are different ways of calculating the relationship between age and mortality risk. Either this relationship could be based on a real cohort – identifying what proportion of persons born in year T=0 are still alive in T=1, T=2 and so on; or, the relationship could be based on a cross-sectional snapshot of the data, looking at mortality rates at different ages for a single year or group of years.

Both estimates are problematic. Following a real cohort necessarily means looking at a group of people who were born a long time ago, and whose life experiences were in many respects unlike and unrepresentative of younger cohorts. The cross-sectional approach involves producing estimates for a 'synthetic cohort', made up of members of all previous cohorts at different ages (two year olds born two years ago, five year olds born five years ago, twenty year olds from twenty years ago, and so on). Figure 5 presents an illustration of this, using data for males from the England & Wales dataset. It plots the relationship between crude mortality rate and age for both a historical cohort of males born in 1929 (solid, red line), and for a synthetic cohort made up of age-specific death rates in 2008 (blue dashed).

Neither the cohort nor the cross-sectional approaches provide estimates of the age-specific mortality risk likely to be experienced by a contemporary cohort, born much more recently. This is because the conditions faced by the historical cohort are unlikely to be representative of newer cohorts, and the estimates based on the synthetic cohort were not experienced by any cohort that has ever existed. This can be seen by comparing Figure 5 with Figure 6, which shows which data the two series sample from on the log mortality surface. The solid red line in Figure 5 effectively shows at which ages the diagonal red line in Figure 6 intersects each of the contour lines. Similarly, the thick dashed blue line in Figure 5 shows at which ages the vertical dashed blue line in Figure 6 intersects the contours.

The bathtub curve for a contemporary cohort, born in 2008, could be estimated by imagining at what ages the thin dashed purple line intersects each of the contour lines. Using the estimates produced by the 2008 synthetic cohort is equivalent to assuming that each of these contour lines should be projected horizontally. As the shaded contour maps show, this seems an unrealistic assumption, as many of the contours also appear to be slanting upwards over time. Shaded contour plots can help us think about which projections of the contours look more and less plausible given how these contours have moved along the Lexis surface. Different projections of the contour lines imply different bathtub curves, with different implications for areas such as pension and healthcare provision. Whether the projection of contour lines is done informally, using a ruler and a pencil, or formally, using advanced statistical methods, comparing between nations and populations within nations can provide further information as to the plausibility of different contour line projections. Differences in projections can have significant implications for, for example, the provision of health and social care services.

The bathtub curve for the synthetic cohort of 2008 appears not simply to be made up of two exponential distributions – one declining with age, and the other increasing. Instead, there is some evidence of a couple of 'kinks' in the function, which perhaps relate to two additional age-related effects which deserve to be incorporated in formal models. These effects will be described as the coming-of-age effect, and the coming-of-ageing effect, although other terms may have been adopted in the broader demographic literature. Both of these effect types will now be discussed in turn.

### 1.1.3. The coming-of-age effect

The coming-of-age effect is evident in some of the visualisations which stretch back over long periods of time. For example, the effect is apparent when looking at the contour map of mortality rates for both males (Figure 7) and females (Figure 8) in Norway. In these figures, the effect can be seen by looking at the contour line marked 0.005. (See Minton 2013a for an example of a contour map where a similar contour line has been highlighted.) From the earliest records in the middle of the nineteenth century until about 1920, this line moves left to right rather than up to down, and divides old children, about fifteen years old, from young adults, about nineteen or twenty years old. Around 1930, this contour line moves upwards almost vertically upwards, meaning the risk receded into late adulthood. The coming-of-age effect indicates that people were exposed to a much increased mortality risk once they were culturally deemed to have 'become men' or 'become women', or equivalently that they were protected from these risks until they came of age.

Although it may appear, when looking at the mortality surfaces, that the coming-of-age effect has disappeared in Norway, this is not the case. Instead, as mortality rates which occur between infancy and old age have reduced so much, absolute mortality rates are so low throughout much of the lifecourse that they appear indistinguishable on the standard mortality plots. Instead, the effect of entering adulthood on mortality is easiest to see by plotting the mortality surface on the logarithmic rather than identity scale. Plots of the log-mortality surface indicate the persistence of the coming-of-age effect in just about every nation and for both genders. For illustration, the shaded contour maps of the log-mortality surface for the Ukraine (Figure 9 for males and Figure 10 for females) and for the USA (Figure 11 for males and Figure 12 for females) are presented. The coming-of-age effect appears as a series of persistent horizontal bands, with a lower series of bands clearly separating childhood from infancy, and a higher series of bands separately childhood from early adulthood.

Within these series of concentric bands, there is evidence that 'middle childhood' has become ever safer, with pre-teen children experiencing extremely low mortality risks. The mortality risk in middle childhood appears lower even than would be predicted by the Bathtub Curve.

The coming-of-age effect appears stronger in males than females. This is apparent by looking at the difference in age-and-year specific log mortality rates between males and females, as shown in Figure 13 in the case of the USA. A positive value indicates that males have higher mortality rates than age and year matched females, and a negative value indicates the converse.

The values are positive for almost all age-year combinations plotted, meaning that males appear to have persistently higher mortality rates than females. The disparity becomes greatest from around the 1950s onwards, with a difference in log mortality rates of more than one. This male log mortality excess stretches from early adulthood, at around the age of 18 years, and continues into people's twenties. Although this effect is already known they are very easy to see using shaded contour plots.

### 1.1.4. The coming-of-ageing effect

The coming-of-age effect demonstrates one way in which the simple 'bathtub' mortality model may be inadequate at representing the true mortality distribution. Instead the mortality curve may be hinged around the age of eighteen. In addition to this coming-of-age hinge which occurs when people have lived to adulthood once over, there is evidence of a second hinge, an acceleration in mortality risk which begins once people have lived to adulthood approximately twice over. Dorling (2011), describing research published in Dorling (1995) and based on data available in the 1980s, suggests that the coming-of-ageing effect occurs at about 35 years old [p. 195] However, because contour lines have moved over time, there is no reason to suppose it still occurs at this age.

#### 1.1.5. The modelling and projection of age effects

At a minimum, a formal statistical model of age effects should incorporate the high mortality risk associated with infancy, and the exponentially rising risk in older age. The discussion above has shown that, to be sufficiently realistic, the model may also have to incorporate some additional effects. Rather than the relationship between age and mortality risk being fixed over time, we know that it varies, as shown by contour lines which have moved up or down the Lexis surface, rather than just across. There is also evidence that mortality rates in childhood would not be represented well enough by models which do not explicitly include a coming-of-age effect, and perhaps that mortality rates in early adulthood would not be predicted well enough by models which do not explicitly incorporate a coming-of-ageing effect.

Along with gender effects, apparent by looking at differences between mortality surfaces within a single country, there are also substantial differences between nations. Does space (geographical proximity, such as France and Germany) matter more than place (cultural proximity, such as sharing the same first language) in affecting how similar the demographic records are to each other? Formal statistical analysis, explicitly incorporating such variables, can help to tease out these influences.

### 1.2. Period Effects

Period effects are obvious in the contour plots as disruptions to the contours parallel to the vertical axis. The most obvious period effects in most of the datasets visualised relate to the two World Wars, but additional period effects exist. The world wars did not, of course, affect all nations of the world equally, with some nations paying a much higher price than others. Nor did the wars affect all nations at exactly the same time.

Spatial factors can therefore be expected to influence the period effects in a number of ways. For example, in countries where fighting took place, there might be more of a spillover of the effect from males of fighting age, to women, and to children of all ages. It is also known that the intensity and epicentres of the fighting shifted over time.

#### 1.2.1. The World Wars

As an example of how spatial factors influence the severity of the period effects associated with the world wars, consider Finland. Finland experienced not just one but two World War two period effects, clashing with the Soviet Union first in 1939, then in 1941, separated by a period of relative peace in 1940. This is evident in the shaded contour plot for Finnish males, as shown in Figure 14, where there are clearly two mortality peaks rather than one.  The effect of being on the front line is also clearly illustrated by comparing the male mortality maps for Finland with neighbouring Norway, shown previously in Figure 7.

The mortality surface for Finnish males also illustrates something about spillover effects. Whereas the period effects of World War Two primarily affected males aged between about 18 and 40, the World War One period effect also appeared to affect much older men. The period effect relating to

World War One appears to be less discriminating, less contained with regard to age, than the World War Two cohort effects.

### 1.2.2. Older period effects

The oldest of the datasets, Sweden, shows that period effects which affected all ages may have been relatively common, showing a number of broad vertical disruptions at all ages throughout the nineteenth and eighteenth centuries, as shown in Figure 15. The specific years in which these occurred are relatively easy to identify, and so can be compared against historical records for the country. It may be that these period effects related to infectious diseases rather than conflict or famine.

### 1.2.3. Newer period effects

The most recent period effect observable from the contour maps is from the Russia dataset, as shown, for males, in Figure 16. This occurred in the early 1990s, after the collapse of the USSR and the rapid economic liberalisation, or 'shock therapy', which followed.(Carlson and Vagero 1998; Marangos 2002, 2003; Rutland 2013)

Period effects are apparent in the contour maps primarily through the deeply wound concentric ovals which appear while the world wars were taking place. Different nations were exposed to this during slightly different years and to different magnitudes. These durations and magnitudes of exposure have a spatial component to them, as the 'fronts' of the war changed over time. When a front was located in a country, we expect the amount of harm to civilians to have increased. This level of spillover may be expected to differ by gender, and between military and civilian populations.

## 1.3. Cohort Effects

### 1.3.1. The 1918 Cohort Effect

Our previous paper discussed the cohort effect associated with being born around about 1918 in some detail, as well as how it can be identified in a number of countries using shaded contour plots. (Minton et al. 2013) An Oxford University Press blog entry promoting the paper offered the opportunity to speculate further as to the causes of the 1918 effect (Minton 2013b). Because of the amount it has already been discussed, the 1918 cohort effect will not be discussed in great detail within this paper, except to note that the variation in effect size between nations and populations within nations should be explored systematically in order to help disentangle contributing factors. Again, spatial factors are likely to be influential, as both war and disease spread across territories. Better understanding the factors which affected exposure and severity may be of contemporary relevance in fields such as international development and public health.

### 1.3.2. World War 2 Cohort Effects

The 1918 cohort effects were not the only cohort effects apparent from the data. By looking on the log scale, there are hints of a smaller 'Baby Boomer' cohort effect too, affecting persons born in the wake of the Second World War. A post World War 2 effect is also apparent for Japanese males (Figure 17) and females (Figure 18).

#### 1.3.3. Positive Cohort Effects?

In theory, a cohort effect does not have to be detrimental to a cohort's health. Positive cohort effects might also exist. The actuary Richard Willets has suggested that, in the UK, such a positive cohort effect exists for persons born between 1925 and 1945, and that this cohort experienced faster improvements in longevity than the previous and subsequent generation. (Willets 2003) However, this positive cohort effect is not readily apparent from the shaded contour plots presented for the UK or elsewhere.

## 2. Discussion

This paper has shown how shaded contour maps can be used to identify age, period and cohort effects within demographic data, and illustrate how they can be used to make informal comparisons about these effects between nations, and between populations within nations. These informal comparisons are a useful prerequisite to the development of more formal statistical analyses, which can be used to test for whether the patterns we see are really there, to estimate the magnitude of the effects observed, and perhaps to more accurately project estimates forwards and backwards in time. The availability of data from a large number of contiguous nations allows the potential for the influence of spatial factors to the patterns observed to be more formally assessed.

The next part of this discussion will suggest a way in which the patterns identified visual inspection of shaded contour plots can be formally tested and quantified. However, we do not claim this approach to be the only or best approach to adopt for such testing. Readers with more specialist knowledge in demographic and spatial statistics are strongly encouraged to develop and apply more sophisticated alternatives. The final part of the discussion, before the conclusion, will consider some of the other sources of data to which shaded contour plots can be usefully applied.

### 2.1. Counterfactual estimation through spatial imputation of Lexis surfaces

In order to estimate the impact of an event, the counterfactual also has to be estimated. Informally, the counterfactual is 'what would have happened if what happened did not happen'. Our noticing of the period effects and cohort effects means we have already estimated the counterfactual informally, because they are based on noticing 'disruptions', and these disruptions are necessarily deviations from expectations. These expectations are the counterfactuals. What we are doing in identifying these counterfactuals can form the starting point for a more formal method.

As we noticed the period and age effects as localised 'disruptions' to the general patterns, we therefore have a sense of what these same sections of Lexis surface would have looked like if they were 'undisrupted'. To describe this another way, if we were shown the contour maps with the suspected period and cohort effects removed, and unaware of these deleted features were asked to fill in the blanks, then we would have produced estimates of the counterfactuals. We can therefore consider approaching estimating the counterfactuals as a missing data and imputation problem.

We are imputing over a two dimensional surface, and therefore methods of spatial data analysis may be useful. The famous 'BYM model' may therefore be helpful in this task. (Besag et al. 1991) Its initial application was, of course, in digital image restoration, and as we saw in Figure 2 , our data is effectively a greyscale image.

A BYM style approach may be useful both for the estimation of the counterfactual, and also for formally testing for the presence of these effects. This latter application might be achieved as follows: copy the Lexis surface and, in this copy, selectively delete a contiguous array of values within it. Then, 'restore' the missing section, and store this restoration, i.e. the imputed part of the surface, in a separate matrix. Do this for the entire image, one deletion-and-restoration at a time, until an imputed version of the entire surface is produced. This imputed surface may be able to help locate the period and cohort effects by comparing the observed and the expected surfaces to produce a surface of residuals. The cohort and period effects may then appear as areas with abnormally large residuals. The magnitude of the period and cohort effects could then be estimated by comparing them with the relevant sections of the counterfactual surface.

There are also a number of existing age-period-cohort (APC) models, some of which explicitly include spatial factors (for example: Lagazio et al. 2003; Aamodt et al. 2007; Xu and Hertzberg 2013). It may be interesting to compare estimates produced by these models with the imputed surface approach described above, as well as with estimates produced informally, through visual inspection of the contour lines.

### 2.2. Extending comparisons further over space and time

Although the Human Mortality Database is a very useful resource, more data is always helpful, both for improving visually derived informal intuitions, and for the formal modelling and testing of hypotheses. Fortunately, more demographic data are becoming more available and accessible. The success of the HMD has helped lead to the development of the Latin American Human Mortality Database, which contains mortality data, including cause specific mortality data, for Argentina, Brazil, Colombia, Mexico and Peru (Urdinola and Queiroz 2013); additionally, there is the Canadian Human Mortality Database, which presents data by county (Wilmoth et al.). We also expect that comparing the mortality surfaces of other subgroups within a nation, such as high and low socioeconomic deprivation subgroups, could be informative. For example, it may show differences in exposure to the mortality effects of war, changes in infant mortality, or changes in mortality risk at older ages. The application of shaded contour maps to other sources of data, including appropriate morbidity data such as prevalence of obesity, and the use of data from poorer nations recorded by health demographic surveillance systems is also encouraged. Another ‘sister’ project to the HMD is the Human Fertility Database, and applying shaded contour plots to fertility data may be similarly informative. (Goldstein et al. 2013)

## 3. Conclusion

This paper has illustrated a number of ways that shaded cohort maps can help researchers understand the influence that gender and nation have on long-term trends in longevity. It has identified a number of patterns both within and between nations. We consider a shared national identity to be a coarse and crude, but easily accessible, indicator of variations in both space and place. It provides an indication of variation in spatial factors, such as the geography, geometry and climate experienced by populations. It also provides some indication variation in place, relating to factors such as culture, language, system of laws, socioeconomic infrastructure, and so on. Where possible, ‘natural experiments’, such as the disunion of Germany after the Second World War, which led to different members of the same population experiencing different political systems for over two generations, should be investigated in order to help tease out the influence of specific variables.

The informal, visual identification of these patterns should be followed up by the development and application of statistical models which allow for the statistical significance of these patterns to be tested for, for the magnitude of the effects to be estimated, and for robust projections to be made. Similarly, the development of formal statistical models should be complemented by appropriate visualisations of the data being modelled, as the human brain may be able to identify patterns which a statistical model would not. The application of shaded contour plots to better understand similarities and differences in the demographic destinies of different nations, and the populations they are inhabited by, is strongly encouraged.

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## Figures


**Figure 1 World Map showing countries for which Human Mortality Database (HMD) data are available, coded by duration of data (Year first reported)**

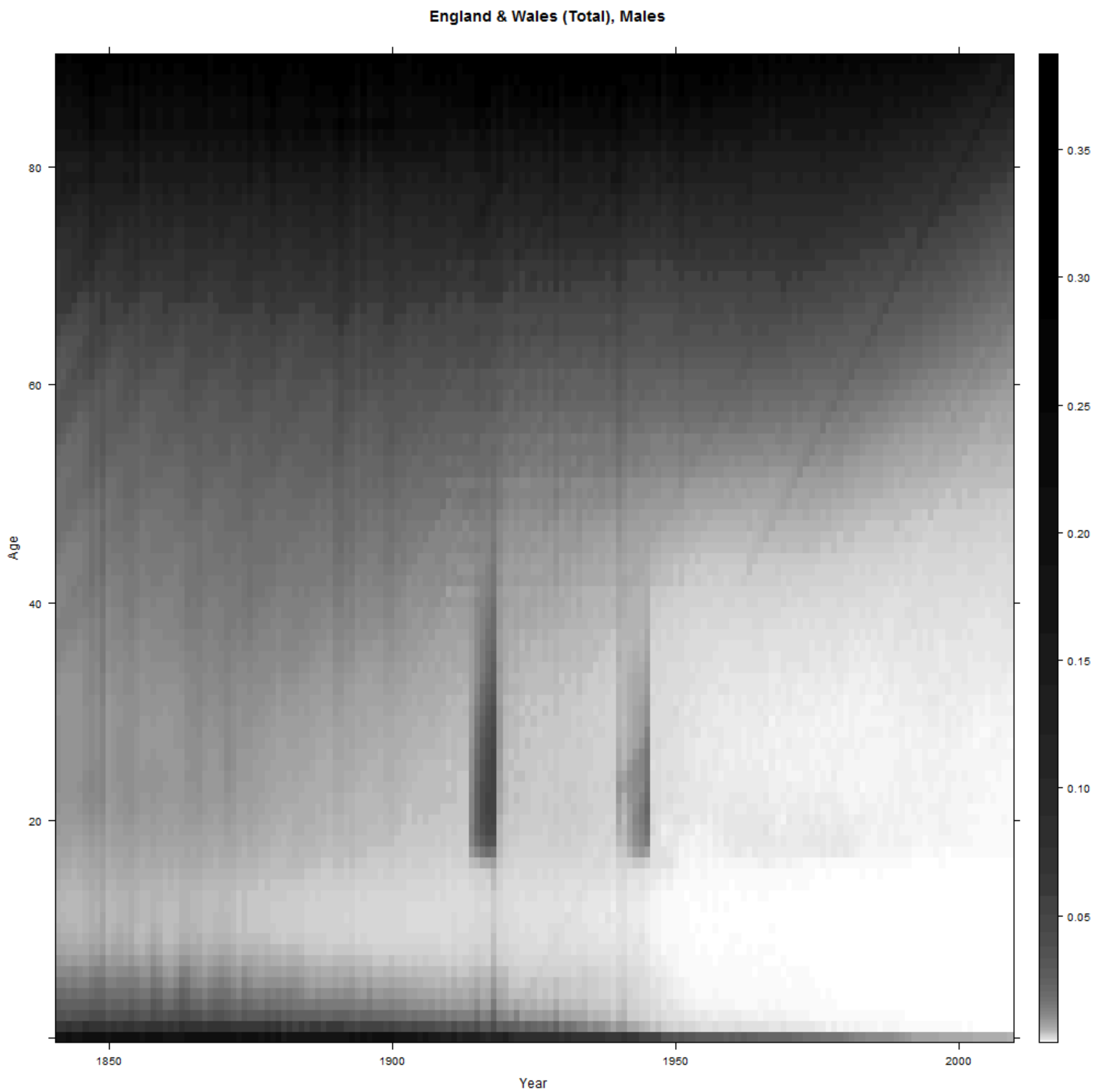


**Figure 2 A heatmap representation of the mortality surface for males in England & Wales, 1847 to 2009. Darker shades of grey indicate higher mortality levels**

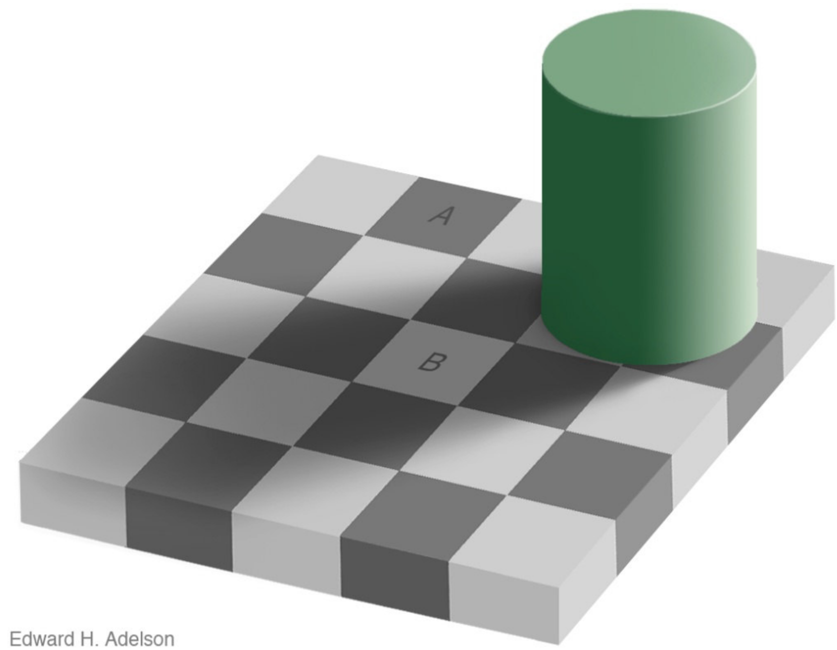


**Figure 3 The Checkerboard Illusion. The tiles marked A and B are of the same shade of grey.**

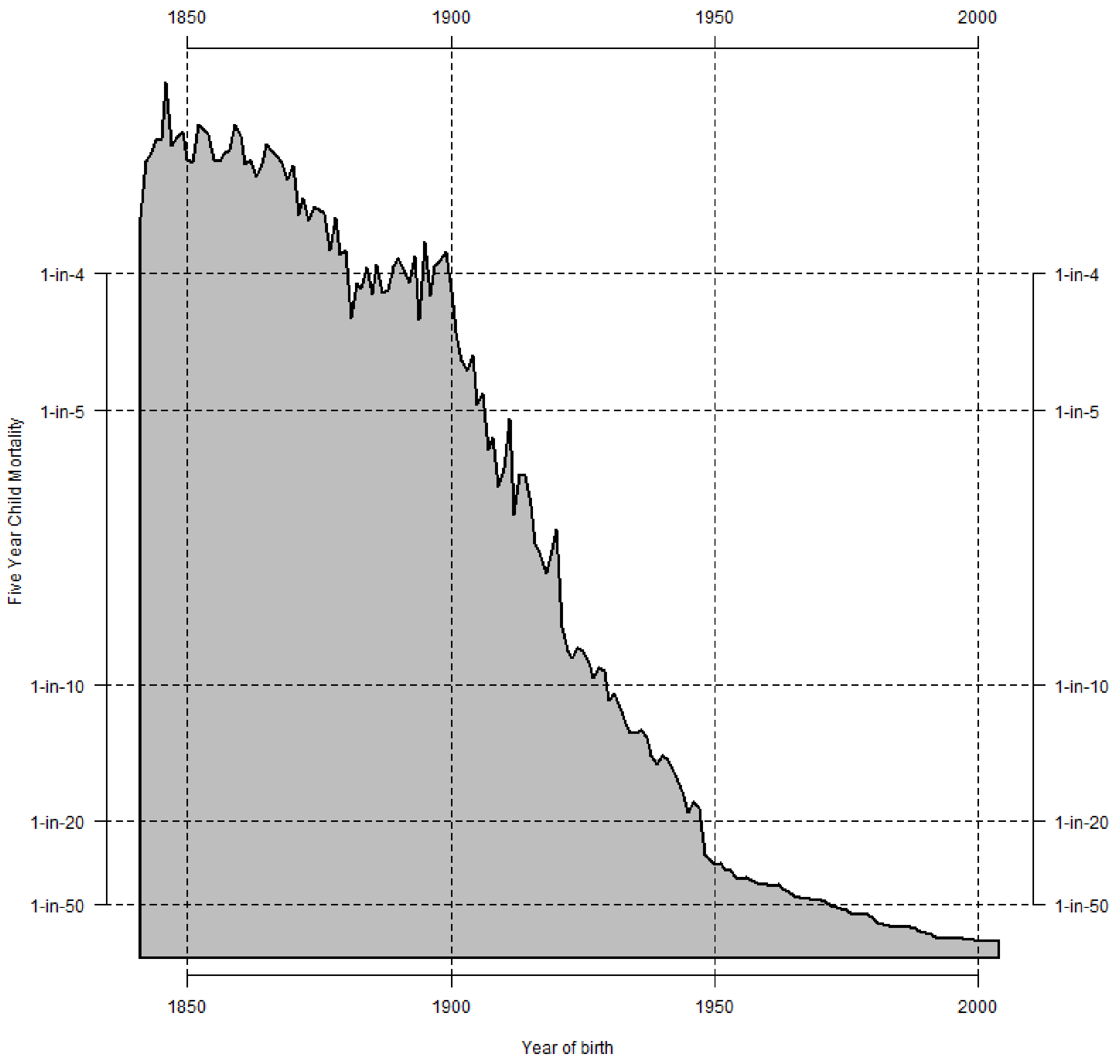


**Figure 4 Change in five year child mortality (probability of dying before the age of five). Males, England & Wales, 1847 to 2010**

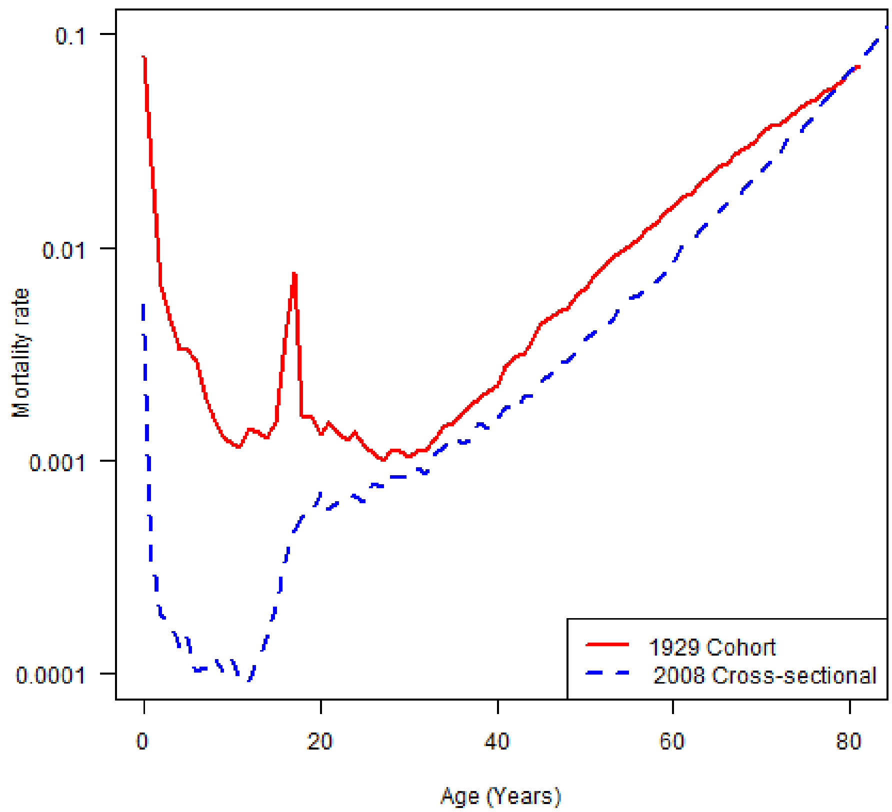


**Figure 5 Crude mortality rates as a function of age, males, England & Wales dataset**

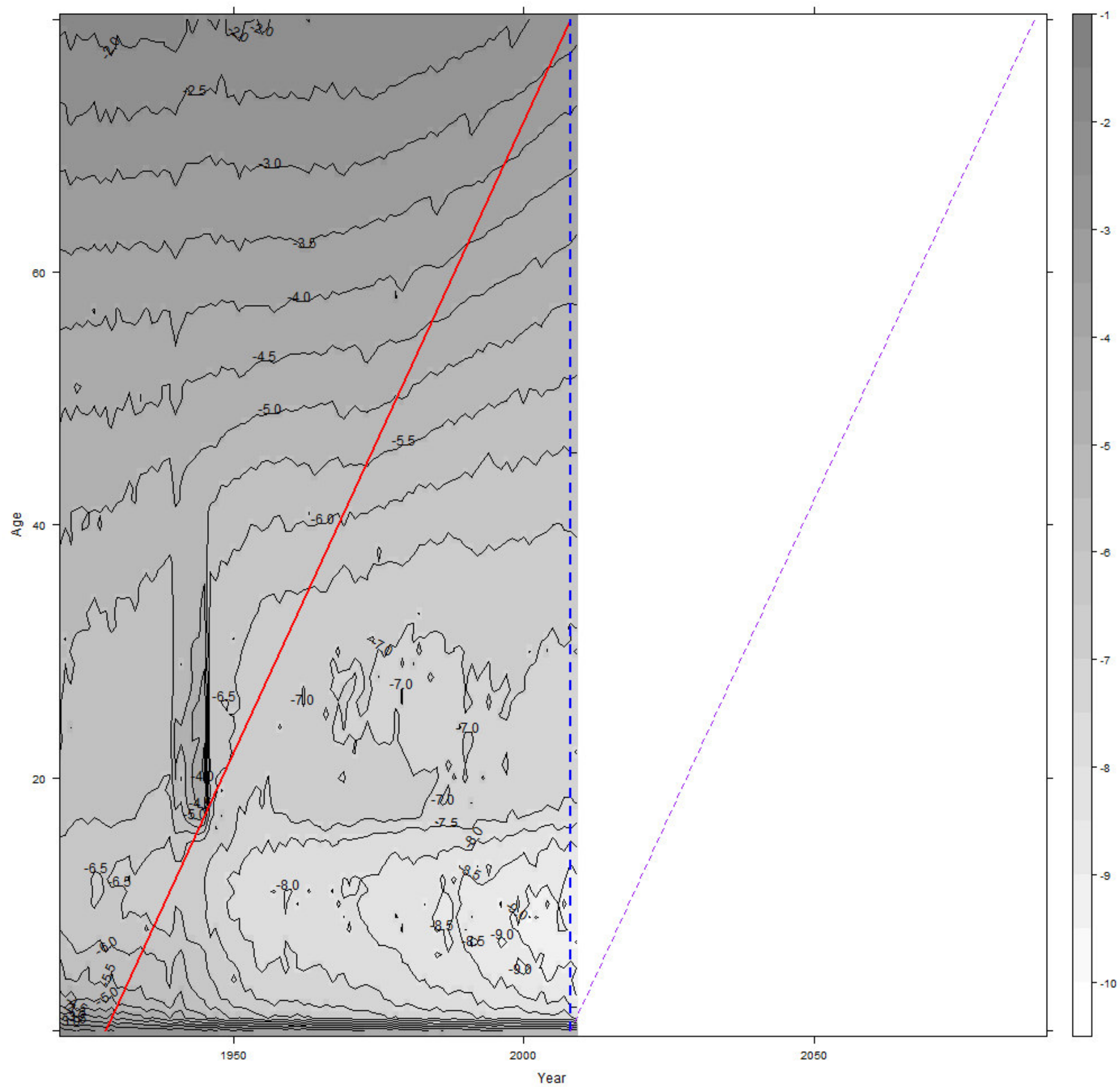


**Figure 6 Shaded contour plot of log mortality rates for males, England & Wales, 1920 to 2009, with lines added to illustrate the differences between the 1928 historical cohort (thick red) and the 2008 synthetic cohort (thick dashed blue). The age-dependent mortality rates of a cohort born in 2008 are represented by the thin dashed purple line**

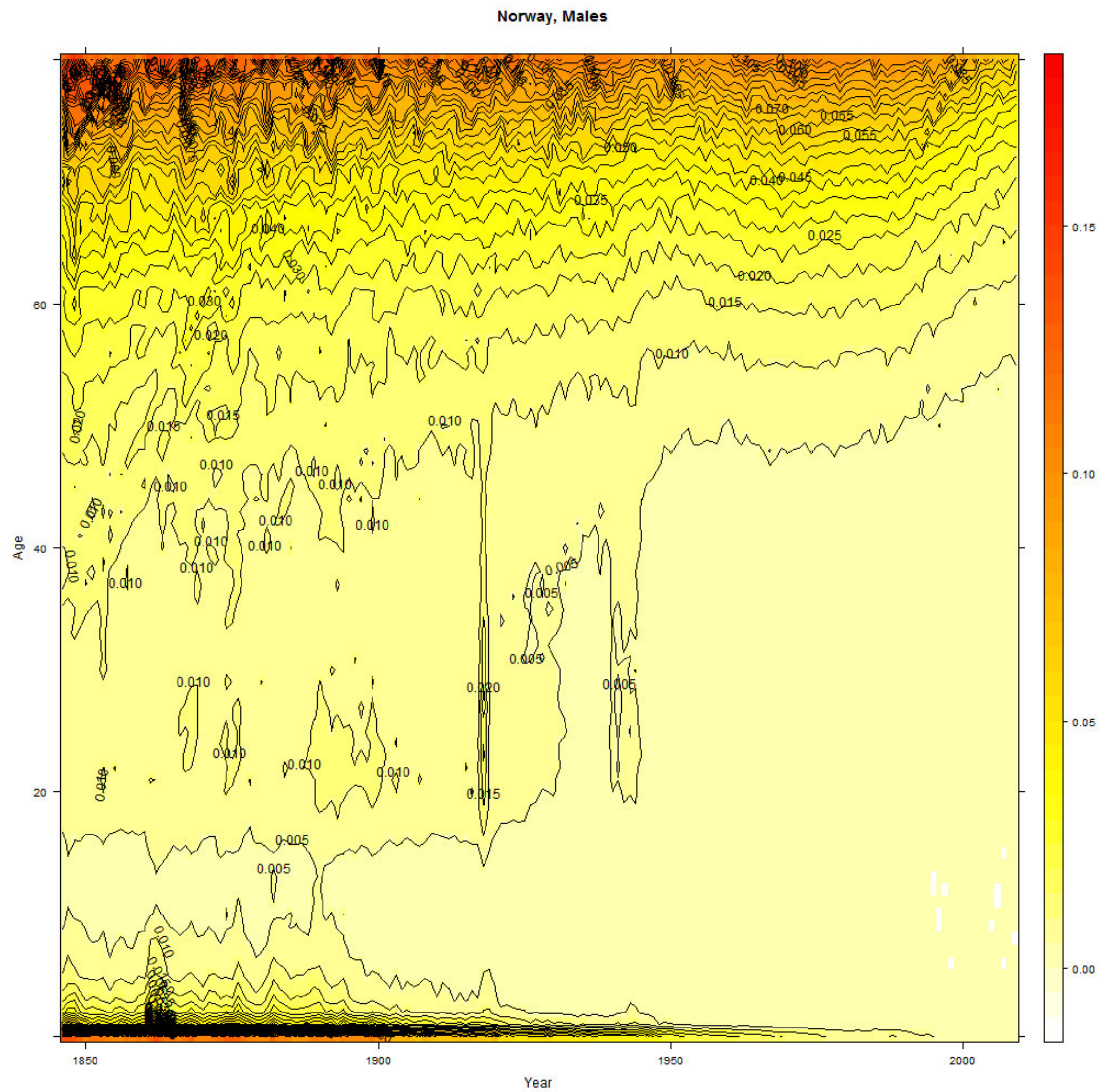


**Figure 7 Shaded contour plot of mortality surface, Norway, males**

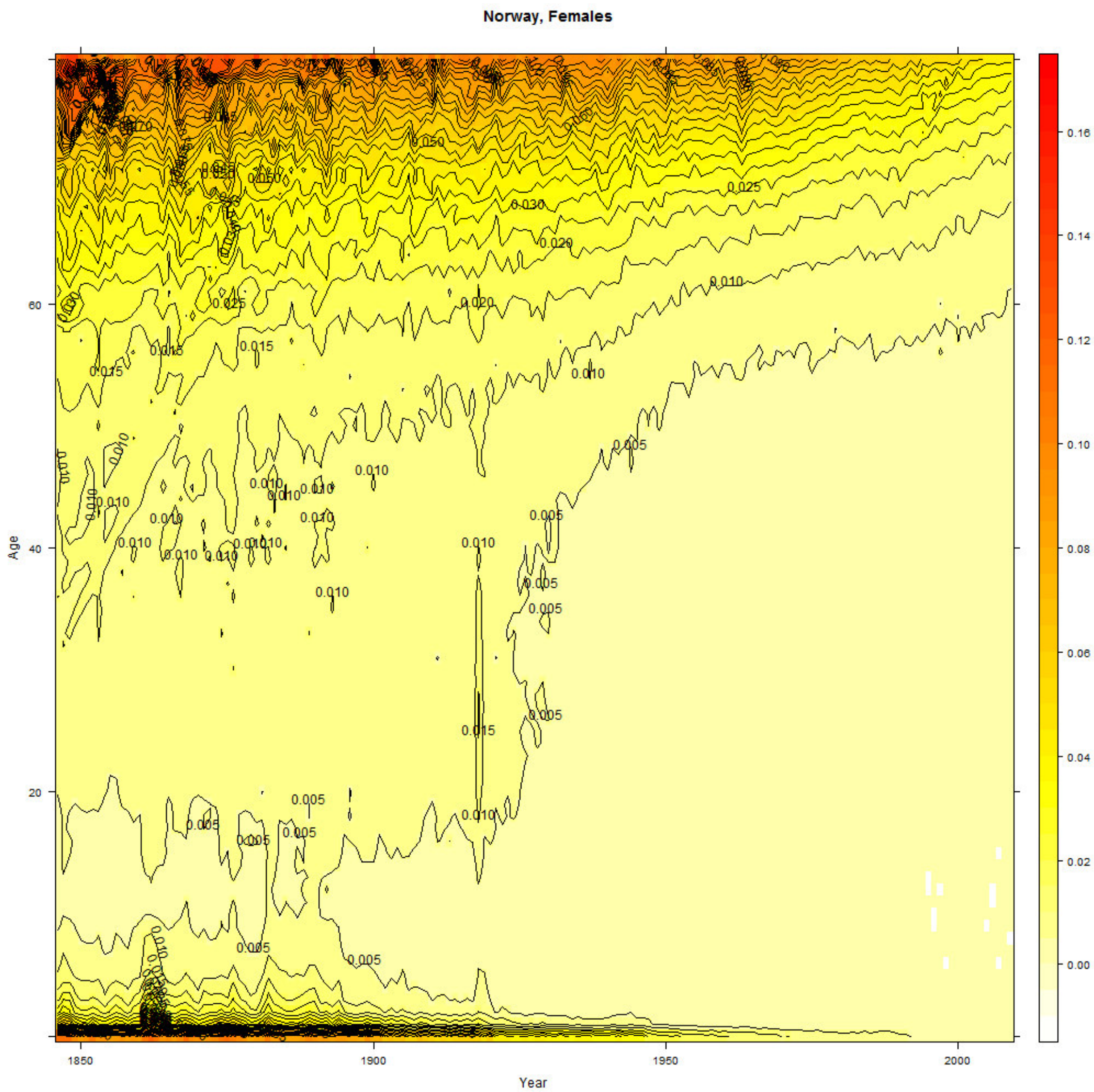


**Figure 8 Shaded contour plot for mortality surface, Norway, females**

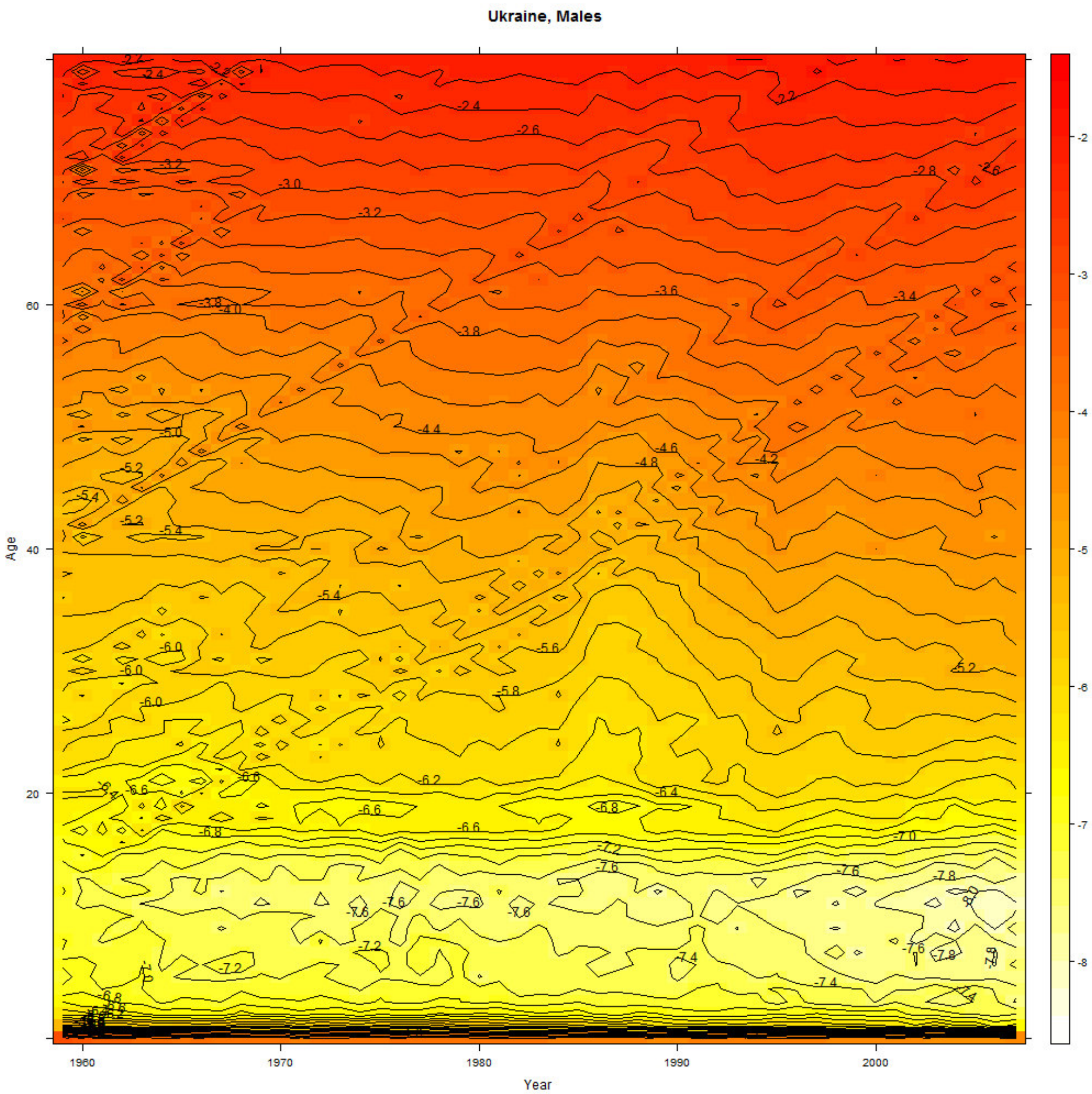


**Figure 9 Shaded Contour plot of log mortality surface, Ukraine, males**

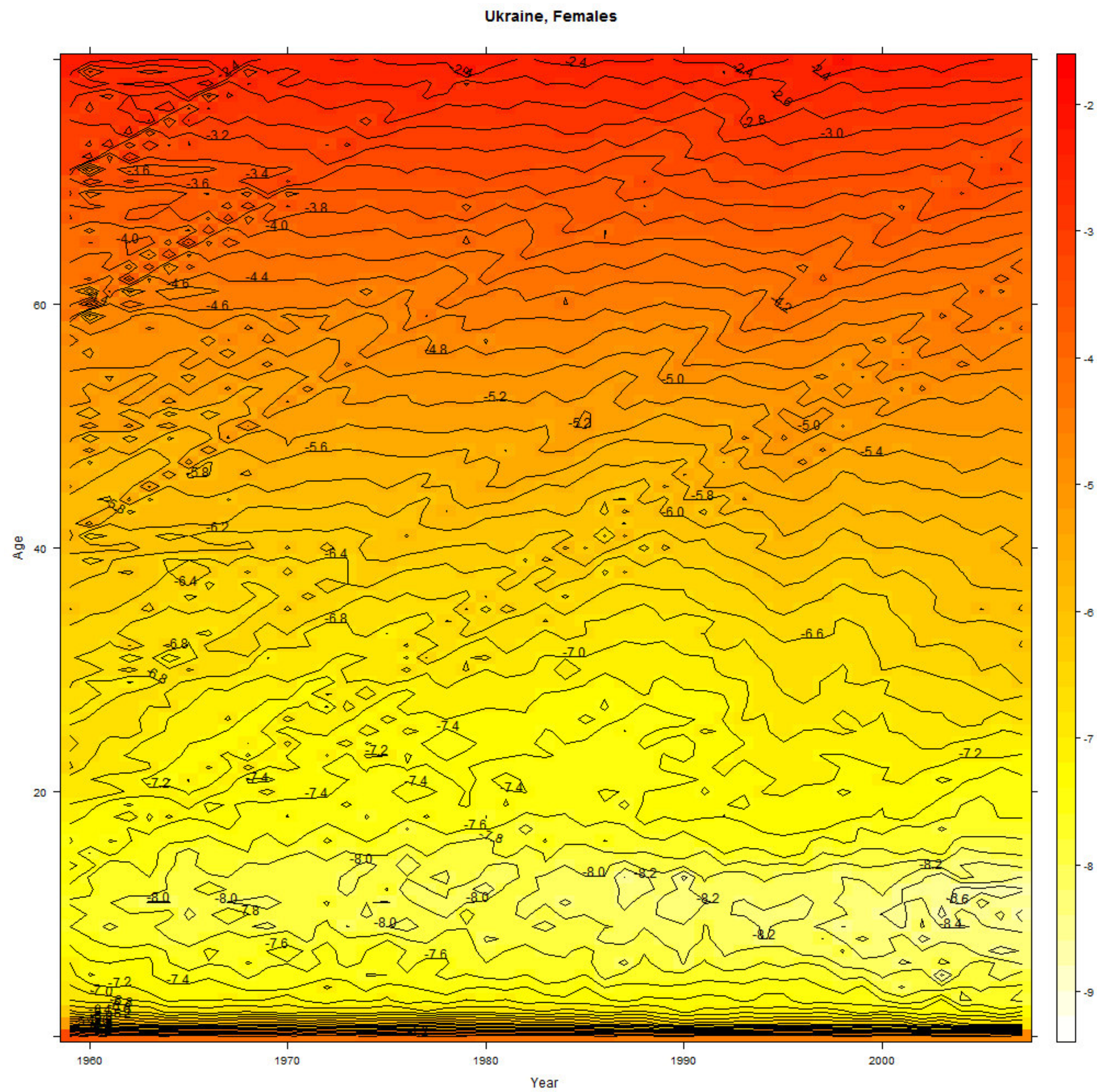


**Figure 10 Shaded contour plot of log mortality surface, Ukraine, females**

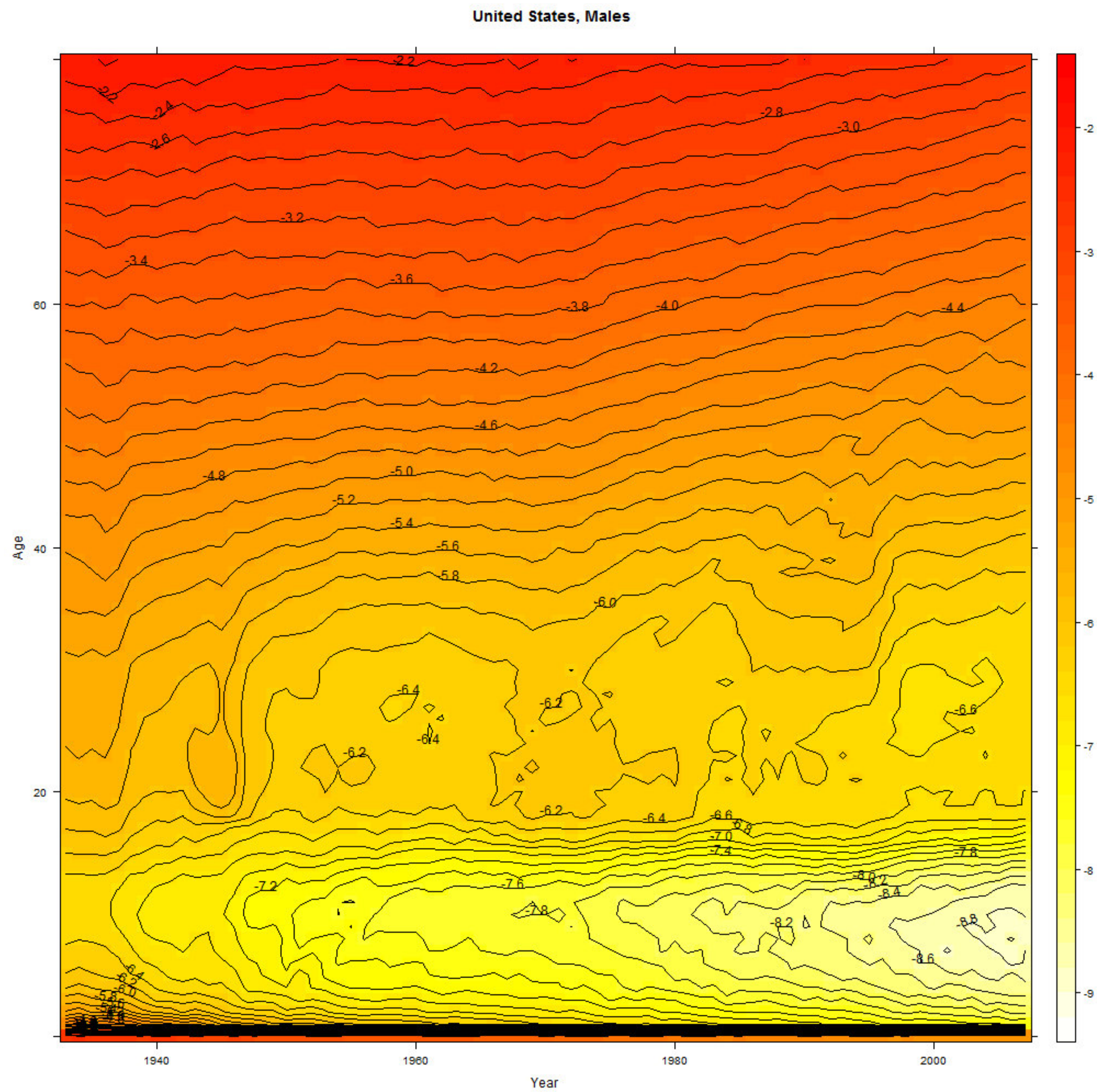


**Figure 11 Shaded contour plot of log mortality surface, United States of America, Males**

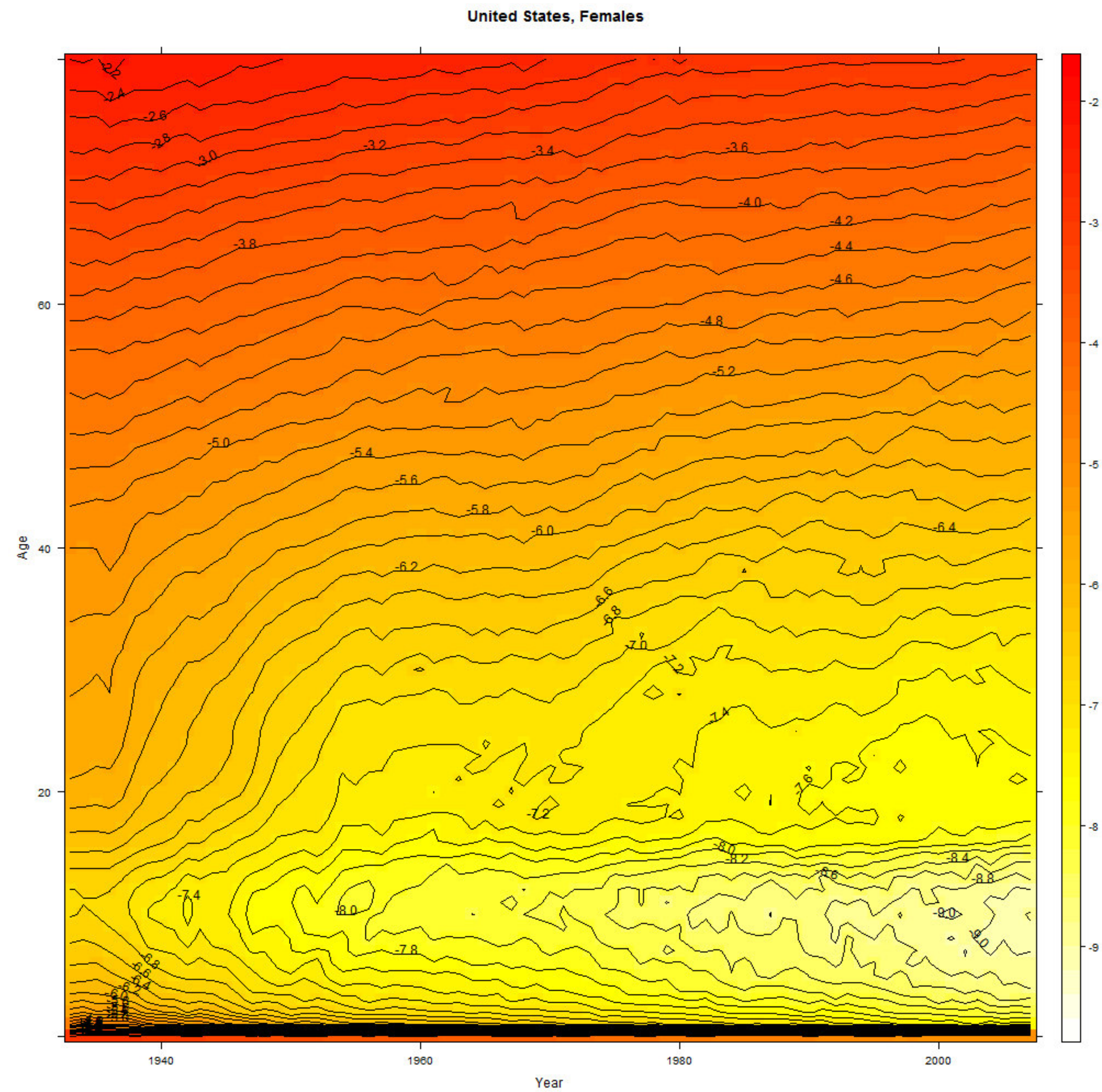


**Figure 12 Shaded contour plot of log mortality surface, United States of America, Females**

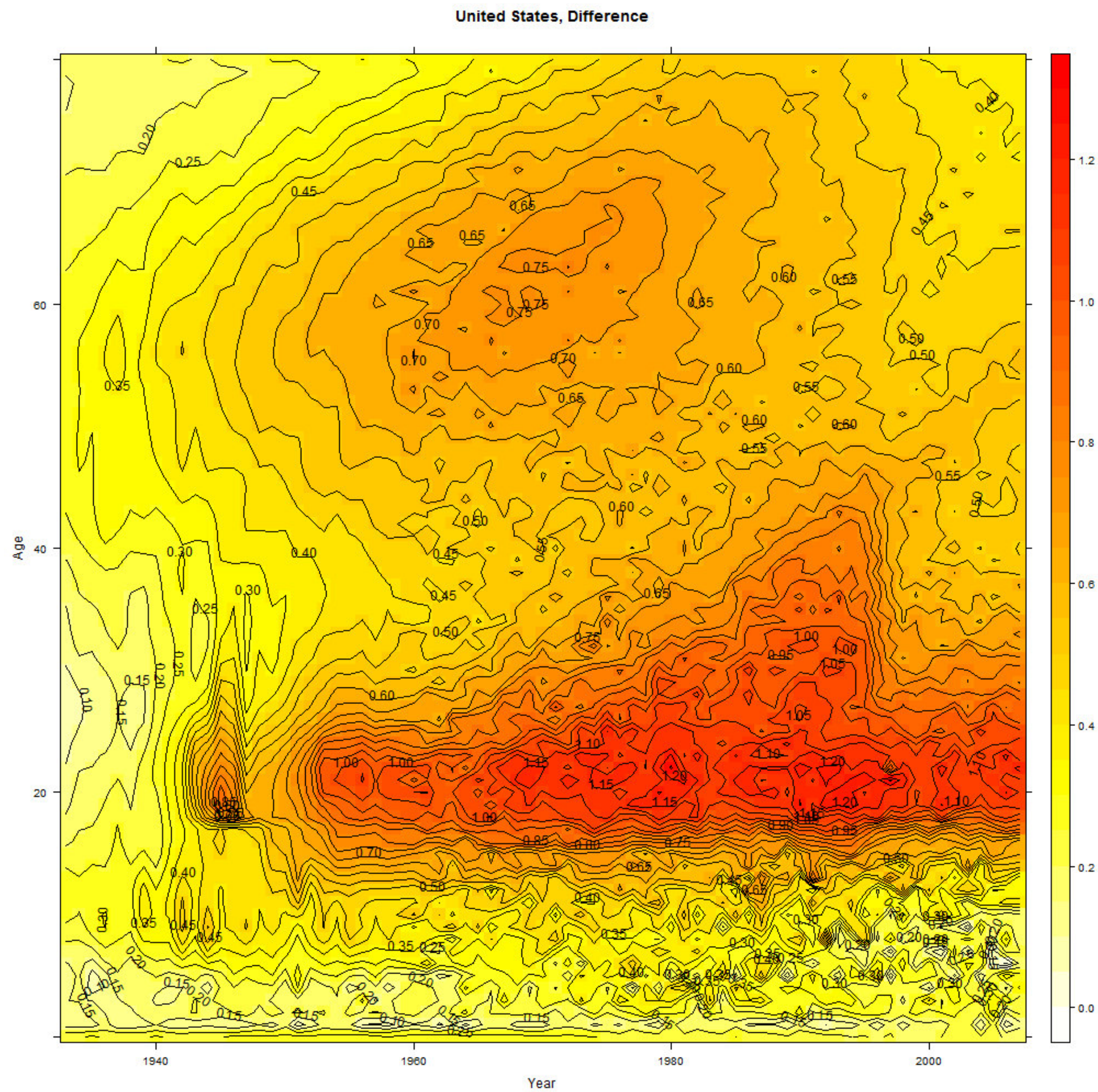


**Figure 13 Difference in male and female log mortality surfaces, United States of America. Positive values indicate higher risks in males than females**

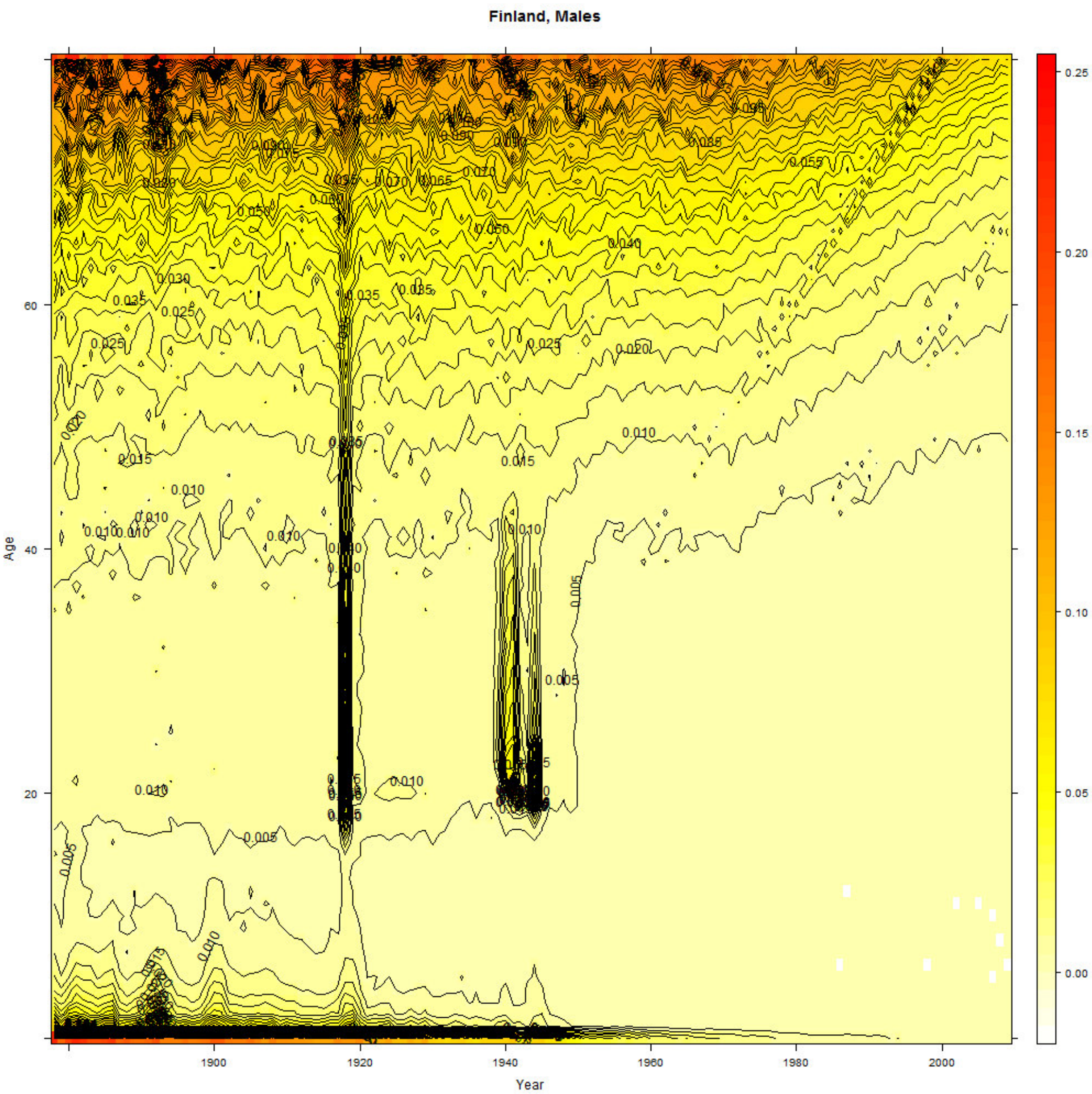


**Figure 14 Shaded contour map of the mortality surface. Males, Finland**

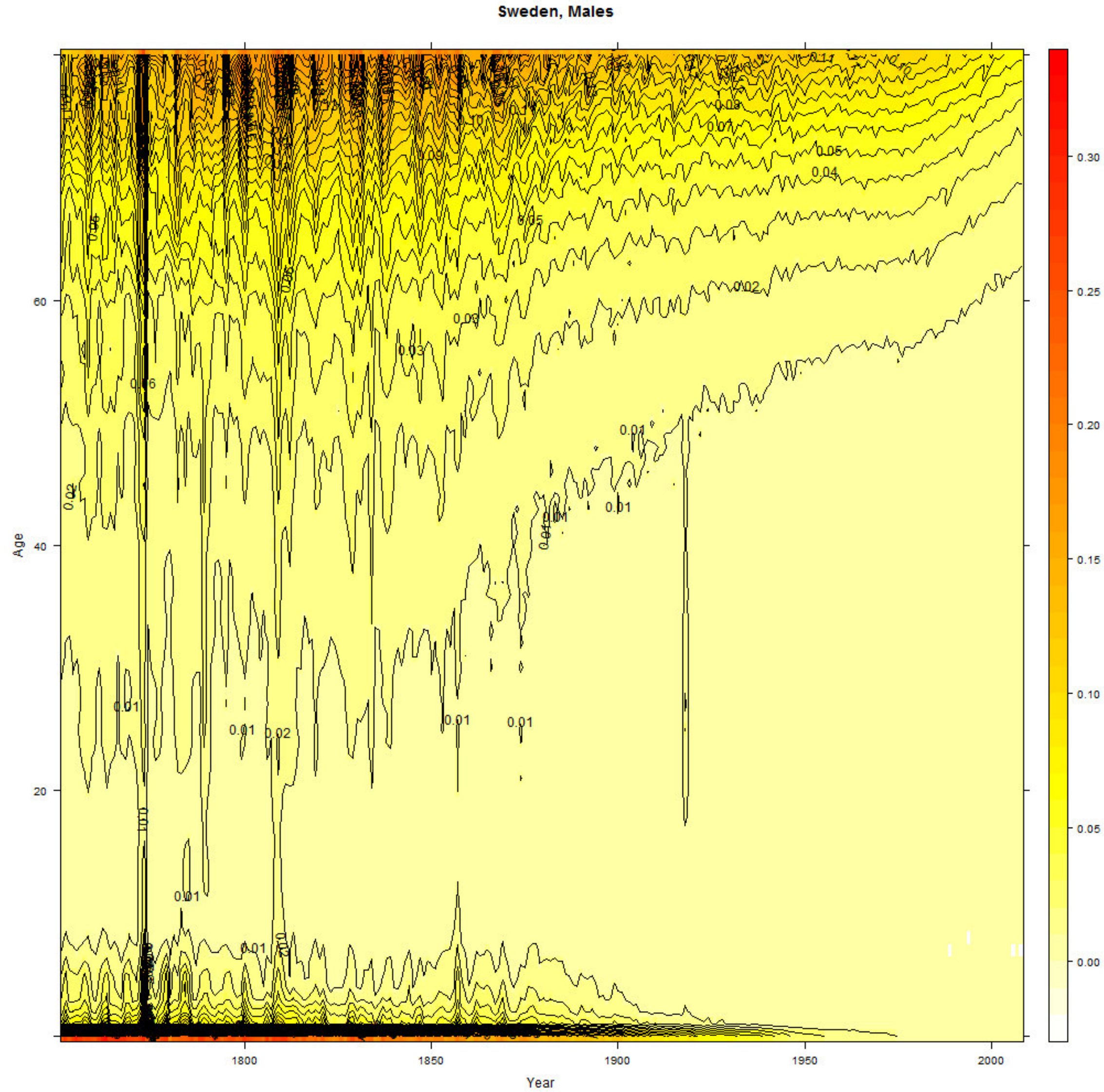


Figure 15 Shaded contour plot of mortality surface. Males, Sweden

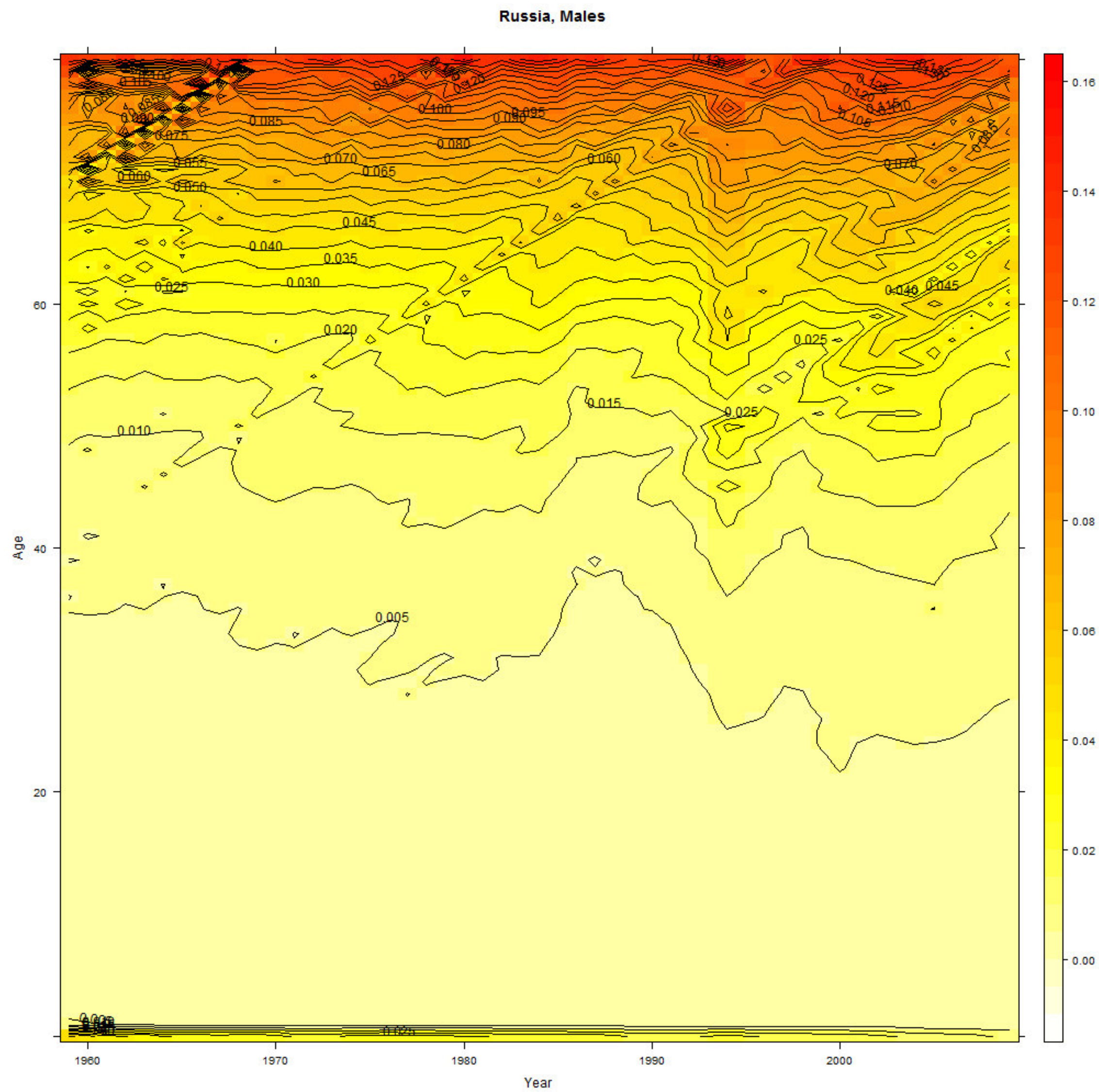


**Figure 16 Shaded contour plot of the mortality surface. Males, Russia.**

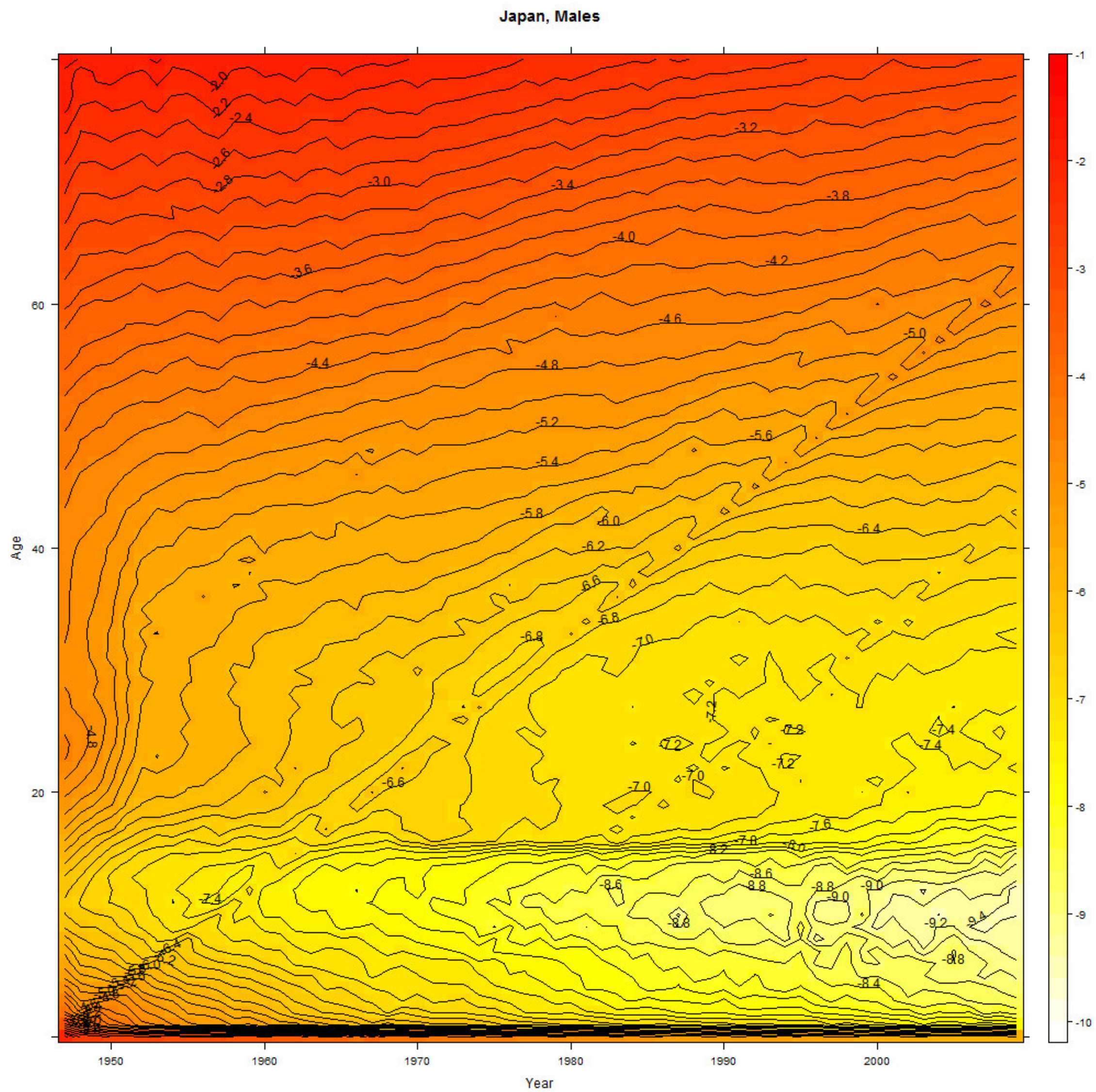


**Figure 17 Shaded contour plot of log mortality surface. Males, Japan**

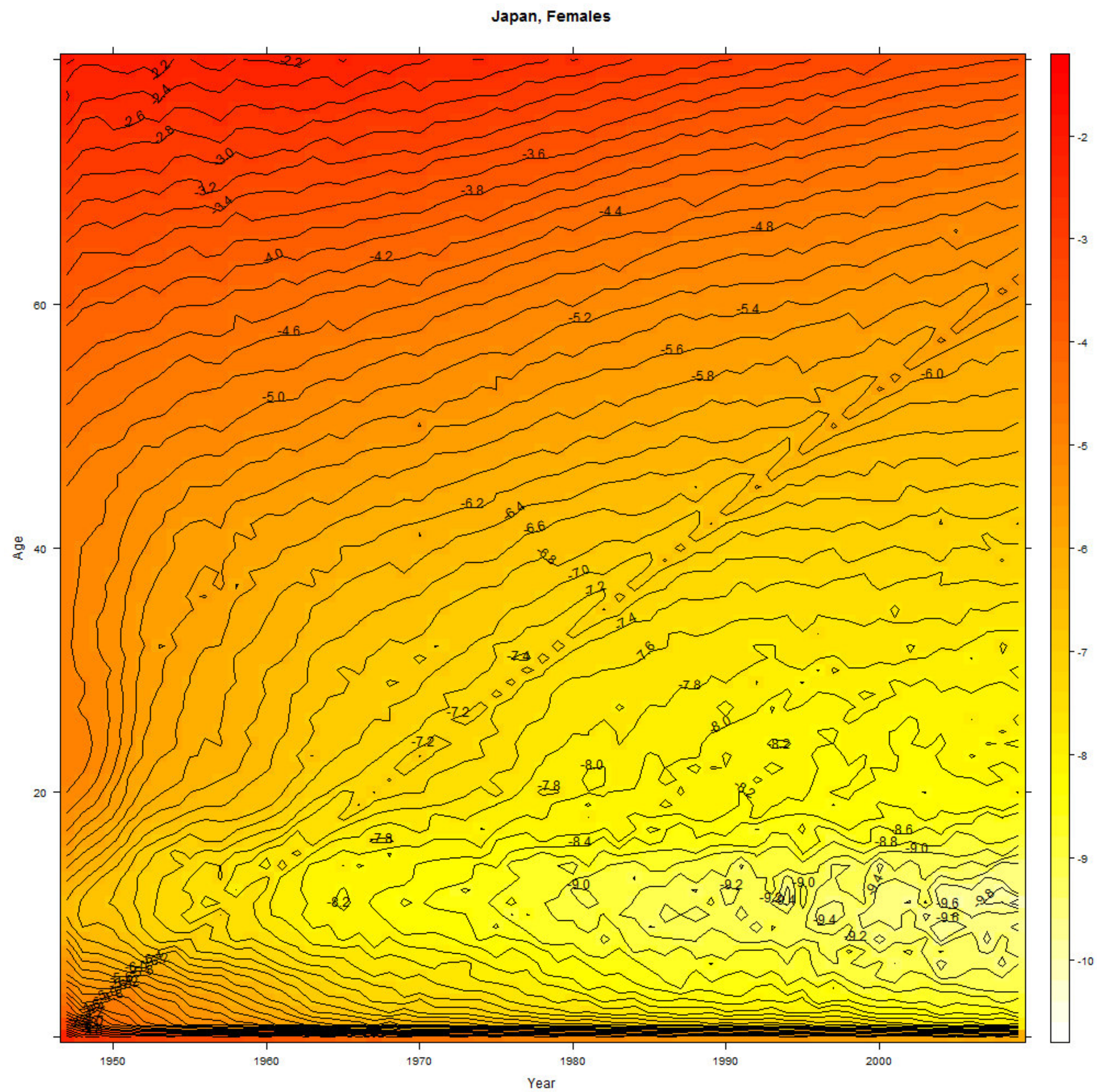


**Figure 18 Shaded contour plot of log mortality surface. Females, Japan**

## Highlights

- Shaded contour maps are a way of showing how something varies over a two dimensional surface.
- A two dimensional surface where the dimensions are age and year is known as a Lexis surface.
- A Lexis surface where the outcome variable is mortality is known as a mortality surface.
- Mortality surfaces for around 100 populations from 37 nations have been produced.
- These surfaces can show how place and space influences health and longevity.

# Using shaded contour plots to estimate bathtub curves

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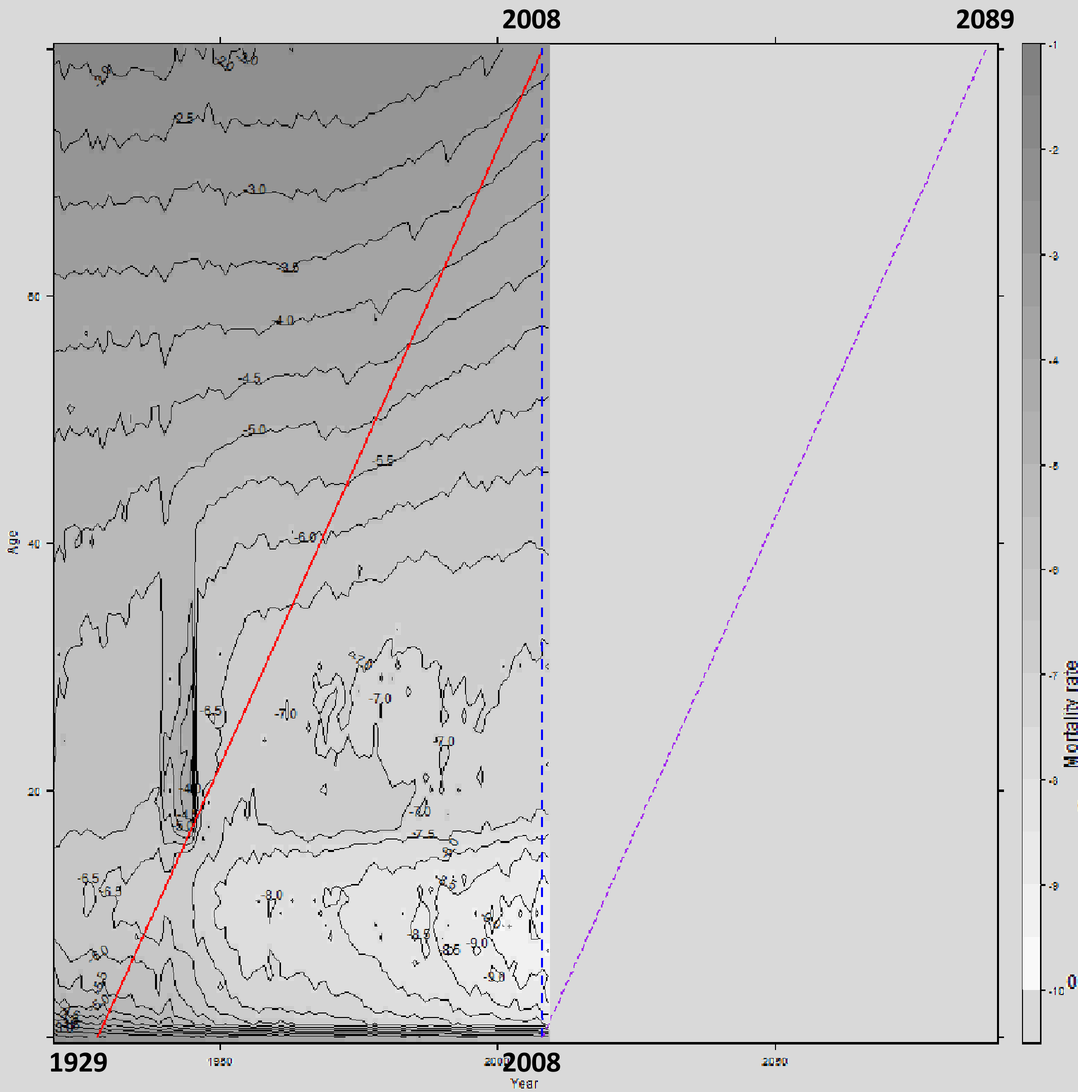


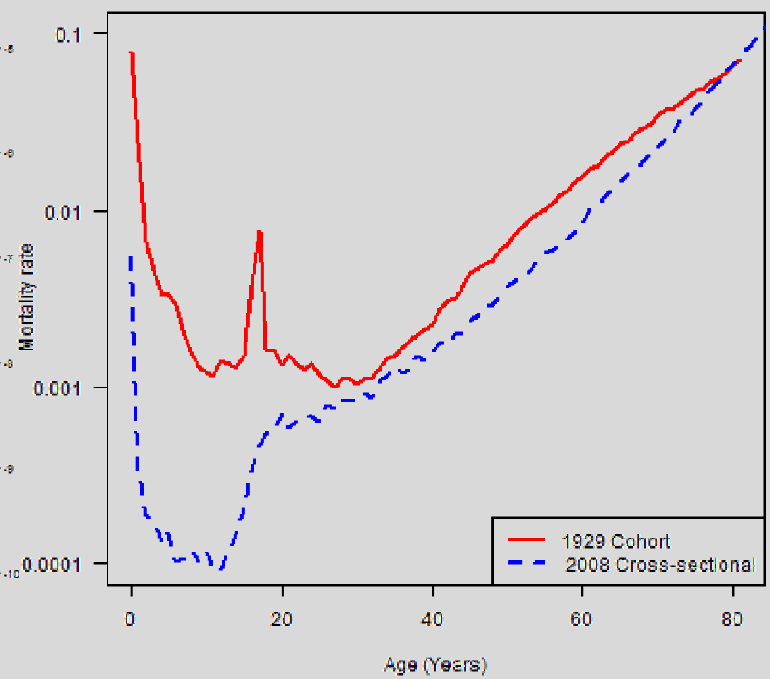

*a) Contour plot of mortality surface for Males, England & Wales with two coloured lines indicating the 1929 cohort (red), and a synthetic cohort (cross section) based on age-related mortality in 2008 (dashed blue line).*

These figures show how 'bathtub curves', mortality rates as a function of age, can be read from contour maps.

The **red** and **blue** lines in figure a indicate two planes which cut the landscape at right angles to both age and year. The corresponding **red** and **blue** lines in figure b effectively shows what the cross-sections formed by 'cutting' these surfaces along the planes would look like, i.e. they are tomographs, as commonly used in medical imaging.

The bathtub curve public health researchers really want to be able to estimate is that associated with the **thin, dashed purple line** in figure a. The corresponding tomograph produced would be the bathtub curve which will be experienced by a new cohort, in this those case born in 2008.

Although we do not have the data to produce the bathtub, we can estimate it by extrapolating the contours produced from the data we do have. This is likely to produce better estimates for the 2008 cohort than the alternatives shown here.




*b) Mortality as a function of age for the two colour lines added to figure a*