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Probabilistic World Population Projections Based on Expert Opinion

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WP-96-17
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ABSTRACT

This paper presents, to our knowledge, the first probabilistic projections of the world population. These projections were carried out as part of the updated 1996 revision (forthcoming in May-June 1996) of *The Future Population of the World. What Can We Assume Today?* (W. Lutz, ed., 1994). Projections are performed at the level of 13 regions to the year 2100. The approach is based on expert judgement about the trend and uncertainty of future fertility, mortality and migration in all the regions. For each of the components a group of experts defined three alternative future paths: low, central, and high. A standard normal distribution is fitted to these assumptions with the central assumption giving the most likely case (mean), and the low and high assumptions giving the range of 90% of all possible cases. Drawing randomly from these distributions, 4000 simulations produced uncertainty distributions for future population size and age structure. The simulations presented consider both the cases of independence/dependance between regions (whether regions follow the same above or below average trend) and between fertility and mortality trends.

One of the many results is that we are able to say now that there is roughly a two-thirds probability that the world population will not double any more in the future. The 95 percent confidence intervals for total world population in 2020 are 7.5-8.3 billion (median: 7.9); in 2050, 8.1-12.0 billion (median: 10.0); and in 2100, 5.7-17.3 billion (median: 10.7).

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1 Introduction

One thing that we know with certainty about the future population sizes is that they are uncertain. The nature of this uncertainty and how to deal with it are highly controversial and still scientifically unresolved issues. Is there a well-defined sense in which there exists a distribution of possible future populations? Can mean, median, and modal future population sizes be determined? Can confidence intervals for future population sizes be derived? The literature on projections contains three views on this, none of which we find wholly satisfactory. In this paper, we provide a fourth prospective.

Most national and international agencies that produce population projections avoid addressing the issue of uncertainty explicitly. Typically they provide one main variant that is to be considered the most likely case. Sometimes high, low, and other variants are added, but these are virtually never given a probabilistic interpretation. If anything is said explicitly, it is that the high and low variants should not be considered to define confidence intervals. Supplementing the variants with presentations of extreme case scenarios can be useful for sensitivity analysis, but it does not help in quantifying the extent of uncertainty.

In contrast, a number of methods of producing fully probabilistic population projections have been proposed and implemented, although so far only on the national level.[1] These approaches, which are almost exclusively based on time series models, produce distributions of future populations sizes, and thus, seem to be able to tell us, quite precisely, how much uncertainty there is in the outcomes of population projections. A third possibility is to make an assessment of the likely error in future projections, by evaluating the errors made in past projections. This approach has been suggested in Keyfitz (1981), and Stoto (1983). Depending on one's perspective, it has the advantage or disadvantage of using past data on projection accuracy.

In this paper, we propose and implement a new method for dealing with the uncertainty of future population sizes. We call our projections "probabilistic population projections based on expert opinion." It is distinguished from the other methods by its use of expert opinion on both the future courses of fertility, mortality, and migration, and on the extent of their uncertainty. To our knowledge this is the first time that probabilistic population projections have been made in this manner, and the first time that a probabilistic model has been applied to all world regions. Therefore, our results should be treated with the same sort of caution that is appropriate for all new ideas before they are thoroughly tested. Nevertheless, we think that the use of expert opinion could have significant advantages over the use of time series models or past projection performance.

In Section 2 of this paper, we briefly discuss the motivation for developing a new approach to probabilistic population projections. Section 3 discusses the interpretation of confidence intervals in the present context. Section 4 contains a description of how we took the opinions of the experts and combined them to produce our probabilistic population projections. In Section 5, we present the information we have obtained on population size and age structure for each of thirteen regions, which together cover the entire globe. In Section 6, we present similar data for the world as a whole. We conclude in Section 7, with a discussion of the implications of the expert-based probabilistic projections for the interpretation of other projections.

2 The Motivation for New Probabilistic Population Projections

The usefulness of a population projection is enhanced by knowing its range of uncertainty. Indeed, the uncertainty as well as the mean of a projection could influence the actions that policy-makers take. There currently exist two methods of quantitatively assessing the likely error of a projection: (1) time series analysis, and (2) ex post error analysis. In time series analysis, parameters are estimated from past data on the determinants of population change, like fertility and mortality. Those parameters, along with estimates of their uncertainty are used to project the information needed for population projections into the future. In ex post error analysis, data is collected on the extent of errors in past projections. On the assumption that those errors are what can be expected in the future, we can tell policy-makers and others what range of errors to expect.

Time series analysis is an approach, not a recipe. Different people using time series analysis on the same data have produced different projections along with different error estimates.[2] Most of the assumptions in the time series approach are statistical in nature. Thus, in evaluating a set of different time series based projections, we need to discuss statistical concepts such as stationarity, linearity, transformations of variables, orders of autoregressive and moving-average processes, autocorrelation, error term correlations equations and a whole host of others that have no easy translation into the birth rates, death rates, and migration rates that we need to make a population projection. It is easy to use a set of statistical assumptions, that although they individually seem plausible, produce implications for future demographic changes that would be thought to be highly unlikely by experts in the field. The problem might not be with any particular assumption, but with a complex interaction of assumptions that is difficult to diagnose. In addition, the information that the time series analysis takes out of a historical dataset is typically short-run in nature. Most commonly, demographic variables are only related to their own values over the previous few years. This is fine for making relatively short-run projections. In making long-run projections it is more appropriate to use a procedure that focuses on the determinants of longer term changes. Because of the indirect connection between assumptions and implications, it is difficult for policy-makers and others not trained in statistics to assess the error bounds produced by time series analysis.

Ex post error analysis is much clearer than time series analysis, but it also has a problem when used in the context of multiple projections of the same population over the same period. Suppose one projection said that the population at some future date would be 10 million people and another said it would be 20 million people. If the mean error of past projections was plus or minus 15 percent, we would have to tell policy-makers that the population would be 10 million plus or minus 15 percent or 20 million plus or minus 15 percent. Thus it is possible that the average of past errors is small compared to the variation in the projections. In such cases, the policy-maker might just ignore the average past errors and use the range of population projections as an indicator of uncertainty. Also the application of *ex post* errors to the future involves the strong assumptions that forecasters today make the same mistakes and miss similar kinds of structural discontinuities as did the forecasters of the past.

All population projections are based on judgment. We feel that the best way to produce projections is to make the judgment very explicit base them on the synthesized opinion of a group of experts.[3] In the case of probabilistic projections, we obtain information from the experts not only on fertility, mortality, and migration trends, but on how uncertain those trends are. This information is provided in a form that is clear and easy to assess. By bringing together information from a variety of experts who are specialists is different fields, we believe that we can capture the best information that the world currently has to offer.

3 The Concept of Confidence Intervals for Population Projections

The future is not only uncertain, but we are not even close to understanding the processes which describe its unfolding. In making a projection, we must abstract from most elements of an extremely complex reality and focus on only a few of them. There are an infinite number of ways of making these abstractions, and it is natural that different projections would embody different assumptions. At any future date, differences in assumptions imply, in general, different distributions of population sizes, in particular, different mean populations and different 95 percent confidence intervals.

Table 1 contains data on various projections of the population of the United States around 2065 made around 1990. The figures in the table are adapted from Lee and Tuljapurkar (1994) and are ordered according to the lower bound of the 95 percent confidence interval. The first column identifies the projection. The second column shows the mean population size and the third and fourth columns show the lower and upper bound respectively of the 95 percent confidence interval. In the table, the mean population of the US around 2065 ranges from 296 million to 680 million people. The lower bound of the 95 percent confidence interval goes from 207 million to 552 million people. The upper bound ranges between 349 and 836 million.

The inconsistencies in this table are clear. According to a time series estimate made in Pflaumer (1992), using the logarithm of population as the variable to be explained, we are 95 percent confident that the US population around 2065 would lie between 551 and 836 million people. According to the US Census Bureau (1989), we are 95 percent confident that the US population at that time would lie between 207 and 456 million people. Clearly, both cannot be correct. For example, we cannot simultaneously believe that the probability of the population being 551 million or less is 2.5 percent and the probability of the population being 456 million or less is 97.5 percent.

There are nine projections given in *Table 1* and they all produce contradictory confidence intervals. How should we interpret this? First of all, it is vital to realize that there is no particular "correct" 95 percent confidence interval in that table. Given that the reality that we are trying to forecast is so distant from our current understanding of it, it is to be expected that different projections would embody different assumptions and produce different confidence intervals. This means that it is never appropriate to say that the future population will certainly lie within a particular 95 percent confidence interval. These confidence intervals are dependent on the assumptions made in the projections and, as can be seen from *Table 1*, can vary dramatically from projection to projection.

Second, the problem of multiple inconsistent confidence intervals is not just a problem with the projections in *Table 1*. It is a generic phenomenon that afflicts all probabilistic population projections regardless of the methodology used. Time series analysis and the projections based on expert opinion presented here both produce different confidence intervals, whenever their underlying assumptions change.

Thus, it is just as impossible to tell policy-makers and others what the future confidence interval for a population would be, as it is to tell them exactly what the future population size would be. We can produce projections of population distributions with associated means, medians, and confidence intervals, but all those statistics depend on the assumptions that are used. The procedure that we use here makes those assumptions crystal clear, but there is no procedure that frees us from our assumptions and provides us with the unique and true future population distributions. We can tell policy-makers and others what future population means and confidence will be, given the set of assumptions that we use. Our assumptions are our best assessment that we can make about future trends and their uncertainties. Tomorrow, however, we may be able to make even better assessments. This will result in different projected mean population sizes and different confidence intervals.

4 The Methodology

In short, the approach chosen here to produce probabilistic population projections is based on three uncertainty distributions (for fertility, mortality, and migration) assumed for each world region. These are standard normal distributions fitted to the low, central, and high values by the experts under the assumption that the range between the low and high values covers 90 percent of all cases, i.e., only 5 percent if all possible cases are assumed to lie above the high value and another 5 percent below the low value. By randomly drawing from these distributions for each region a total of 4,000 simulation runs (with the multistate population projection model DIALOG) resulted in the distributions of future population size and age structure that will be discussed below.

4.1 Fertility

Our fertility assumptions are based on the data in *Appendix Table 1. Appendix Table 1* gives four numbers for each region, the 1995 total fertility rate (TFR), and low, central, and high values for the interval 2030–2035, and defines in more detail the three paths from 1995 to 2100. Clearly, there are a large number of ways to use these data to generate random TFR paths into the future. We have chosen a particularly simple procedure of random lines (or piece-wise linear paths, to be more precise) here.[4] A standard normal distribution is used to specify random lines that conform to the 90 percent confidence intervals in *Appendix Table 1.*

In our procedure, we only make use of one random draw from the normal distribution to determine the full fertility path from 1995 to 2100. We do not literally believe that all time paths of the total fertility rate will be random lines. An alternative view would be that the TFRs would behave like a bounded random walk. Each bounded random walk would produce a population total (see Goldstein *et al.* (1994) for a model of this sort) and in the aggregate a distribution of populations would be generated for each projection period. These sort of bounded random walks produce distributions of population sizes that are concentrated around a central value, and which are qualitatively identical to those obtained using the assumptions described above.

We believe that the prime advantage of the combination of normality and linearity assumptions (random lines instead of random walks) is that they provide a simple and reasonably robust way of generating population distributions. Their main disadvantage is that they are inappropriate to predict short-term population dynamics because of its greater volatility.

4.2 Mortality

The procedure chosen to produce mortality paths that are randomly chosen from a normal distribution is analogous to that described for fertility. Because the mortality scenarios had been defined in terms of improvements over 10 year periods, the low, central, and high values first need to be converted into values of life expectancy. This provides us with three points of the 2030–2035 distribution of life expectancies, which is the exact analog of three points of the distribution of TFRs in 2030–2035 given by the experts. As in the case of fertility, random points are determined for the life expectancies in 2030–2035 and 2080–2085. Next, the time path of the life expectancy is linearly interpolated from the 1995 to the randomly chosen 2030–2035 level, and again from the 2030–2035 to 2080–2085. After 2080–2085, all life expectancies are assumed to remain constant. Given the chosen path of change in life expectancy at birth, age-specific mortality rates were derived using Brass' relational logit model life tables.

4.3 Migration

Expert opinion guided the production of a table of interregional migration flows, in terms of the annual levels of net migration, *Appendix Table 2*. These flows are assumed to remain constant over time. The figures in *Appendix Table 2* represent the high values of those flows. The central value is assumed to be half of the high value, and the low value is assumed to be zero for all migration flows.[5] Again a standard normal distribution is assumed with the high and low values covering 90 percent of all cases. If a random migration flow is less than zero, the migration flow that we use in the projection is assumed to be zero. The age-specific interregional migration rates are derived from age-specific schedules in Rogers and Castro (1981).

4.4 Interrelationships between the components

Population projections typically do not assume that the trends in the three components of population change are related to one another. In this paper, we also consider migration to be independent of the other two components and of the age structure and size of the population, but we do consider the possibility of a correlation between fertility and mortality. In following sections, we provide population projections where fertility and mortality are perfectly (positively) correlated and where fertility and mortality are uncorrelated.

4.5 Interrelationships between regions

Most international population projections assume that in their high variants all countries and regions simultaneously have higher than expected fertility and vice versa in the low variant. Nevertheless, fertility and mortality might or might not follow parallel trends across regions. The interdependencies between the two can be quite complex. For example, fertility might be correlated across the regions in which the majority of inhabitants are Muslim, but this fertility level might be uncorrelated with trends in Europe and Latin America.

In dealing with interrelations between regions, we again choose a simple strategy. We consider the situations in which fertility and mortality are either perfectly correlated across regions or uncorrelated. Fertility levels could be correlated across regions and so might mortality levels, but, within regions, fertility and mortality could still be either correlated or uncorrelated with one another. Similarly, fertility and mortality could be uncorrelated with fertility and mortality respectively across regions, but correlated with one another within each specific region.

Both in the case of interrelationships between components and interrelationships between regions, we are dealing with long-term dependencies. The procedures that we use link the entire time paths of fertility and mortality together within regions and across regions.

5 Regional Results

5.1 Regional population sizes

Table 2 shows the populations of each our thirteen regions for 1995. In addition, it shows the mean and median projected populations in 2020, 2050, and 2100, as well as the bounds of 95 percent confidence interval for each date. These numbers were produced on the assumption that there was no long-run correlation between fertility and mortality within regions. In Section 5.3 below, we provide an example of the impact of that such a correlation could have.

There is so much information in this table that we have space here to point out only a few of the interesting findings. The table contains two indicators of asymmetric population size distributions: (1) the difference between the mean and median population, and (2) the difference between the average of lower and upper bounds of the 95 percent confidence interval and the median. Roughly speaking, when the mean is greater than the median and the difference between the average of the bounds and the median is positive, then the distribution of population sizes is asymmetric and has a relatively long right tail (i.e., in the direction of higher population sizes).

Consider first, the data for China and centrally planned Asia. In 1995, the region had a population of 1.36 billion people. Let us look at what happens to lower bound of the 95 percent confidence intervals. By 2020 according to our population distribution, there is a 2.5 percent chance that the population would be below 1.53 billion. Thirty years later, there is a 2.5 percent chance that the population would be below 1.35 billion, and by the end of the 21st century, there is a 2.5 percent chance that the population would be below 0.71 billion. The table tells us that between 2050 and 2100, there is a chance that China's population would fall by almost half. At the high end of the spectrum, the table tells us that China in 2100 has a 2.5 percent chance of having a population above 4.43 billion. The population distribution for China in 2100 is very skewed, with relatively high probabilities of having relatively high population sizes. The future distributions of population for China behave in this way because it is assumed that the lower end of their TFR range is below replacement level, while the upper end is above replacement. With below replacement fertility, population size goes to zero and with above replacement fertility, the population increases exponentially. The lower bound of the 95 percent confidence interval shows the possibility of the population declining toward zero and the upper bound shows the possibility of exponential growth.

The time paths of the populations of North America and the European portion of the former Soviet Union (predominantly Russia) are interesting to compare. The population of the European part of the former Soviet Union was 238 million in 1995 (which includes the Russian Federation with 147 million). *Figure 1* shows how its population distribution changes from 1995 to 2100 using the assumption that there are no relationships between the future paths of fertility, mortality, and migration. The figure has six lines. Each is labeled with the probability that the population would lie below it. According to those assumptions, there is a 2.5 percent chance that the population would be below the lowest line and a 2.5 percent chance that it would lie above the highest line. Thus, the interval between the lower and upper lines gives the 95 percent confidence interval. There is a 20 percent chance that the population would lie between the two innermost lines and a 60 percent change that the population would lie between the second and fifth lines.

Over the course of the 21st century, population change in the EFSU region is likely to be negative. By 2020, the mean population falls from 238 million in 1995 to 224 million. By 2050, the mean population falls to 189 million and by 2100 to 147 million. At the midpoint of the century, according to our methodology, there is a 2.5 percent chance that the population would be below 144 million and a 2.5 percent chance that it would be above 241 million people. This means that there is slightly over a 2.5 percent chance that the population of the EFSU region will not decline between 1995 and 2050.

The causes of the decline in the EFSU population are assumed below replacement fertility, relatively high mortality, especially for males, and net out-migration. After 2030, there is a possibility of above replacement fertility and significantly improved mortality rates. This accounts for the possibility of population growth in the second half of the century that we see from the upper two lines in *Figure 1*.

Figure 2 shows the same information for North America. The population of North America in 1995 was 297 million. The means of our population distributions increase to 356 million in 2020, 405 million in 2050, and 482 million in 2100. The possibility that the population of North America would be smaller in 2100 than in 1995 exists, given our assumptions, but it less than 20 percent. The continued growth of the US population according to our assumptions is largely fueled by continuing migration. The population would only shrink in the circumstance where migration was greatly restricted from its current level and the US had a long period of below replacement fertility.

It is interesting to compare our 95 percent confidence intervals for North America in 2065 with those for the US shown in *Table 1*. The lower bound of our 95 percent confidence interval is around 280 million and our upper bound is around 610 million. Taking into consideration the larger population of North America, our 95 percent confidence intervals are roughly similar to those in Lee and Tuljapurkar (1994) and the US Bureau of the Census (1992) and only slightly lower than the Pflaumer (1992) time series model with the population size as the dependent variable.

5.2 Regional age structures

Tables 3 and *4* are arranged like *Table 2* except that they refer to the percentage of the population in the age group 0–14, and the percentage of the population in the age group 60 and above, respectively. It is interesting to note that while the percentage of children 14 and under will likely be falling over the 21st century in all regions, the percentage 60 and above will be growing. For example, in North Africa, 38.8 percent of the population were age 14 and below in 1995. In 2050, the mean percentage falls to 27.0 percent, with the 95 percent confidence interval lying between 18.6 and 34.2 percent. By 2100, the mean is 18.7 percent and the 95 percent confidence interval lies between 11.5 and 25.1 percent. On the other hand, the proportion of the North African population age 60 and above was 5.9 percent in 1995. In 2100, the mean percentage is 24.0 percent with its 95 percent confidence interval between 15.2 and 37.4 percent. This phenomenon of population aging, having relatively fewer younger people and relatively more older people in the population, will be happening on a worldwide scale during the 21st century. As examples, we look again at the case of China and centrally planned Asia and at the comparison between the EFSU region and North America.

In China and centrally planned Asia, 27.3 percent of the population in 1995 were 0–14 years old. By 2020, the mean of that percentage falls to 21.2 with a 95 percent confidence interval stretching from 16.5 to 25.6 percent. This means that, given our assumptions, the probability of a falling percentage of 0–14 year olds is over 97.5 percent. The reduction in the percentage in this group continues over the century, with the mean reaching 17.1 percent in 2100 and a 95 percent confidence interval between 9.8 and 24.1 percent. It is interesting to note that the skewness in the distribution of population sizes that emerges in the region between 2050 and 2100 is not mirrored in the distribution of the percentage of younger people, which remains quite symmetric. Indeed, the distribution of the percentage of younger people in the population, given our assumptions, remains quite symmetric throughout the 21st century for all the regions in *Table 4*.

The other side of the fall in the percentage of younger people in the China and centrally planned Asia region is the rise in the percentage of the population age 60 and above. In 1995, 9.2 percent of the population was 60 and above. By 2050, the mean of our distribution of percentages is 25.3 percent, and by 2100, it increases to 28.3 percent. Clearly, most of the increase in the older population takes place in the first half of the 21st century. Given the assumptions, we are quite confident of this, because the 95 percent confidence interval for 2050 lies between 17.8 and 34.1 percent. Even at the lower bound, the percentage 60 and above almost doubles between 1995 and 2050.

The comparison of the age structure changes between the EFSU region and North America is especially interesting in view of the differences in their population growth trends. *Figures 3a* and *3b* show the comparisons for the population 0-14 and *Figures 4a* and *4b* for the population 60 and above. In the EFSU region and in North America, the percentage of the population 0-14 were almost identical in 1995, 21.6 and 22.0 percent respectively. In 2100, the means of the percentages is even closer, 17.6 and 17.5 percent respectively.

Given our assumptions, there is slightly more uncertainty about the percentage 0-14 in the EFSU region than in North America in 2100. The 95 percent confidence interval for the EFSU region is between 9.5 and 24.7 percent, while for North America it is between 11.6 percent and 23.3 percent. Most of the difference between the two 95 percent confidence intervals is in their lower bounds. The large gap between the lowest two lines in *Figure 3a* for the EFSU region indicates that the distribution has a slight skewness in the direction of the smaller percentages. We can see the same thing in *Table 2* because the mean of the distribution of the percentages of the population 0-14 is less than the median. Indeed, in all our regions it is generally the case that the mean of the percentage 0–14 is less than the median.

The percentage of the population 60 and above also were very close in the two regions in 1995. In EFSU it was 16.9 percent and in North America 16.4 percent. By

2050 the two percentages are 34.5 and 30.5 percent respectively. That difference of four percentage points is small compared to the 95 percent confidence intervals. In the case of EFSU, given our assumptions, we are 95 percent confident that the percentage would lie somewhere between 26.3 and 44.5 percent. For North America, the 95 percent confidence interval is bounded by 24.0 and 38.6 percent. Clearly, we cannot be very sure in which region the percent will rise more rapidly. In the case of both the percentage 0–14 and the percentage 60 and over, the differences between the two regions are relatively minor. This is the case, even though the trends in population growth are very different.

5.3 An example of correlated fertility and mortality

The regional data presented above were computed on the assumption that there would be no future long-run relationship between fertility and mortality. In order to see the effect of such a correlation, *Table 5* contains a comparison for Sub-Saharan Africa in 2100 for two cases, one where the time paths of fertility and mortality are uncorrelated over time and one in which they were perfectly positively correlated. Fertility is currently high in Sub-Saharan African. According to our assumptions, it is likely to fall by over half its 1995 level by 2030–2035. We allow for two possibilities: (1) that fertility will decline from 1995 and 2030–2035, and (2) that the onset of the decline is postponed to 2000–2005. In either case, Sub-Saharan Africa will be experiencing its demographic transition during the period of our projection. It is possible, based on the experience of other countries that have passed through their transitions that the speeds of mortality and fertility decline will be positively correlated over time. In other words, correlated fertility and mortality means that if, in the future, Sub-Saharan Africa has a relatively fast decline in mortality, it would also have a relatively rapid decline in fertility, but if the decline in mortality were slower the fall in fertility would also be slower.[6]

According to the figures in *Table 2*, Sub-Saharan Africa is the region of the world with the greatest population uncertainty. In 1995, the population of that region was 558 million people. By 2100, the mean population size is 1.909 billion, the median is 1.738 billion and the 95 percent confidence interval encompasses almost 4 billion people, with a lower bound of 578 million and an upper bound of 4.345 billion. This gigantic confidence interval is the result of unusually large uncertainty with respect to both fertility and mortality, and the assumption that the speeds of the decline in fertility and mortality are unrelated to each other. *Table 5* provides information for Sub-Saharan Africa for 2100 in the case of independent trends in fertility and mortality, and for perfectly correlated trends.[7]

Under either assumption, the median population size remains about the same, 1.738 billion when the paths of fertility and mortality are independent and 1.728 billion when they are perfectly correlated. The means of the population size distributions vary considerably more. If fertility and mortality trends were unrelated, then the mean of the population distribution in 2100 would be 1.909 billion, while if the trends were perfectly positively correlated its mean would be 1.663 billion. The greatest difference comes in the extent of uncertainty. In the case of uncorrelated trends the 95 percent confidence interval lies between 578 million and 4.345 billion people. If the trends were perfectly correlated the 95 percent confidence interval would lie between 1.174 and 1.859 billion people. Thus, for Sub-Saharan Africa the mean population size in the future and especially the 95 percent confidence intervals depend importantly on the assumption that is made with respect to correlation between future fertility and mortality trends.

Although uncertainty with respect to population size shrinks dramatically when future trends in fertility and mortality are perfectly correlated, uncertainty with respect to the age structure measures does not necessarily follow suit. The 95 percent confidence interval for the percentage of the population 0-14 is slightly smaller when we assume a perfect correlation, but the confidence interval for the percentage of the population 60 and above is larger.

6 World Projections

In this section, we produce world population projections by combining the regional ones discussed in the last section. The process of aggregation adds a new element of complication, because it is not appropriate just to add the regional figures together. We must also take into account the possibility that fertility and mortality paths are correlated across regions.

6.1 Five possible world population projections

Table 6 shows five possible world population projections. In the first, fertility and mortality are uncorrelated both across regions and within regions. These figures are the result of aggregating the figures presented in Section 4.2 above. Here, the mean population size of the world at a future date can be derived by summing the means for each of the regions. The medians and particularly the bounds on the 95 percent confidence interval, on the other hand, are not derived through addition. They must be simulated. In the second, fertility and mortality separately are perfectly correlated across regions, but not within regions (i.e., high fertility in one region goes along with high fertility in all other regions, etc.). In theory, the mean populations are the same as in the first case. In practice, they are slightly different from one another because the random samples are different.

To illustrate the difference between these two assumptions visually *Figures 5a* and *5b* show the resulting distributions of total population size for all world regions together in the case of perfect correlation between regions (A) and in the case of independence between regions (B). The X-axis is given on a relative scale with 1.0 corresponding to the mean. The distributions result from one thousand simulations each. It is clearly visible that in the case of independence between regions the distribution is much more concentrated. This is due to the fact that under the independence assumption, e.g., an unusually low fertility level in one region may partly be compensated by higher fertility in another region. In the case of perfect correlation such compensations are not possible (for the same component) thus resulting in many more extreme cases.

The third and fourth projections are based on the assumption that fertility and mortality are perfectly positively correlated within regions. This is most plausible for regions that are still undergoing their demographic transitions. The third projection assumes no correlation of fertility and mortality across regions, while the fourth presumes a perfect positive correlation across regions. Again, in theory the mean populations should be identical, but are not because of sampling.

We call the fifth projection the "merged" case, because it is literally computed by merging the outcomes of the other four. Each of the first four projections is based on a sample size of 1,000 observations. The merged projection is based on 4,000 observations. The experts were not asked about correlations of fertility and mortality within and between regions, but in order to produce world population projections, information about these correlations is required. In particular, we need to know both the correlations themselves and the uncertainty associated with each one of them. If we had numbers, we would have to take into account the distribution of correlations just as we did the distributions of fertility and mortality. In the absence of explicit expert opinion, we allow uncertainties in the correlations by equally weighting, or merging, the four extreme case projections.[8]

The 95 percent confidence intervals depend on which projection is chosen. For example, if we were certain that future time paths of fertility and mortality were uncorrelated within and across regions, then, according to the assumptions, the mean of the world's population in 2050 would be 10.0 billion people, with a 95 percent confidence interval between 9.0 and 11.3 billion. On the other hand, if we were certain that future fertility and mortality trends were perfectly correlated across regions, but not within regions, the mean of the world's population in 2050 would also be 10.0 billion, but the 95 percent confidence interval would be wider, between 7.4 and 13.0 billion. When we take uncertainty about the correlations into account, the mean population in 2050 is again 10.0 billion and the 95 percent confidence interval lies between 8.1 and 12.0 billion.

It is not correct to ask which 95 percent confidence interval is the "correct" one. There does not exist a unique "correct" 95 percent confidence interval. Each projection embodies different assumptions about the correlations and their uncertainties and, therefore, produces different confidence intervals. We prefer the merged projection, because it is the only one of the five that incorporates uncertainty about the correlations in addition to uncertainty with respect to fertility and mortality. For this reason, in the remainder of this section we focus on the merged projection.

Figure 6 shows distributions of future population sizes for the merged projection at 5-year intervals to the year 2100. The two lines on the outside give the 95 percent confidence interval. The upper line indicates that there is an unlikely possibility of almost linear population growth between 1995 and 2100. The lower line shows that there is also an equally unlikely possibility that the world's population would peak in the middle of the 21st century and fall thereafter to below 6 billion by 2100. The range covering 60 percent of all cases (between the 0.2 and 0.8 fractiles) is remarkably small. By 2050 this uncertainty range is less than 1.5 billion people and by 2100 it doubles to about 3 billion people.

The figure also shows that in more than 60 percent of all cases the growth of the total world population would be leveling off during the second half of next century or even start to decline. Given that the world population by the beginning of the year 1996 is estimated at 5.75 billion, we can look with what probability it will double, i.e., hit the 11.5 billion mark at any point during the next century. Roughly two-thirds of our simulated cases do not reach 11.5 billion during the 21st century; the rest of the cases surpasses that mark. Because those paths that do not reach 11.5 billion level off by the end of the century, they will also not surpass that level during the 22nd century according to our assumption. From this we can derive the strong statement that given our assumptions there is a two-thirds probability that the world population will not double any more.

Figure 7 shows the distribution of the percentage of the world's population who are 0-14 years old. In 1995, 31.4 percent of the world's population was in that group. The percentage will clearly fall over time, the only question is how fast. In 2100, its 95 percent confidence interval lies between 10.6 and 22.7 percent. It is interesting to note that the uncertainty with respect to the percentage of younger people in the population does not increase much in the second half of the next century, even though there is substantial increase in the uncertainty with respect to population size.

The percentage of the population at age 60 and above can be seen in *Figure 8*. All the lines are rising, indicating that we are quite confident that the percentage of older people in the population will rise over time. In 2050, the mean percentage is 19.7 compared with 9.5 in 1995, with a 95 percent confidence interval between 15.1 and 25.7 percent. By 2100, the mean increases to 27.1 percent, with a 95 percent confidence interval between 18.6 and 40.6 percent. Hence, with a probability of 97.5 percent the proportion of elderly will at least double; in the most likely case it will almost triple and it may even more than quadruple. The uncertainty with respect to the percentage above age 60 grows significantly during the second half of the 21st century, in contrast with the case of the percentage of age 14 and below. This uncertainty especially increases at the upper end due to the uncertainty about future old-age mortality when combined with low fertility. By 2100, there is a 20 percent chance that 30 percent or more of the world's population would be age 60 or above.

7 Discussion

In order to make population projections, we must make assumptions about an unknown future. There are a large number of ways of making these assumptions and, in general, different assumptions will imply different future population sizes and different confidence intervals. There is no way to get around this. One tempting shortcut is to assume that the processes which generated fertility, mortality, and migration in the past will continue unchanged into the future. Unfortunately, this assumption does not get us very far, because there are a large number of different structures that could have generated the same past data (see Sanderson, 1995). We must first specify the equations for the past processes before we can estimate their parameters. Therefore, in making projections, and in particular probabilistic ones, there is no substitute for judgment. The main question to be addressed is how best to incorporate judgment into projections.

In this paper we make a methodological proposal for the use of judgment in making probabilistic projections. We suggest that experts be asked about: (1) the time paths of fertility, mortality, and migration, (2) how uncertain they think they are with respect to those time paths, (3) the correlations between those time paths both within and between regions, and (4) their assessment of the uncertainty of those correlations. We also implement the proposal by using information obtained from experts on future fertility, mortality, and migration paths and the uncertainty that they had with respect to those trends. The experts were not asked about correlations and so we assumed a wide range of uncertainty about them.

Asking experts about future trends and uncertainties is one way to derive the information needed to make population projections. Another is to use statistical analyses of various sorts to determine the parameters of specifications that are assumed to characterize the past. These parameters and the estimated randomness of past time series data can be used to make projections into the future. We believe that the use of expert opinion is preferable because it makes the inputs into the projections crystal clear. Statistical assumptions like whether to use some transformation of the dependent variable or the untransformed variable can have important implications for the outcome of a projection (see the discussion of Pflaumer's projections in connection with *Table 1* above), but it is often unclear exactly what they mean. Since our proposal on how to use expert opinion to make probabilistic projections is a new one, it will take time to assess whether or not it has significant advantages over the alternative ways of making probabilistic projections.

The variation that we have seen in the confidence intervals based on different assumptions about correlations is not just of theoretical interest. The United Nations regularly publishes its population projections with low, medium, and high variants for each country. Low, medium, and high variants for the world are derived by summing the respective variants for each country. By doing so the UN implicitly assumes that fertility trends in all countries of the world are perfectly correlated. In the more likely case that trends are divergent the uncertainty range for the world population becomes smaller because diverging country trends partly compensate for each other.

Finally, it is important to stress once again, even at the risk of being overly repetitive, that the confidence intervals that we produced are not "true" confidence intervals in the sense that we know that the future population, at a specific future date, has, say, a 95 percent probability of being within some interval for that date. Our probabilistic projections are our best estimates of the expected future population sizes at future dates combined with our best estimates of the associated confidence intervals. The population sizes and confidence intervals are based on expert opinions on both the components of population growth and on the uncertainty of those components. Expert opinion can be wrong and often is wrong. But there is no better alternative. Expert opinion - especially when derived in an interactive group process - incorporates the relevant knowledge that has been accumulated over years of experience and study in a wide range of disciplines. It can also accommodate human intuition and non-quantitative judgment and is therefore more comprehensive than any specific formal model. It is far from perfect, but until we learn the true model that generates future fertility, mortality, and migration, using expert opinion is the best guide that we have.

Notes

[1] See, for example, Alho (1990), Carter and Lee (1986), Lee and Tuljapurkar (1994), McNown *et al.* (1995), and Pflaumer (1992).

[2] This can be seen in *Table 1*. Sanderson (1995) also shows this same phenomenon using a simulation approach.

[3] The procedure that we used to elicit the expert opinion required that they reach a consensus and thus synthesizes their opinions. Those who have studied a particular issue in detail can influence the opinions of those who have not. We believe that we obtain better measures of the extent of uncertainty by using the synthesized opinions than if we used the opinions of the experts singly. (More details about the process by which the assumptions were derived can be found in Lutz, 1995).

[4] Let x_i be the i-th draw from a standard normal distribution. We use x_i to choose three TFRs, one for 2000, one for the period 2030–2035, and the third for the interval 2080–2085. We denote these TFRs by $\text{TFR}_{i,j}$, where j = 1,2, or 3 depending on the date of the TFR. To complete our notation, we call the central value at time j, μ_j, and the difference between the high and low value at time j, Δ_j. We can express the i-th random TFR at date j as:

$$\text{TFR}_{i,j} = \mu_j + x_i \cdot \frac{\Delta_j}{1.63} \quad ,$$

where 1.63 is the difference between the upper and lower bound of the 90 percent confidence interval for the standard normal distribution. Note that the same x_i term appears in the expression for each of the TFR dates. This means that we are assuming persistence in fertility patterns. If fertility starts out lower than the average in 2000, it will be lower than average in 2100. TFRs at other dates are computed from linear interpolation between two adjacent dates. TFRs after 2080–2085 are assumed to remain at their 2080–2085 values.

[5] Let $M_{i,r,j}$ be the migration flow in the i-th random draw for cell r in *Appendix Table 2*, at date j. We can write:

$$M_{i,r,j} = \mu_r + x_i \cdot \frac{\Delta_r}{1.63} \quad ,$$

where μ_r is the central migration level for region r, x_i is the value of the i-th random draw from a standard normal distribution, Δ_r is the difference between the high and low values for region r, and the constant 1.63 is the difference between the upper and lower bound of the 90 percent confidence interval of the standard normal distribution. Note that the subscript j does not appear on the right-hand side of the equation, indicating that the migration flow is constant over time.

[6] A different scenario would be to assume that increasing mortality due to AIDS would be associated with a rapid fertility decline due to the spread of condoms and a higher awareness of reproductive health.

[7] In the future, experts should be asked about these correlations too.

[8] An alternative is to allow the two correlations to be uniformly distributed over a unit square. This would have been consistent with our emphasis on distributions, but it would have been computationally more burdensome.

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Table 1. Forecasts and 95 percent confidence intervals for the population of the US forecasts to around 2065 from around 1990.

Forecast	Popul. around 2065	Lower bound of 95% confidence interval	Upper bound of 95% confidence Interval
US Census Bureau (1989)	296	207	456
Pflaumer (1988)	301	253	349
Lee-Tuljapurkar (1994)	398	259	609
US Census Bureau (1992)	413	268	599
Pflaumer (1992)	443	270	611
ARIMA with dep.var.POP	443	270	611
Social security (1989)	324	272	389
Social security (1991)	351	291	435
Pflaumer (1992)	680	551	836
ARIMA with dep.var.log(POP)	680	551	836
Logarithmic estimate	620	552	701

Note: Estimates are ordered in ascending order of the lower bound of the 95 percent confidence interval. Source: Adapted from Lee and Tuljapurkar (1994) Table 1, p. 1177. That table includes detailed explanatory notes that are not reproduced here.

Table 2. Population in 2020, 2050, and 2100 by regions, independent case (in million). Mean, median, and 95 percent confidence intervals.

		2020				2050				2100			
Regions	1995	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%
North Africa	162	277	277	254	300	440	439	309	583	630	598	228	1202
Sub-Saharan Africa	558	1059	1058	965	1159	1625	1605	1085	2316	1909	1738	578	4345
China & CPA	1362	1670	1670	1526	1826	1888	1865	1351	2574	2051	1873	709	4428
Pacific Asia	447	629	629	576	678	802	796	579	1047	876	829	322	1696
Pacific OECD	147	155	155	145	167	146	146	117	182	125	120	59	221
Central Asia	54	87	87	76	100	139	137	88	206	212	194	65	477
Middle East	151	300	300	279	324	520	515	380	692	786	738	320	1516
South Asia	1240	1845	1845	1737	1949	2380	2368	1833	2970	2365	2246	1014	4327
Eastern Europe	122	124	124	116	133	111	110	86	141	83	78	31	168
European Former Soviet Union	238	224	224	209	240	189	188	144	241	147	138	53	290
Western Europe	447	479	479	446	512	472	471	370	584	430	416	196	769
Latin America	477	697	696	646	746	930	925	707	1177	1163	1106	489	2142
North America	297	356	356	320	400	405	403	303	534	482	467	229	865
World	5702	7902	7900	7671	8144	10047	10040	8965	11260	11259	11190	8200	15490

Table 3. Age group 0–14 in 2020, 2050, and 2100 by regions, independent case (in percent). Mean, median, and 95 percent confidence intervals.

		2020				2050				2100			
Regions	1995	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%
North Africa	38.8	33.9	34.0	30.0	37.5	27.0	27.3	18.6	34.2	18.7	19.0	11.5	25.1
Sub-Saharan Africa	45.4	39.7	39.8	36.1	42.9	28.0	28.3	19.2	35.2	18.1	18.3	11.0	24.5
China & CPA	27.3	21.2	21.3	16.5	25.6	19.9	20.0	12.3	27.3	17.1	17.2	9.8	24.1
Pacific Asia	33.2	26.5	26.6	22.6	29.9	21.8	21.9	15.0	27.8	16.4	16.5	9.0	23.1
Pacific OECD	17.1	13.9	13.9	10.8	16.7	13.0	13.0	8.1	17.8	13.1	13.1	7.0	19.4
Central Asia	36.3	31.5	31.7	25.0	37.0	26.5	26.8	16.8	34.7	18.7	18.9	11.4	25.7
Middle East	42.8	37.0	37.0	33.4	40.3	27.1	27.3	18.8	34.3	18.2	18.3	11.2	24.5
South Asia	36.6	30.1	30.1	27.4	32.7	22.5	22.6	16.4	28.1	15.3	15.4	8.7	21.8
Eastern Europe	21.3	16.5	16.6	13.3	19.6	14.1	14.1	8.9	19.4	15.0	17.3	7.8	15.6
European Former Soviet Union	21.6	16.0	16.0	12.3	19.2	14.5	14.5	8.8	19.8	17.6	17.7	9.5	24.7
Western Europe	19.9	15.8	15.9	12.8	18.8	14.2	14.3	9.3	19.3	15.2	15.3	8.7	21.6
Latin America	33.7	27.0	27.1	23.5	30.4	22.2	22.3	16.0	28.2	18.7	18.7	11.8	25.2
North America	22.0	17.9	17.9	14.6	21.1	16.7	16.7	11.8	21.3	17.5	17.6	11.6	23.3
World	31.4	27.1	27.1	25.6	28.5	22.7	22.7	20.0	25.6	18.2	18.1	15.6	21.2

Table 4. Age group 60+ in 2020, 2050, and 2100 by regions, independent case (in percent). Mean, median, and 95 percent confidence intervals.

		2020				2050				2100			
Regions	1995	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%
North Africa	5.9	7.9	7.9	7.2	8.7	13.6	13.3	9.4	19.2	24.0	23.0	15.2	37.4
Sub-Saharan Africa	4.7	5.4	5.4	5.1	5.9	9.3	9.2	6.9	12.8	22.5	21.7	15.0	34.3
China & CPA	9.2	15.4	15.4	14.0	16.8	25.3	24.9	17.8	34.1	28.3	27.6	18.0	41.2
Pacific Asia	6.8	11.2	11.2	10.2	12.3	19.7	19.4	14.4	26.5	28.0	27.3	18.0	42.6
Pacific OECD	19.4	31.2	31.2	29.0	33.4	39.6	39.5	31.5	48.7	40.2	40.0	28.4	53.8
Central Asia	7.8	9.7	9.7	8.5	11.2	15.9	15.4	10.2	24.0	24.7	23.7	15.5	38.0
Middle East	5.4	6.8	6.8	6.2	7.4	12.6	12.5	9.1	17.3	25.5	24.9	16.5	38.4
South Asia	6.7	10.1	10.1	9.5	10.7	16.7	16.6	13.4	20.8	28.7	28.1	19.9	40.7
Eastern Europe	16.7	24.0	23.9	22.3	25.8	34.4	34.0	26.7	43.4	35.7	34.4	23.3	52.7
European Former Soviet Union	16.9	23.7	23.6	21.8	25.6	34.5	34.1	26.3	44.5	30.7	29.9	18.9	48.0
Western Europe	18.6	25.2	25.2	23.3	27.1	35.1	35.0	27.5	43.9	35.7	35.4	24.3	49.9
Latin America	7.6	11.9	11.9	11.0	12.8	20.6	20.4	15.8	26.4	27.4	26.8	18.6	39.3
North America	16.4	24.0	24.0	21.8	26.4	30.5	30.2	24.0	38.6	31.4	30.9	22.3	43.1
World	9.5	13.2	13.2	12.8	13.6	19.4	19.4	17.4	21.6	26.1	26.0	21.9	30.2

Table 5. Sub-Saharan Africa: Year 2100. Mean, median, and 95 percent confidence intervals.

		Independent variables				Correlated (reg.ind.m&f cor.)			
	1995	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%
Population (in million)	558.0	1909.4	1738.0	578.4	4345.0	1662.7	1728.0	1174.0	1859.0
Age group [0–14] (in %)	45.4	18.1	18.3	11.0	24.5	17.8	18.4	10.2	22.9
Age group [60+] (in %)	4.7	22.5	21.7	15.0	34.3	23.1	21.4	14.7	40.0

Table 6. Summary of world population projections with different assumptions about the correlation between fertility and mortality and between regions.

Correlation														
Between	Between f&m		2020				2050				2100			
regions	within region	1995	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%	Mean	Median	2.5%	97.5%
0	0	5702	7902	7900	7671	8144	10047	10040	8965	11260	11259	11190	8200	15490
1	0	5702	7900	7902	7315	8464	10035	10000	7361	12950	11212	10600	4374	21370
0	1	5702	7890	7893	7736	8045	9948	9947	9343	10590	10644	10620	8869	12640
1	1	5702	7880	7881	7488	8239	9906	9891	8285	11490	10521	10330	5945	15710
merged		5702	7893	7895	7474	8290	9984	9963	8108	11950	10909	10710	5715	17330

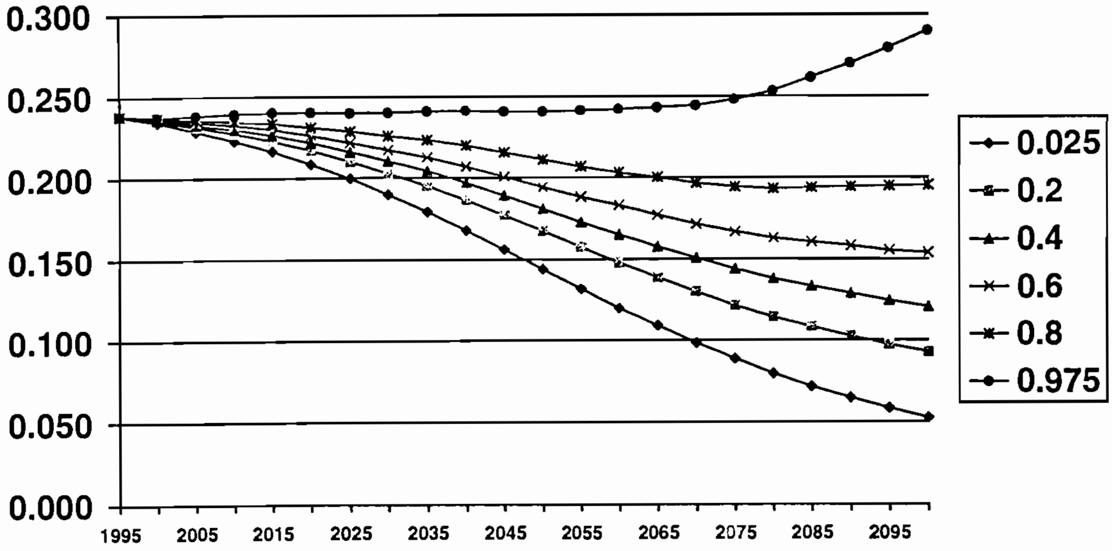

Figure 1. Fractiles of distribution of future population size: European former Soviet Union, non-correlated population in billion.

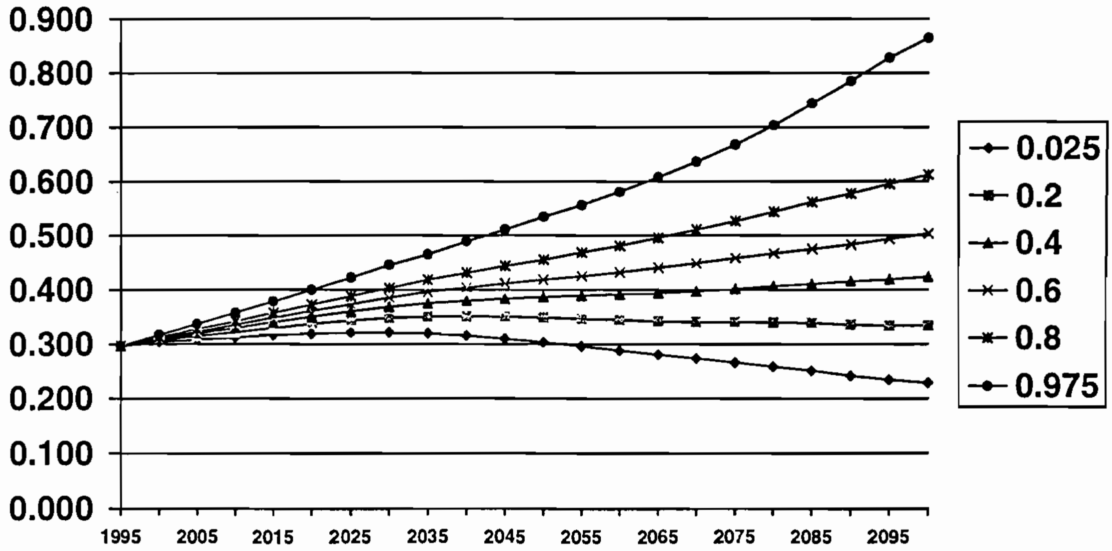

Figure 2. Fractiles of distribution of future population size: North America, non-correlated population in billion.

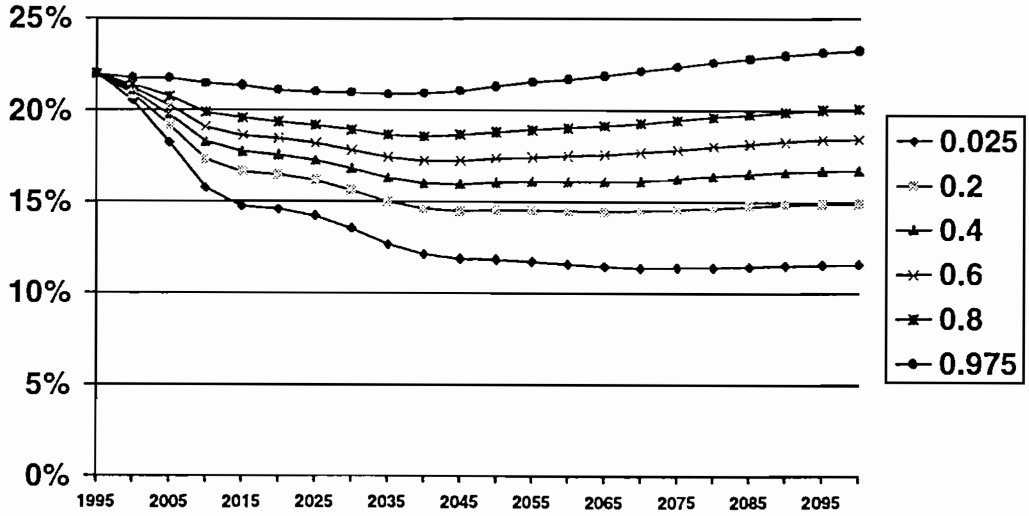

Figure 3a. Fractiles of distribution of future population in age group (0–14) in percent: North America (non-correlated).

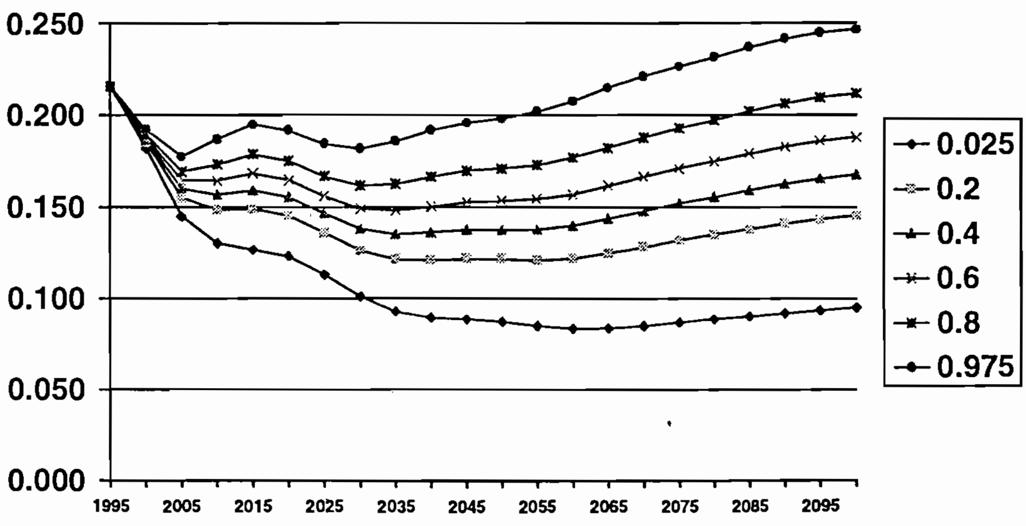

Figure 3b. Fractiles of distribution of future population in age group (0–14) in percent: European former Soviet Union (non-correlated).

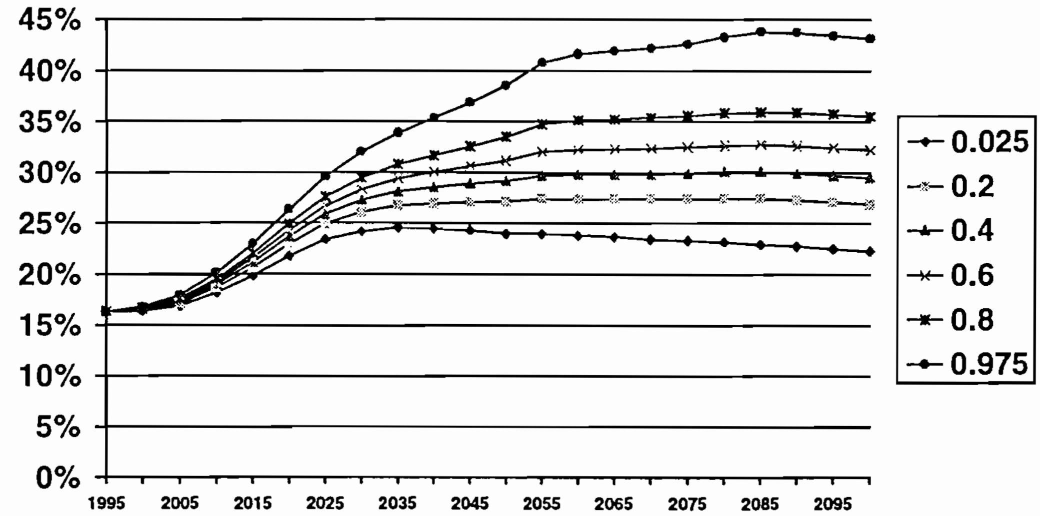

Figure 4a. Fractiles of distribution of future population in age group (60+) in percent: North America (non-correlated).

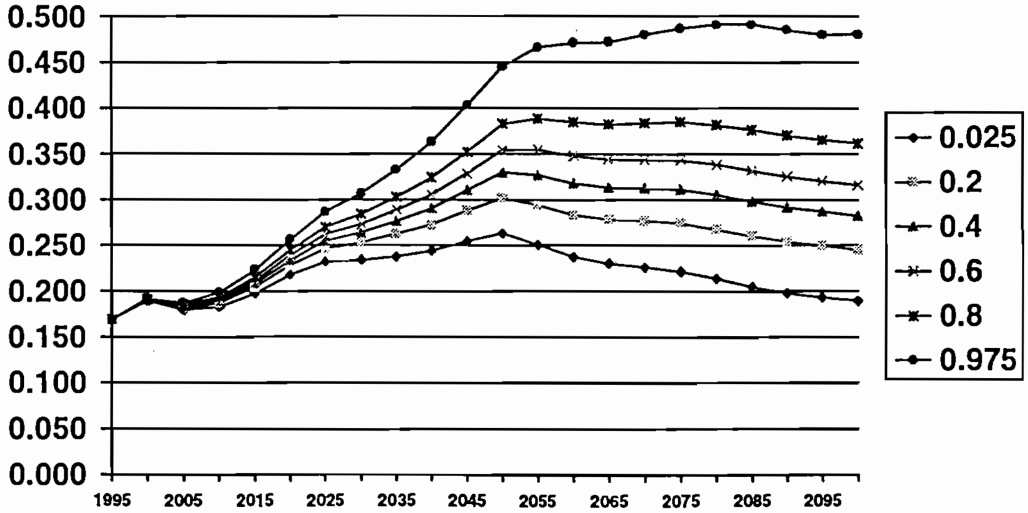

Figure 4b. Fractiles of distribution of future population in age group (60+) in percent: European former Soviet Union (non-correlated).

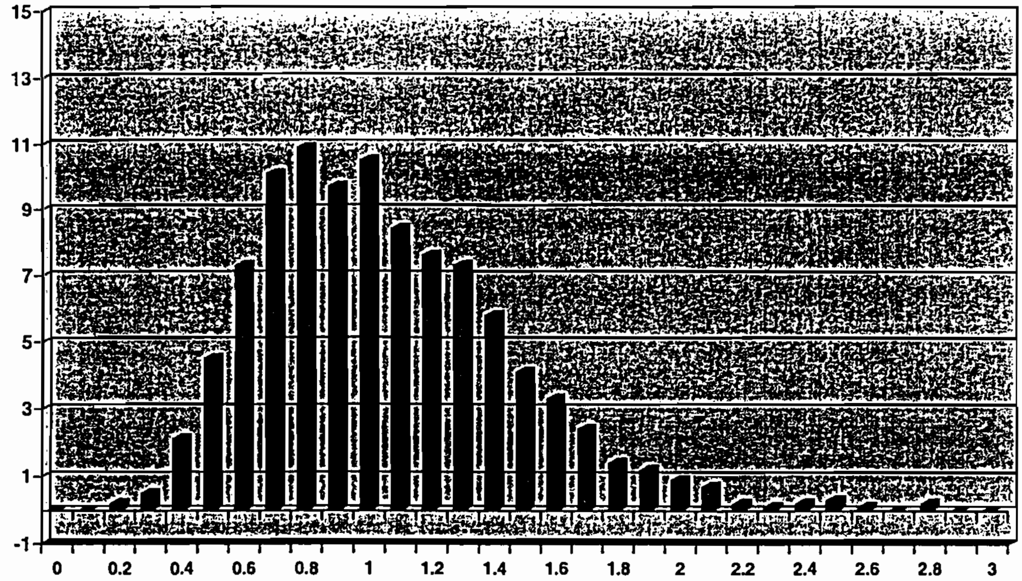

Figure 5a. Probability distribution of world population in 2100, regions dependent, fertility and mortality independent.

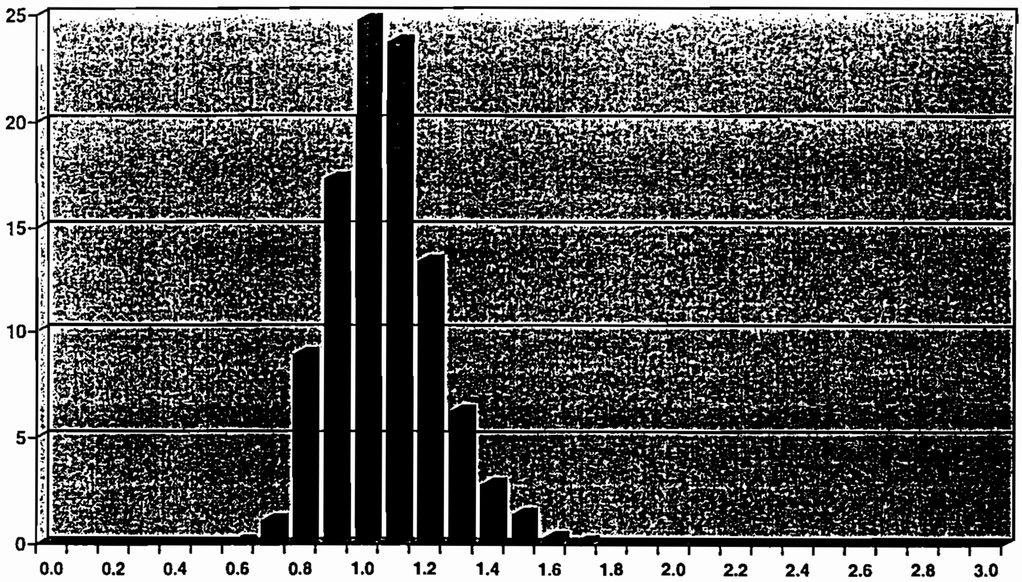

Figure 5b. Probability distribution of world population in 2100, regions independent, fertility and mortality independent.

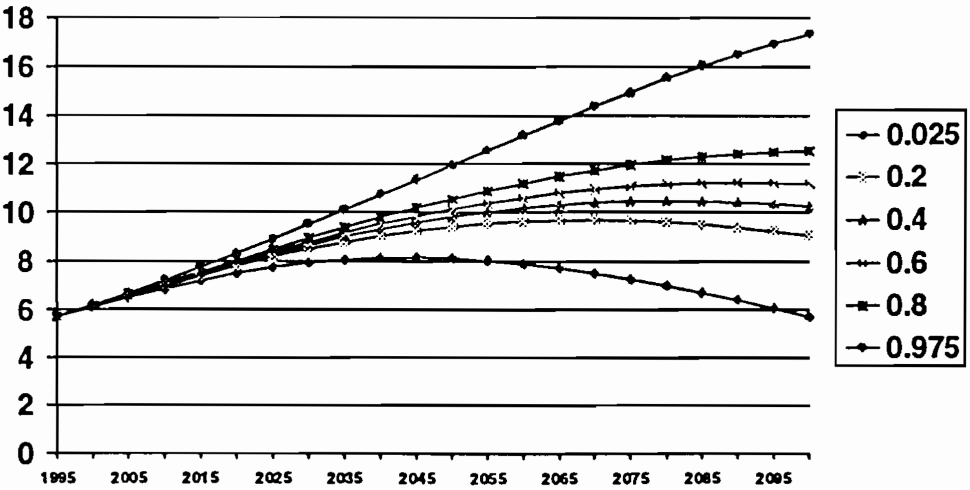

Figure 6. Fractiles of distribution of future world population: Merged population in billion.

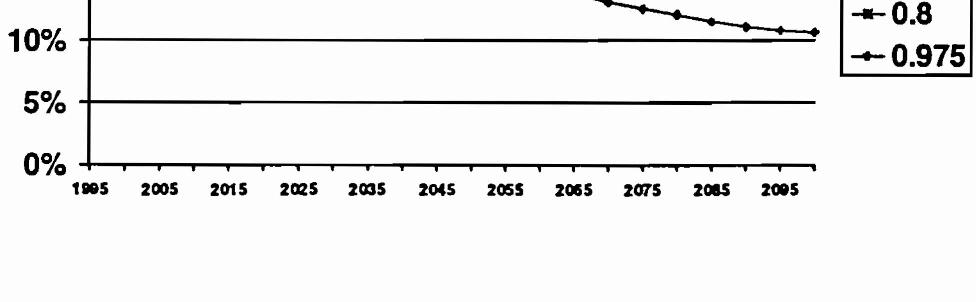

Figure 7. Fractiles of distribution of future world population in age group (0–14) in percent: merged.

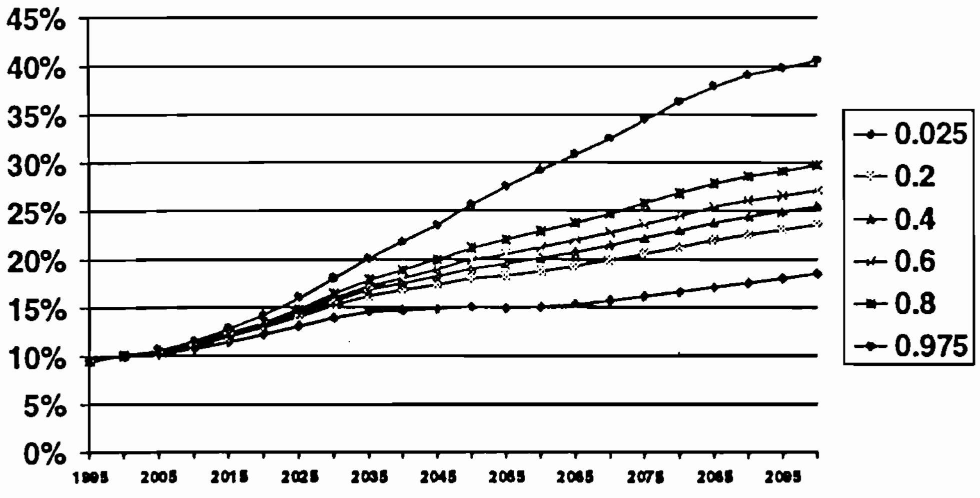

Figure 8. Fractiles of distribution of future world population in age group (60+) in percent.

Appendix Table 1. Alternative fertility assumptions used in projections.

Region	TFR 1995	TFR 2030–2035 Low	Central	High
Africa				
North Africa	4.35	2.00	3.00	4.00
Sub-Saharan Africa	6.18	2.00	3.00	4.00
Asia-East				
China & CPA[a]	2.00	1.50	2.25	3.00
Pacific Asia	2.88	1.70	2.35	3.00
Pacific OECD	1.53	1.30	1.70	2.10
Asia-West				
Central Asia	3.35	2.00	3.00	4.00
Middle East	5.47	2.00	3.00	4.00
South Asia	3.77	1.70	2.35	3.00
Europe				
Eastern Europe	1.66	1.30	1.70	2.10
European Former USSR	1.50	1.30	1.70	2.10
Western Europe	1.67	1.30	1.70	2.10
Latin America	3.10	1.70	2.35	3.00
North America	1.97	1.40	1.85	2.30

[a] Centrally Planned Asia.

Appendix Table 2. Matrix of assumed high values of annual net migration flows, in thousands.

From	To: North America	Western Europe	Pacific OECD	Middle East	Total
Africa					
North Africa	90	250	20	15	375
Sub-Saharan Africa	115	150	40	5	310
Asia-East					
China & CPA	270	50	50	0	370
Pacific Asia	400	50	100	10	560
Asia-West					
Central Asia	10	30	–	–	40
Middle East	15	30	10	–	55
South Asia	300	100	80	15	495
Europe					
Eastern Europe	50	100	–	–	150
European Former USSR	50	150	25	–	225
Latin America	700	90	25	5	820
Total	2,000	1,000	350	50	3,400