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RESEARCH ARTICLE

Assessments of mortality at oldest-old ages by province in China's 2000 and 2010 censuses

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Abstract: This study examined the possible underestimation and age-trajectories of mortality at oldest-old ages in China's 2000 and 2010 censuses. By linking logit-transformed conditional probabilities of dying from 13 countries with the highest data quality in the world, this study found that many Chinese provinces had underestimations of mortality at oldest-old ages when a relatively lenient criterion was applied. When a relatively strict criterion was applied, most provinces had a 30% or more underestimation in the probability of dying. We also investigated age trajectories of death rates after age 80 in these two censuses by applying the Kannisto model. Results showed that the age trajectories were distorted in most provinces after age 95. Overall, eastern-coastal provinces had higher data quality — in terms of low underestimation rates and less distorted age trajectories — whereas western China had provinces with problematic data. Females had greater rates of underestimation yet less distorted age-trajectories than males; and the 2010 census had greater rates of underestimation yet less distorted age-trajectories than the 2000 census. We conclude that appropriate adjustments with simultaneous applications of the Kannisto model are needed for direct estimates of mortality at oldest-old ages in the 2000 and 2010 censuses for China and for its provinces.

Keywords: China, oldest-old, Kannisto model, logit, underestimation, death underreports, death rate, provincial variation, census, age exaggeration, age misreporting

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1. Introduction

Research on mortality at oldest-old ages (ages 80 or older) has received increasing attention in Western countries since the mid-1980s, with studies on age trajectories, the accuracy of data, and levels of mortality (Kannisto, 1988, 1994; Kannisto, Lauristen, Thatcher *et al*., 1994; Kostaki, 2000; Kostaki and Lanke, 2000; Jeune and Vaupel, 1995; Nagnur, 1986; Robine, Crimmins, Horiuchi *et al*., 2007; Robine, Vaupel, Jeune *et al*., 1997; Suzman, Willis and Manton, 1992; Thatcher, 1992;

Thatcher, Kannisto and Andreev, 2002). In doing so, researchers have used various mathematic functions to simulate age trajectories of mortality at oldest-old ages. Based on age-specific mortality data between the ages of 80 and 98 from 1960 to 1990 in 13 countries with the world's highest quality of mortality data (Austria, Denmark, United Kingdom (England and Wales), Finland, France, Germany (West), Iceland, Italy, Japan, the Netherlands, Norway, Sweden, and Switzerland), Thatcher, Kannisto, and Vaupel (1998) showed that mortality estimates from ages 80 to 120 derived from the Kannisto model fit the data best compared with those from Gompertz, Weibull, Heligman-Pollard, Quadratic, and Logistic models. The Human Mortality Database (HMD) uses the Kannisto model to adjust mortality from ages 80 to 110 for its included countries (Wilmoth, Andreev, Jdanov *et al*., 2007). The United Nations Population Division (UNPD) also uses the Kannisto model in its biennial World Population Prospects (UNPD, 2015). One reason that the Gompertz model fails to accurately capture mortality rates at oldest-old ages is possibly because it does not account for the deceleration in death rates at advanced ages (Horiuchi and Wilmoth, 1998). The wide recognition of the Kannisto model and its broad application in estimating human mortality at oldest-old ages clearly establishes it as a relatively standard model to assess whether the trajectory of age-specific mortality at oldest-old ages in a given population follows the Kannisto function. Moreover, the increasing rate of mortality with age embedded in the Kannisto model serves as an important indicator to assess discrepancies in age trajectories of death rates between the expected trajectory and the observed trajectory. In other words, the quality of mortality data is likely to be problematic if the age-specific death rates at oldest-old ages do not follow the Kannisto model.

It is problematic to study mortality at oldest-old ages without reliable data; however, obtaining accurate data on deaths at advanced ages is challenging, even in many developed countries. For example, Andreev and Gu (2017) recently examined the accuracy of death rates at oldest-old ages in the United States in 1959–1969 and 2001–2011 using the rate of mortality increase with age in octogenarians (aged 80–89), nonagenarians (aged 90–99), and centenarians (aged 100+) in comparison with the 13 countries with world's highest quality of mortality data used by Thatcher and colleagues (1998). They found that the United States had very low growth rates in all three age groups in the period 1959–1969 compared with those in the 13 countries. Together with other evidence, Andreev and Gu concluded that U.S. death rates for overall mortality of aged 80 and over in the period 1959–1969 were not reliable. However, they found that the quality of death rates in 2001–2011 had greatly improved. These conclusions are further substantiated by the fact that birth registration was not complete in the United States before the 1930s.

In studying mortality at older or oldest-old ages in populations where data at these ages are not available or reliable, the relational logit system can be applied to obtain indirect estimates (Brass, 1971). The purpose of the relational logit system is to find a regression-based relationship between a study population and a standard mortality scheme (normally from a model life table or a scheme based on reliable data) by linking some reliable logit-transformed mortality indicators (normally two of three indicators: infant/child mortality, adult mortality, or life expectancy) of the study population with the corresponding indicators in a standard scheme (see Murray, Ferguson, Lopez *et al*., 2003; Rob, 2013; Wilmoth, Zureick, Canudas-Romo *et al*., 2012).

In China, some scholars have applied the abovementioned methods to census data. For example, Zeng and Vaupel (2003) applied a similar approach with six models used by Thatcher and colleagues (1998) to oldest-old mortality data in the 1990 census — for Han Chinese who have the highest quality of age-reporting data in China because they use a lunar calendar to accurately remember their dates of birth (Coale and Li, 1991; Zeng and Gu, 2008). Zeng and Vaupel demonstrated that the Kannisto function fit the observed data best from ages 80 to 96 compared with five other models. However, they also found that the death rates among Han Chinese were not reliable after age 96 in the 1990 census. Duan and Shi (2015) applied Gompertz, Makeham, Beard, Kannisto, and Logistic functions to data in the 2000 and 2010 Chinese censuses and concluded that the logistic function fit the data best from ages 65 to 95 and that the mortality decline at older ages is real rather than an artifact of biases. Wang (2013) applied the Brass logit system to the 1990, 2000, and 2010 Chinese censuses by using the mortality scheme in the 1982 census as a standard. He found that there was an approximately 20-30% rate of underreporting in female deaths at ages after 65 in the 1990 census and 10–12% rate of underreporting in male deaths in the 2010 census. Huang and Poston (2000) applied linear regressions between the logit-transformed death rates and age from ages 50 to 89 in the 1981 and 1990 censuses and identified biases between fitted and observed rates for these ages. They found that the observed rates in most ages from 50 to 89 had a slight to mild (±3%) bias with fitted rates in terms of their overestimation in even ages and underestimation in odd ages.

Among these Chinese applications, however, almost all of the studies suffered from some design or methodological issues, with the exception of that from Zeng and Vaupel (2003). Duan and Shi's (2015) conclusion of actual mortality deceleration at old ages is likely true; however, the degree of deceleration is presumably incorrect because many of these methods have been shown to be inadequate at such age ranges — and thus cannot capture the actual underestimation of mortality at these ages in the censuses. Likewise, the findings by Wang (2013) are likely biased due to reported inaccuracies in the mortality scheme in the 1982 census (Banister and Hill, 2004). In the case of Huang and Poston (2000), as the linear relationship between the logit-transformed mortality and age is another form of the Kannisto model (Thatcher, Kannisto and Vaupel, 1998), the approach is only valid when mortality after age 50 follows the Kannisto model. However, the HMD data show that death rates from age 50 to 89 do not follow the Kannisto model. Therefore, the linearity is presumably due to an underestimation of mortality at later ages.

In examining the accuracy of death rates and age aggregation at oldest-old ages, Coale and Kisker (1986) investigated the ratio of the population aged 95 or older versus the population aged 70 or older — in 23 countries/areas with relatively accurate data — and found that this proportion was less than 6 per thousand. However, they found that the proportion ranged from 1–10% in 28 countries with poor data. Zeng and Vaupel (2003) found that this ratio was 1 per thousand for male Han Chinese and 2 per thousand for female Han Chinese in the 1990 census, almost exactly the same as the values for Sweden in the period 1985–1994. However, because such a ratio increases with reductions in mortality, the absolute value of the ratio has a limited meaning.

Numerous recent studies have documented subnational variations of mortality in China and have shown substantial provincial differences in life expectancy at birth and overall mortality for the general population (Bignami-Van Assche, 2005; Fang, 1993; Hao, Arriage and Banister, 1988; Li, Bateman and Liu, 2015; You and Zheng, 2005; Zhou, Wang, Zhu *et al*., 2016). For example, Zhou *et al*. (2016) reported significant heterogeneity in life expectancy at birth and in mortality rates at ages 0–14, ages 15–49, and ages 50–74 across provinces — with provinces in eastern-coastal areas exhibiting the highest life expectancy; whereas provinces in western China exhibited the lowest life expectancy. Moreover, these provincial patterns have remained consistent since the early 1980s (Hao, Arriage and Banister, 1988; Ren, You, Zheng *et al*., 2004; You and Zheng, 2006; Zhou, Wang, Zhu *et al*., 2016). The provincial/regional variations may be attributable to differences in socioeconomic development (Zhang, Wu and Zhang, 2004), incompleteness of registration systems (Song, 2000; Wang, Wang, Cai, *et al*., 2011), and age misreporting in censuses/surveys (Guo and Che, 2008; Liu, 1991).

With one exception (Huang and Poston, 2000), however, no existing study has focused on provincial variations in mortality after age 80 in China. The lack of research on mortality at oldest-old ages in China is largely because of concerns about the low-quality of mortality data in the census and the inaccuracy of age reporting, especially among non-Han minorities. For example, Coale and Li (1991) found that death rates at very-old ages in China exhibited serious distortions from age exaggeration in the Xinjiang province. In Xinjiang, Han Chinese account for only about 40% of the total population in 2010 (National Bureau of Statistics of China, 2012). The majority of Xinjiang inhabitants belong to Uyghur and other ethnic groups for which age-reporting is not reliable. Thus, Coale and Li concluded that death rates in China as a whole up to age 100 in the 1982 census were relatively accurate if data from Xinjiang were excluded (Coale and Li, 1991: 298–300). These distortions in mortality associated with Xinjiang were consistent with the reported age-exaggerations in population counts in Xijiang noted by other researchers (e.g., Liu, 1991; Wang, 2012; Yang, 1988). Accordingly, Huang and Poston (2000) found that Xinjiang and Tibet had much larger deviances between fitted and observed death rates than other provinces; whereas provinces in eastern China had smaller deviances.

In sum, the number of oldest-old adults has grown rapidly in China (United Nations, 2015) as mortality rates at older ages have declined in recent decades (Gu, Gerland, Li *et al*., 2013; Zhou, Wang, Zhu *et al*., 2016). With the exception of a few studies (Coale and Li, 1991; Duan and Shi, 2015; Huang and Poston, 2000; Wang, 2013; Zeng and Vaupel, 2003), our knowledge about underreporting and age-trajectories of mortality at oldest-old ages in China remains limited. Even less clear is the accuracy of oldest-old mortality in the two latest censuses (2000 and 2010) and variations at the provincial-level. Because most approaches in the existing literature in China suffer from some methodological limitations, it is critical to re-examine the underestimation of mortality at oldest-old ages using more appropriate methods. The purpose of this study is to examine the quality of age-specific death rates at oldest-old ages by province in the 2000 and 2010 Chinese censuses with comparisons to high-quality data from countries in the HMD. Specifically, we focused on comparisons of conditional probabilities of dying at specific ages between Chinese and HMD data and comparisons of age trajectories of mortality between observed and those from the Kannisto model.

2. Data and Methods

2.1 Data Sources and Age-specific Death Rates

Data used in this study came from the 100 percent province-age-sex-specific tabulations of de facto population at the time of the 2000 and 2010 censuses and number of deaths in the past twelve months prior to the census (National Bureau of Statistics of China, 2002; 2012). The age-sex-specific tabulations for the entire country and the average population in the past twelve months were also used to estimate age-specific death rates for the entire country. The age-sex-specific death rates by province in the two censuses were estimated by the number of deaths in the past twelve months and the average population in the same period. The age-sex-specific average population by province during the twelve months prior in a census was estimated from age-sex-specific population counts at census and the number of deaths in the past twelve months based on cohort components by assuming the even distribution of deaths and populations in neighboring age groups (without consideration of migration). Because the migration flow at old ages — especially at oldest-old ages — in the censuses was very small, the omission of migration would not introduce noticeable biases. Furthermore, as the National Bureau of Statistics of China only published province-specific population and deaths in the form of five-year age groups, the death rates used in the present study were measured by five-year age groups from ages 60–64 to ages 95—99. The reason why we included age-specific death rates at ages 60-80 is that we aimed to establish some relationship between mortality at these ages and mortality at oldest-old ages. Mortality at childhood was not reliable in the Chinese census due to severe underreporting (see Appendix A: Note 1) and adult mortality at ages 15–59 also was not reliable due to their high domestic migration.

The sex-specific annual life tables of the 13 countries used by Thatcher and colleagues (1998) from 1950 to the latest available year in the HMD (mostly until 2014) were also used and considered as the standard criterion to evaluate the accuracy of the Chinese data. The HMD data are available at its official website (www.humanmortality.org).

2.2 Methods and Analytical Strategy

Two sets of approaches were used. The first set estimated the overall underestimation of mortality at old ages. Specifically, we investigated two pairs of associations for logit-transformed probabilities of dying. One pair of logit-transformed probabilities of dying at ages 70–95 ($_{25}q_{70}$) versus dying at ages 60–70 ($_{10}q_{60}$). The other pair is the logit-transformed probabilities of dying at ages 80–95 ($_{15}q_{80}$) versus dying at ages 70–80 ($_{10}q_{70}$) (see Appendix A: Note 2). Because age misreporting at younger ages was generally less severe, we would expect the results from the first pair are more reliable. In other words, we investigated two conditional probabilities of dying. To assess the accuracy of the Chinese data, we compared with those in the 13 HMD countries — particularly in Sweden and Japan, the two countries with the most accurate mortality data in the contemporary world. The HMD life tables were used to generate the probabilities of dying for the 13 countries. We further developed the mathematical form of these two associations based on logit-transformed linear regression models and the confidence ellipse with data from the 13 HMD countries. We did not apply the modified logit methods because we are not confident about the reliability of mortality at very young ages and the life expectancies at birth in each province from the censuses. We argue that these methodological applications would be meaningful only when mortality at these younger ages are appropriately adjusted, which is beyond the scope of this research.

Two linear regression models were established for two pairs of probabilities of dying for each sex: $\text{logit}(_{25}\hat{q}_{70}) = \beta_0 + \beta_1 * \text{logit}(_{10}q_{60})$ and $\text{logit}(_{15}\hat{q}_{80}) = \beta_0 + \beta_1 * \text{logit}(_{10}q_{70})$, where $_n\hat{q}_x$ is the probability of dying from age *x* to age *x+n* that needs to be estimated, β_0 is the intercept, and β_1 is the slope, $\text{logit}(_nq_x) = 0.5 * \ln\left(\frac{_nq_x}{1-{_nq_x}}\right)$. The R^2 for these four linear regressions were approximately 0.86~0.93, indicating that a high proximate linear relationship existed among these probabilities. We also applied quadratic forms; however, the improvement was too small to warrant inclusion.

Based on the difference between the observed $_{25}q_{70}$ in the Chinese data and $_{25}\hat{q}_{70}$ derived from the HMD regression model by using $_{10}q_{60}$ from the Chinese censuses and assuming that $_{10}q_{60}$ in Chinese censuses was accurate, we then calculated the average possible underestimation rate in the probability of dying for each five-year age group over ages 70–95. We used $100*(1-{_5\bar{q}_x}/{_5\hat{\bar{q}}_x})$ to estimate the average underestimation of a five-year age group over the ages 70–95, where $_5\bar{q}_x$ represents the observed average probability of dying over a five-year age group in the entire age group 70–95 (i.e., $_5\bar{q}_x = 1-\sqrt[1/5]{(1-{_{25}q_{70}})}$) and $_5\hat{\bar{q}}_x$ represents the corresponding estimated average probability of dying derived from the HMD linear regression model by using $_{10}q_{60}$ from the Chinese censuses. This criterion is more strict; therefore, the results of this approach can be interpreted as the highest possible underestimation of mortality for a given province.

To make our approach more reasonable, we further used the boundary of the confidence ellipse — which included 95% of data points of $_{25}q_{70}$ and $_{10}q_{60}$ in the 13 HMD countries — to estimate alternative underestimations of mortality. The confidence ellipse was estimated using the R package of CAR (Fox and Weisberg, 2011). Specifically, we assumed that there was no mortality underestimation if the observed data points in the Chinese censuses fell within the confidence ellipse or above the lower boundary of the confidence ellipse. This is a very lenient criterion; therefore, the results can be interpreted as the lowest possible underestimation of mortality for a specific province. The confidence ellipse-based approach was defined as Scenario A and the linear regression-based approach was defined as Scenario B. Similar procedures of Scenarios A and B were applied to the pair of $_{15}q_{80}$ and $_{10}q_{70}$.

In the second set of our approach, the Kannisto model was applied by fitting the age-specific death rates from ages 80 to 98 by sex for China (as a whole) and for each province in the 2000 and 2010 censuses. The Kannisto model is a special case of the Gamma-Makeham model (see Thatcher, 1999). The purpose of this application is to investigate whether the age trajectories in the censuses matched the well-established model. The Kannisto model was based on single years of age of death rates that were split from five-year age groups the piecewise cubic Hermite interpolating polynomial and were smoothed with iterations under a constraint that the new five-year age group probabilities of dying calculated from split and smoothed single years equal the original five-year age group probabilities of dying (United Nations, 2013). A relational technique for estimating the age-specific mortality pattern from grouped data (Kostaki, 2000; Kostaki and Lanke, 2000) was also applied and the results was very similar. The Kannisto function is $\mu(x) = c + \frac{ae^{bx}}{1+ae^{bx}}$, where $\mu(x)$ denotes the force of mortality at age *x*, also known as the central death rate, or simply death rate, and *a*, *b*, and *c* are parameters to be estimated. Maximum likelihood estimation procedures were used to fit death rates for the Kannisto function, which is the same used by Thatcher, Kannisto, and Vaupel (1998:36) and Zeng and Vaupel (2003: 236). The logarithm of the maximum likelihood function is $L = \sum_x [D(x)\ln(q(x)) + (N(x) - D(x))\ln(1-q(x))]$, where $q(x) = 1 - e^{-\int_x^{x+1}\mu(t)dt}$ is the probability for an individual who ages *x* and would die before age *x*+1, N(*x*) is the number of individuals who live to age *x*, and D(*x*) is the number of people who die before age *x*+1. To a sufficient approximation $\mu(x) = \theta(x + \frac{1}{2}, \alpha)$ for all *t* between ages *x* and *x*+1, we estimate the parameters $\alpha \in (a,b,c)$ by maximizing L with $q(x) = 1 - \exp(-\theta(x+\frac{1}{2},\alpha))$ with a convergence criterion of $1*10^{-8}$ for q(*x*) and $1*10^{-4}$ for each parameter.

Given the inaccuracy of mortality at oldest-old ages in China, we did not directly apply the Kannisto model to the observed data. To examine the accuracy of the age trajectory, we assumed that the death rates at ages 60–70 were accurate and then applied the Gompertz model to the observed death rates from ages 60 to 84 and then extrapolated to age 98. Finally, we applied the Kannisto model to these rates from ages 80 to 98. The selection of the inclusion of the observed death rates from ages 60 to 84 in the Gompertz model was because the average error between the fitted and observed death rates for ages 60 to 80 was smallest in comparison to other cut-points, such as ages 70, 75, 80, 90, and 95. The formula of the Gompertz model is $\mu(x) = ae^{bx}$. The maximum likelihood formula is the same as noted above.

3. Results

3.1 High Underestimation of Death Rates at Oldest-old Ages in Most Chinese Provinces

The upper panel in Figure 1 presents the logit-transformed ${}_{10}q_{60}$ against ${}_{25}q_{70}$ in the 2000 and 2010 Chinese censuses in comparison with corresponding values for Sweden, Japan, and the 11 other HMD countries with high quality of mortality data in the period 1950–2014. The results show that many Chinese provinces were below the lower boundary of the confidence ellipse. The ellipse includes 95% of data points from the 13 HMD countries based on the linear associations of all data points in these 13 countries (see below). Provinces in northeastern and western China such as Xinjiang, Hainan, Tibet, Guangxi, Ningxia, Gansu, Jilin, and Heilongjiang were far below the lower boundary of the ellipse, indicating a substantial underestimation of mortality after age 70 in these provinces. The results further show that the underestimation was more dramatic in the 2010 census compared with the 2000 census, although provinces in the 2010 census had lower mortality than in the 2000 census.

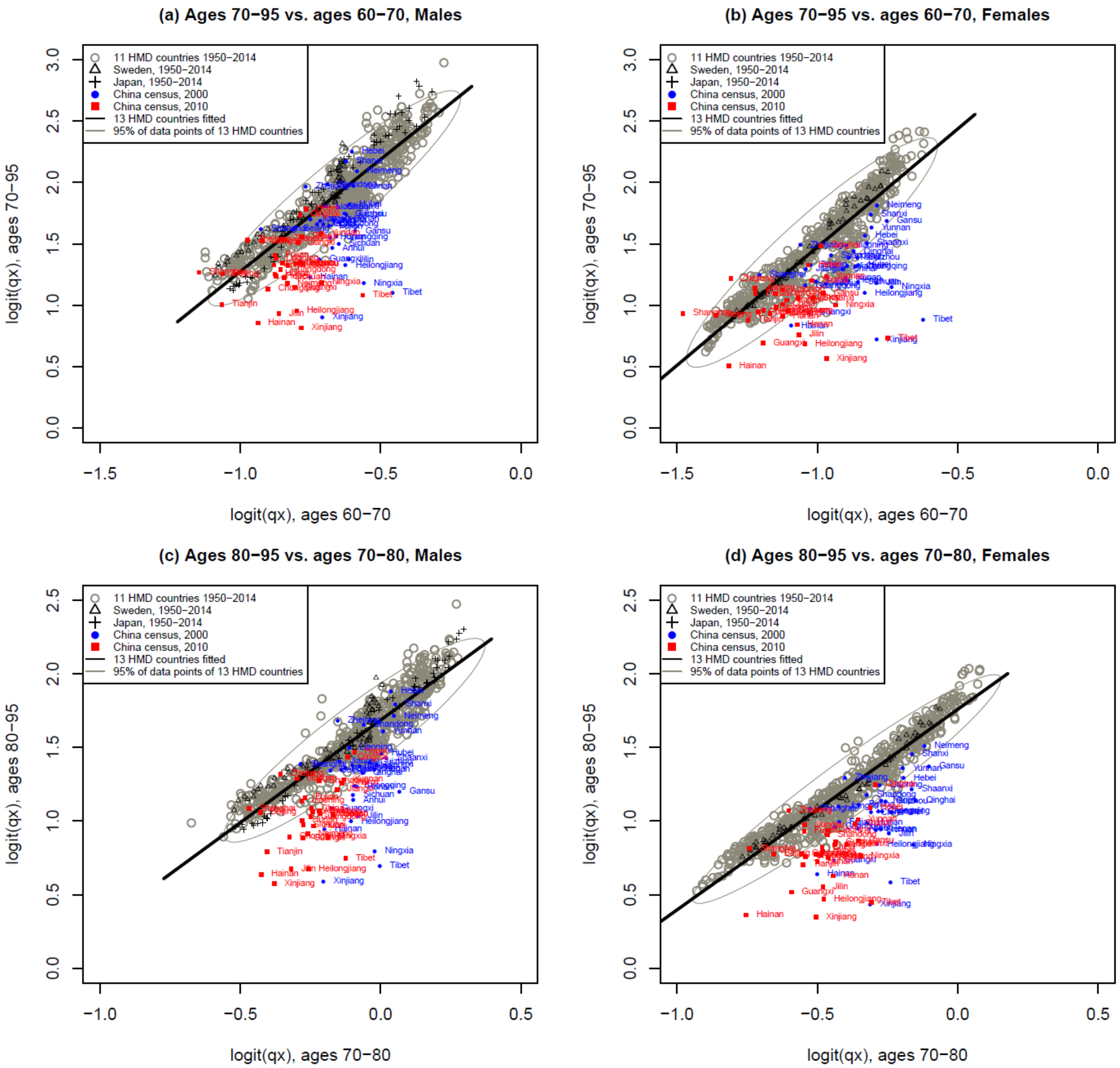

Figure 1. Logit-transformed probabilities of dying at ages 60-70 by ages 70-95 and at ages 70-80 by ages 80-95 in the Chinese censuses by sex and province in comparison with those in 13 HMD countries

The lower panel of Figure 1 presents comparisons for the logit-transformed $_{15}q_{80}$ against $_{10}q_{70}$. Compared with the upper panel, more provinces in China fell below the lower boundary of the ellipse, although the underestimation of mortality was relative smaller due to their relatively large value of probability of dying. The upper and lower panels also indicate that the underestimation of mortality after age 70 or 80 had worsened in the 2010 census relative to the 2000 census.

From Figure 1, some possible linear associations exist between the first pair $_{10}q_{60}$ and $_{25}q_{70}$ and the second pair $_{10}q_{70}$ and $_{15}q_{80}$ for all 13 HMD countries. We obtained the following four linear regression models: $\text{logit}({}_{25}\hat{q}_{70}) = 3.104212 + 1.830234 * \text{logit}({}_{10}q_{60})$ for males ($R^2 = 0.86$), $\text{logit}({}_{25}\hat{q}_{70}) = 3.400152+1.927309* \text{logit}({}_{10}q_{60})$ for females (R^2=0.88), $\text{logit}({}_{15}\hat{q}_{80}) = 1.686355+ 1.393994* \text{logit}({}_{10}q_{70})$ for males (R^2=0.87), $\text{logit}({}_{15}\hat{q}_{80}) = 1.758806 + 1.362084* \text{logit}({}_{10}q_{70})$ for females (R^2=0.93). The results of linear regression models based only on Sweden and Japan were very similar to these four equations and thus not presented.

Based on the lower boundaries of the 95% confidence ellipses (Scenario A) and the four linear regression equations (Scenario B), we estimated ${}_{25}\hat{q}_{70}$ and ${}_{15}\hat{q}_{80}$ for individual provinces in China. We then estimated the average possible rates of underestimation for each five-year age group at ages 70–95 and at ages 80–95, respectively (see Tables 1 and 2). For the probabilities of dying at ages 70–95 (Table 1), under Scenario A (lenient criterion), we found almost no underestimation for China as a whole for males and females in both censuses (because these four data points fell within the 95% confidence ellipse). About 10–15 provinces were below of the lower boundary of the 95% confidence ellipses in the two censuses for males and females — assuming the probability of dying at ages 60–70 was accurate. Under Scenario B, however, the underestimation rate of ${}_{25}q_{70}$ for China as a whole was 11.5% for males and 22.2% for females in the 2000 census; and 16.5% for males and 24.3% for females in the 2010 census, respectively, if the linear associations between ${}_{25}q_{70}$ and ${}_{10}q_{60}$ was valid and if ${}_{10}q_{60}$ was accurate in both censuses. For individual provinces, most provinces had 10% or higher rates of underestimations. In some cases, the rates of underestimation were more than 40%. For both scenarios, provinces in western China had greater rates of underestimation than in eastern-coastal provinces; females had greater rates of underestimation than males; and the 2010 census had larger rates of underestimation than the 2000 census. The patterns of underestimation for probabilities of dying at ages 80–95 (Table 2) were similar to probabilities of dying at ages 70–95.

To account for possible underestimations in mortality at ages 60 to 70 (or ages 70–80) in Chinese censuses, we applied 1.15 to death rates at these two age groups, respectively (see Appendix A: Note 3). The results were reported in Appendixes B1 and B2 and showed that these rates of underestimation were larger than those reported in Table 1. Appendix C re-plotted scattered distributions of two pairs of probabilities of dying with these adjustments, and with few exceptions, the vast majority of provinces were located below the lower boundary of the confidence ellipses.

3.2 Death Rates after Age 90 in Many Provinces are not Reliable

Figures 2 and 3 compare sex-age-specific death rates for ages 80–84 to ages 95–99 between the unadjusted observations and the fitted Kannisto-model estimates. Results are presented for all of China and selected provinces in the 2000 and 2010 censuses, together with observed and fitted death rates for Japanese males and females in the 2000s. For illustrative purposes, death rates from ages 60-64 to ages 75-79 were also presented.

For China as a whole, the age trajectory of mortality from the Kannisto model fit the data well before age 90 for males and females if death rates at ages 60-70 were accurate. On average, age trajectories of mortality in some eastern-coastal provinces fit the Kannisto curves better than other provinces; whereas the age trajectories in some western provinces — such as Ningxia and Gansu — fit poorly. It is also clear from the figures that the observed age-trajectories of mortality in the 2010 census fit the Kannisto curve slightly better than in the 2000 census. Figures 2 and 3 further demonstrate that some provinces in China — such as Hainan, Tibet, and Xinjiang — exhibited a crossover with the age-trajectory of mortality for Japanese females in the 2000s. Considering the fact that Japanese females have the lowest mortality in the contemporary world and that Japan has among the highest quality of data on death rates, the crossover of these provinces with Japan suggests a substantial underestimation of death rates at oldest-old ages.

Table 3 presents the relative root-mean-square error (RMSE) between the fitted and observed death rates for ages 80 to 99 by province in the 2010 census. With few exceptions, provinces with majority populations of ethnic minorities generally had greater values of RMSE than other provinces where Han Chinese dominate. The RMSE was much higher after age 90 than ages below 90, indicating a deviation from the expected line for the age trajectory of mortality after age 90. On average,

age-trajectories for females fit the Kannisto curve better than for males. We also found that the age trajectory for the 2010 census fit the Kannisto model better than for the 2000 census. More socioeconomically developed provinces — such as Beijing and Shanghai — generally had better fit than those in relatively less developed provinces. However, it is also important to note that Hainan, Tibet, and Xinjiang where deaths rates are supposed to be less accurate had a value of RMSE as low as or even lower than Shanghai and Beijing. This suggests potentially systematic underreports of death at ages 60 to 70 in these remote provinces, a finding that concurs with our earlier estimates.

Table 1. Average five-year age-specific rate (%) of underestimation in probability of dying at ages 70-95 under the assumption that the death rates at ages 60-70 were accurate

Regions	Provinces	2000 census				2010 census			
		Males		Females		Males		Females	
		A	B	A	B	A	B	A	B
China		0.0	11.5	0.1	22.2	0.0	16.5	0.0	24.3
North	Beijing	0.0	7.2	0.0	14.9	0.0	7.9	0.0	12.4
North	Tianjin	0.0	9.5	0.0	19.4	0.0	20.5	0.0	23.6
North	Hebei	0.0	0.0	0.0	15.2	0.0	3.6	0.0	14.6
North	Shanxi	0.0	0.0	0.0	10.0	0.0	11.2	0.0	20.9
North	Neimeng	0.0	2.4	0.0	8.6	3.9	24.6	0.0	28.2
Northeast	Liaoning	0.0	6.4	0.0	14.9	0.0	13.7	0.0	18.3
Northeast	Jilin	11.5	25.3	17.3	31.5	16.4	34.3	15.8	39.5
Northeast	Heilongjiang	12.7	26.6	17.9	33.4	19.5	35.7	23.1	44.0
East	Shanghai	0.0	0.5	0.0	6.6	0.0	0.8	0.0	0.0
East	Jiangsu	0.0	7.4	0.0	15.4	0.0	4.9	0.0	11.3
East	Zhejiang	0.0	0.0	0.0	5.7	0.0	1.1	0.0	0.0
East	Anhui	3.0	19.6	0.1	24.5	0.0	15.7	0.0	22.8
East	Fujian	0.0	12.5	0.0	22.0	0.0	12.5	0.0	13.6
East	Jiangxi	0.0	11.9	1.4	22.0	0.0	12.5	0.0	23.6
East	Shandong	0.0	0.8	0.0	15.7	0.0	8.5	0.0	18.4
South Central	Henan	0.0	12.8	7.5	26.9	0.0	19.4	10.2	35.2
South Central	Hubei	0.0	9.6	4.4	23.3	0.0	20.1	0.0	24.3
South Central	Hunan	0.0	15.9	5.1	25.7	0.0	19.0	0.0	29.3
South Central	Guangdong	0.0	11.1	0.0	21.7	0.0	18.4	0.0	22.4
South Central	Guangxi	3.5	21.1	7.7	32.4	8.3	27.1	6.4	37.0
South Central	Hainan	8.1	25.8	8.2	34.7	15.4	34.8	7.5	40.8
South Central	Chongqing	0.0	16.7	3.9	23.4	1.4	23.4	0.0	25.6
Southwest	Sichuan	3.2	19.2	11.3	28.8	0.2	21.8	0.0	28.1
Southwest	Guizhou	0.0	11.5	1.4	20.8	0.0	19.0	0.0	24.9
Southwest	Yunnan	0.0	5.5	0.0	13.9	0.0	13.5	0.0	22.0
Southwest	Tibet	32.1	39.9	42.4	47.8	27.2	37.9	42.4	50.9
Northwest	Shaanxi	0.0	8.6	0.0	17.7	0.0	18.2	1.6	27.6
Northwest	Gansu	3.2	17.8	0.0	14.3	0.8	20.3	3.4	27.6
Northwest	Ningxia	23.6	34.3	23.5	34.5	13.6	29.1	13.8	33.6
Northwest	Qinghai	0.0	10.1	0.0	18.2	0.0	4.1	0.0	10.4
Northwest	Xinjiang	28.1	41.1	40.2	50.4	27.9	42.4	36.5	52.1

Note: (1). A: The average five year age underestimation rate was calculated as (100*(1- ${}_n\bar{q}_x$ / ${}_n\hat{\bar{q}}_x$), where ${}_n\bar{q}_x$ represents the observed average probability of dying over the five-year age group in the entire age group [x, $x+n$) (i.e., ${}_{25}\bar{q}_{70} = 1 - \sqrt[1/5]{(1 - {}_{25}q_{70})}$) and ${}_n\hat{\bar{q}}_x$ represents the corresponding average probability of dying derived from fitted estimates of the low boundary of the confidence ellipse in Figure 1. (2). B: ${}_n\hat{\bar{q}}_x$ was estimated from the linear regression models between logit-transformed probabilities of dying at ages 70-95 and at ages 60-70. The R^2 was 0.86 for males and 0.88 for females. (3) These average rates of underestimation for five-year age group were mildly lower than those for single years of age.

Table 2. Average five-year age-specific rate (%) of underestimation of probability of dying at ages 80-95 under the assumption that the death rates at ages 70-80 were accurate

Regions	Provinces	2000 census				2010 census			
		Males		Females		Males		Females	
		A	B	A	B	A	B	A	B
China		0.0	8.0	4.2	14.4	0.0	13.0	4.5	18.8
North	Beijing	0.0	4.9	0.0	10.2	0.0	5.4	0.0	12.4
North	Tianjin	0.0	6.8	1.3	12.2	8.0	20.8	6.7	22.2
North	Hebei	0.0	0.0	0.0	9.0	0.0	3.6	0.7	12.8
North	Shanxi	0.0	0.0	0.0	3.9	0.0	9.9	3.6	15.8
North	Neimeng	0.0	0.9	0.0	3.6	8.7	20.7	9.8	23.4
Northeast	Liaoning	0.0	1.9	0.0	7.4	0.0	9.1	0.0	13.6
Northeast	Jilin	12.2	21.3	14.7	23.5	19.7	30.5	22.0	33.9
Northeast	Heilongjiang	12.7	22.2	16.0	25.5	22.5	32.8	27.5	38.6
East	Shanghai	0.0	0.0	0.0	2.6	0.0	1.7	0.0	4.4
East	Jiangsu	0.0	3.8	0.0	7.3	0.0	1.6	0.0	7.3
East	Zhejiang	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East	Anhui	6.4	16.2	5.3	17.7	1.8	14.2	5.2	20.3
East	Fujian	0.0	6.3	0.0	12.7	0.0	8.6	0.0	9.6
East	Jiangxi	0.7	9.6	5.0	15.6	0.0	11.0	6.6	19.8
East	Shandong	0.0	0.0	0.0	8.4	0.0	6.0	0.3	15.1
South Central	Henan	1.5	10.6	11.3	21.0	6.7	17.5	18.9	31.0
South Central	Hubei	0.0	7.4	7.9	16.9	7.0	18.7	6.3	20.5
South Central	Hunan	3.0	13.0	6.3	17.2	2.3	15.4	8.7	23.4
South Central	Guangdong	0.0	6.4	0.0	13.6	2.9	15.4	0.5	17.8
South Central	Guangxi	4.2	15.8	12.2	25.4	9.6	21.3	16.9	31.4
South Central	Hainan	10.4	21.4	14.4	28.2	17.0	28.4	16.8	33.6
South Central	Chongqing	2.0	12.4	4.0	15.0	6.1	19.0	2.8	19.4
Southwest	Sichuan	4.7	14.6	10.7	20.7	4.7	17.0	6.8	21.5
Southwest	Guizhou	0.0	8.1	2.6	13.1	3.0	14.8	5.5	19.1
Southwest	Yunnan	0.0	2.8	0.0	6.2	0.0	9.3	1.9	14.7
Southwest	Tibet	32.8	38.6	33.3	39.8	25.2	33.2	37.9	44.9
Northwest	Shaanxi	1.0	9.2	4.8	13.0	3.8	15.7	9.5	21.5
Northwest	Gansu	12.6	19.0	2.1	9.1	7.1	17.9	11.1	21.9
Northwest	Ningxia	26.9	33.7	23.6	29.8	13.7	24.2	17.0	27.4
Northwest	Qinghai	0.3	10.0	9.1	16.7	0.0	4.0	0.0	6.7
Northwest	Xinjiang	30.3	38.8	37.9	45.4	23.1	33.7	34.1	44.6

Note: (1). A: The average five-year age underestimation rate was calculated as (100*(1- ${}_n\bar{q}_x$ / ${}_n\hat{\bar{q}}_x$), where ${}_n\bar{q}_x$ represents the observed average probability of dying over the five-year age group in the entire age group [x, $x+n$) (i.e., ${}_{15}\bar{q}_{80}$ =1- $\sqrt[1/3]{(1-{}_{15}q_{80})}$) and ${}_n\hat{\bar{q}}_x$ represents the corresponding average probability of dying derived from the fitted estimates of the lower boundary of the confidence ellipse in Figure 1. (2). B: ${}_n\hat{\bar{q}}_x$ was estimated from the linear regression models between logit-transformed probabilities of dying at ages 80-95 and at ages 70-80. The R^2 was 0.87 for males and 0.93 for females. (3) The average rates of underestimation for five-year age group were mildly lower than those for single years of age.

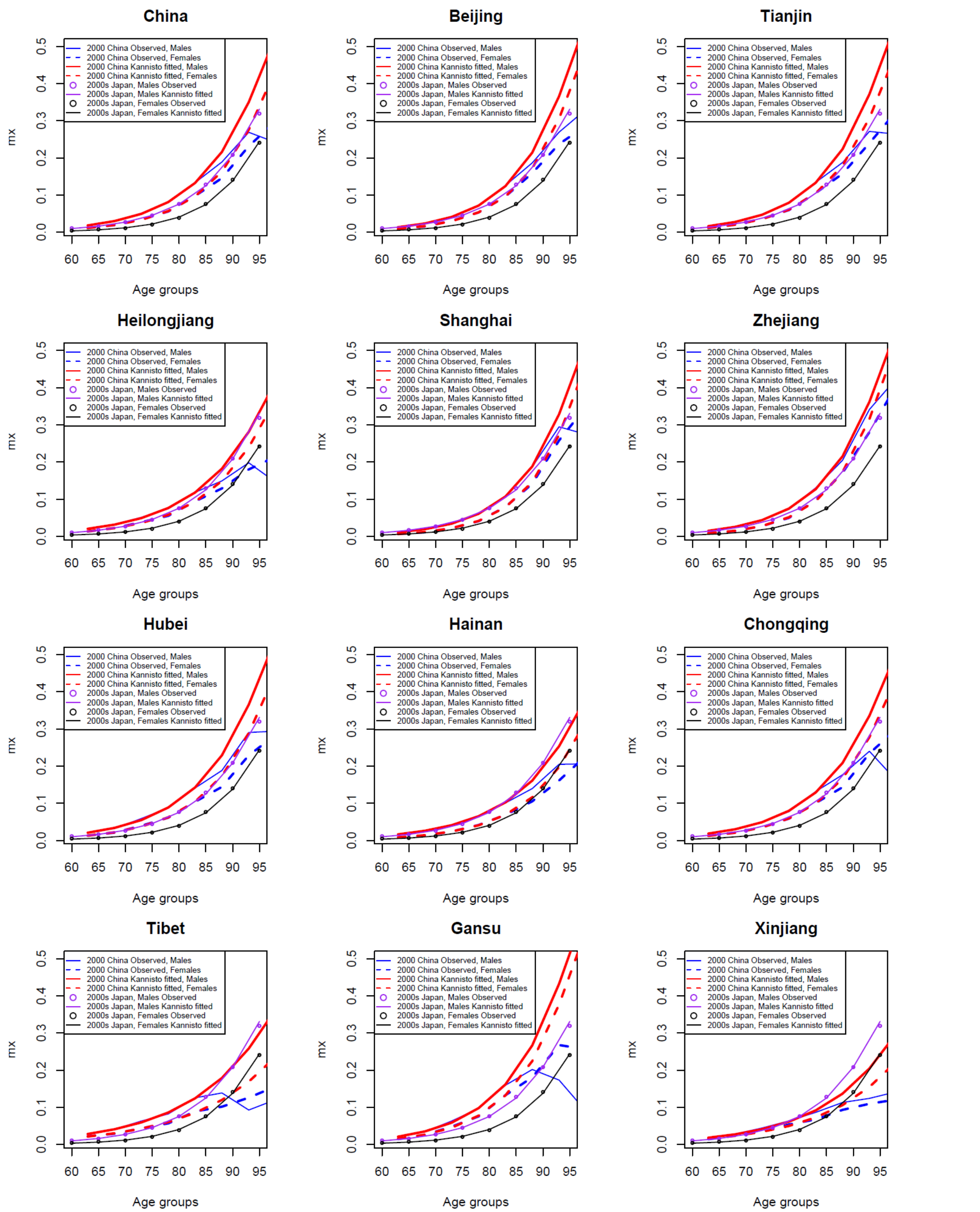

Figure 2. Age-trajectories of observed death rates in China's 2000 census for selected provinces by sex in comparison with the Kannisto model and those of Japan in the 2000s

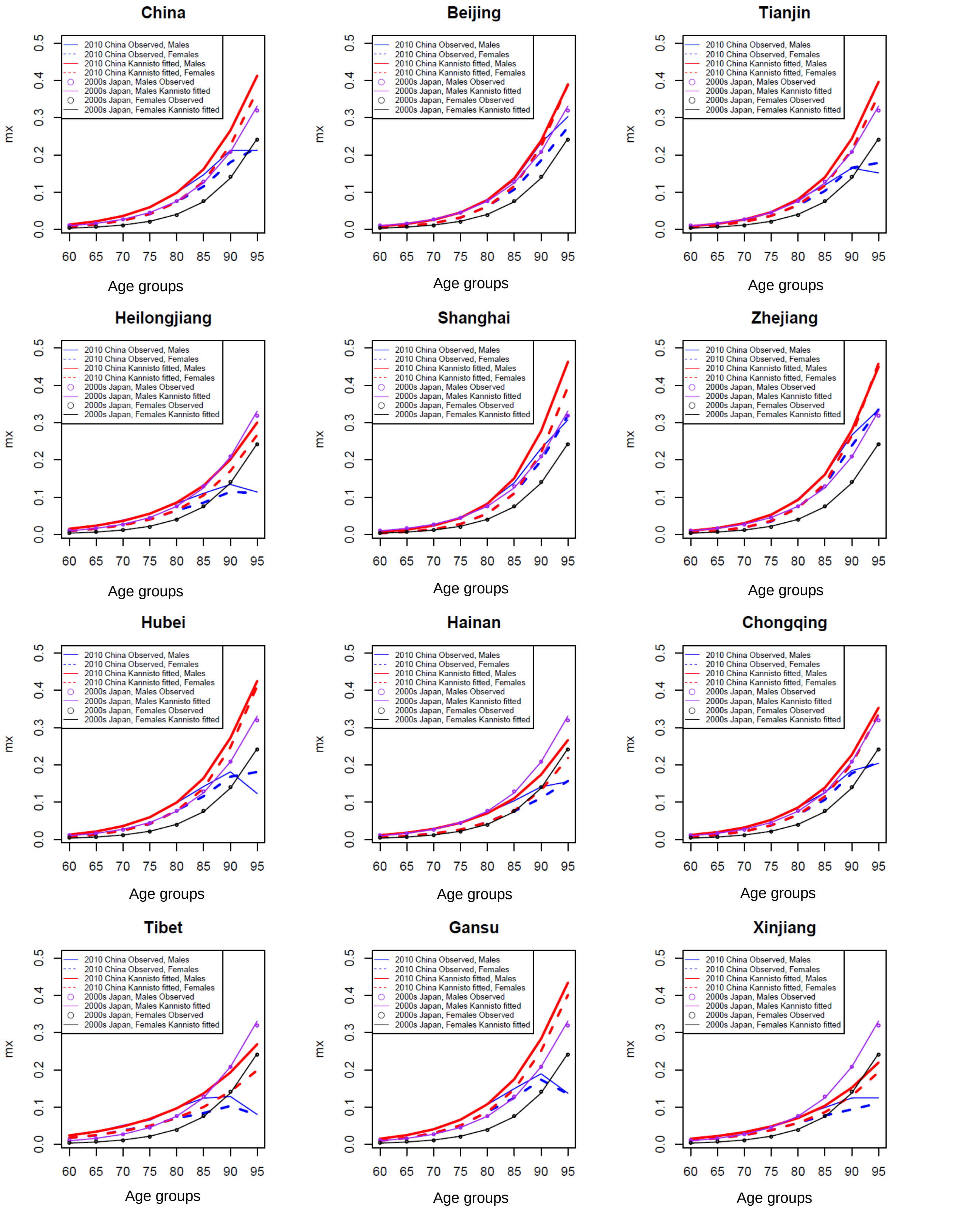

Figure 3. Age-trajectories of observed death rates in China's 2010 census for selected provinces by sex in comparison with the Kannisto model and those of Japan in the 2000s

Table 3. Root-mean-square error (RMSE) between the Kannisto Model and observed death rates for ages 80-99 by province and census

Regions	Provinces	2000 census				2010 census			
		Males		Females		Males		Females	
		Ages 80-89	Ages 90-99	Ages 80-89	Ages 90-99	Ages 80-89	Ages 90-99	Ages 80-89	Ages 90-99
China		0.041	0.294	0.031	0.159	0.026	0.233	0.026	0.190
North	Beijing	0.042	0.249	0.022	0.228	0.009	0.098	0.019	0.142
North	Tianjin	0.054	0.306	0.037	0.183	0.039	0.297	0.030	0.226
North	Hebei	0.056	0.264	0.048	0.163	0.052	0.249	0.056	0.229
North	Shanxi	0.057	0.456	0.039	0.246	0.051	0.278	0.042	0.235
North	Neimeng	0.040	0.478	0.050	0.245	0.034	0.271	0.036	0.269
Northeast	Liaoning	0.017	0.228	0.022	0.141	0.017	0.117	0.024	0.162
Northeast	Jilin	0.035	0.306	0.032	0.213	0.039	0.224	0.033	0.215
Northeast	Heilongjiang	0.054	0.316	0.037	0.199	0.041	0.263	0.043	0.235
East	Shanghai	0.002	0.246	0.009	0.120	0.023	0.173	0.001	0.092
East	Jiangsu	0.023	0.234	0.013	0.109	0.013	0.222	0.012	0.163
East	Zhejiang	0.018	0.127	0.007	0.117	0.007	0.122	0.010	0.135
East	Anhui	0.067	0.335	0.050	0.178	0.055	0.291	0.054	0.289
East	Fujian	0.017	0.215	0.007	0.110	0.027	0.176	0.021	0.167
East	Jiangxi	0.054	0.370	0.042	0.208	0.048	0.297	0.042	0.256
East	Shandong	0.037	0.259	0.026	0.141	0.015	0.193	0.026	0.173
South Central	Henan	0.064	0.308	0.058	0.172	0.049	0.282	0.050	0.237
South Central	Hubei	0.060	0.254	0.050	0.192	0.039	0.350	0.042	0.278
South Central	Hunan	0.050	0.347	0.035	0.164	0.020	0.232	0.027	0.187
South Central	Guangdong	0.020	0.139	0.016	0.098	0.036	0.270	0.024	0.183
South Central	Guangxi	0.022	0.221	0.026	0.171	0.012	0.180	0.022	0.172
South Central	Hainan	0.038	0.213	0.023	0.128	0.014	0.163	0.006	0.102
Southwest	Chongqing	0.050	0.360	0.040	0.157	0.025	0.189	0.018	0.162
Southwest	Sichuan	0.044	0.248	0.035	0.185	0.017	0.209	0.021	0.176
Southwest	Guizhou	0.054	0.318	0.051	0.226	0.011	0.237	0.020	0.218
Southwest	Yunnan	0.038	0.339	0.033	0.203	0.013	0.240	0.016	0.194
Southwest	Tibet	0.067	0.366	0.038	0.137	0.024	0.278	0.037	0.204
Northwest	Shaanxi	0.083	0.475	0.063	0.251	0.043	0.318	0.038	0.280
Northwest	Gansu	0.089	0.559	0.065	0.323	0.043	0.342	0.041	0.316
Northwest	Ningxia	0.117	0.468	0.066	0.251	0.011	0.242	0.028	0.216
Northwest	Qinghai	0.085	0.436	0.083	0.413	0.048	0.373	0.044	0.373
Northwest	Xinjiang	0.047	0.238	0.031	0.172	0.013	0.152	0.021	0.152

Note: The RMSE is estimated using the formula $\sqrt{\frac{\sum({}_n\hat{m}_x - {}_nm_x)^2}{N * {}_nm_x}}$, where ${}_n\hat{m}_x$ and ${}_nm_x$ are the fitted and observed death rates for age group [*x*, *x*+*n*), respectively, with n denoting age interval (i.e., 5 years herein); *N* is the number of five-year age groups. We added a term of ${}_nm_x$ in the denominator to represent their relative errors.

4. Discussion

Because of the low data quality of mortality at oldest-old ages in China, research on death rates at these ages has been limited, particularly at the province level. Based on criterion from data in 13 countries with the world's highest quality of mortality data and the Kannisto function, this study investigated the possible underestimation of mortality at oldest-old ages and discrepancies from an established age-trajectory of mortality. Following a similar approach used by Coale and Kisker (1986), we examined the ratio of the probability of dying at ages 60–70. We further estimated the regression-based linear relationships between logit-transformed $_{10}q_{60}$ and $_{25}q_{70}$ and between logit-transformed $_{10}q_{70}$ and $_{15}q_{80}$ from 13 countries together with the confidence ellipses that includes 95% of data points in these 13 HMD countries. Given the high quality of demographic data (and high R^2) in the 13 HMD countries, the established regression relationship and the confidence ellipse are effective comparisons to assess the reliability of mortality estimates at oldest-old ages for other countries, such as China. If the probabilities of dying $_{10}q_{60}$ and $_{25}q_{70}$ or the probabilities of dying $_{10}q_{70}$ and $_{15}q_{80}$ for a country under study do not fall into the ellipse, there is evidence to suggest that the death rates calculated from enumerated population and deaths in the census(es) for a given country could suffer from age-misreporting or death undercounts.

By comparisons with the regression-based linear relationship between logit-transformed $_{10}q_{60}$ and $_{25}q_{70}$ from the 13 HMD countries (the strict criterion) — and the relationship implied by the lower boundaries of their confidence ellipses (the lenient criterion) — we found that many Chinese provinces in general had at least a 10% rate of underestimation in mortality at ages 70 or older in the 2000 and 2010 censuses if the death rates at ages 60 to 70 were accurate. Some western provinces had more than a 40% rate of underestimation in the regression-based scenario. The rates of underestimation at oldest-old ages would be greater if underestimations at ages 60 to 70 were also taken into account. Rates of underestimation were slightly smaller for probabilities of dying at ages 80–95.

For age trajectories of mortality, when the underestimation of mortality at ages 60–70 was not taken into account, our findings revealed that death rates after age 90 were not reliable in most provinces in the 2000 and 2010 Chinese censuses because the observed death rates after age 90 either plateaued or declined with age, which is off the Kannisto curve. This distortion in mortality rates increased with age for both sexes and for all provinces. Simply put, death rates are progressively more unreliable with advancing age. Furthermore, if the rate of underestimation in mortality at ages 60–70 was taken into consideration, the distortion would be even more severe.

Our conclusions about the underestimation and inaccuracy of age-trajectories of mortality at oldest-old ages in China are strongly supported by the fact that death rates for China (overall and for each province) began to decline at ages 90 to 95, which is implausible. In fact, there is no evidence in the literature to suggest that human mortality declines after age 90 if the data on deaths and population counts are accurate (Andreev and Gu, 2017). The decline in death rates after age 95 was only found in HMD countries with lower-quality data and/or HMD countries at periods when their registration systems were incomplete and age exaggerations were documented (i.e., before 1900 or 1950). For example, death rates in the United States declined at ages 98 and older in the 1950s and 1960s. Nowadays, such declines are not observed because of improvements in vital registration systems; and death rates are shown to increase continuously with age when based on death records with extensive age validation (see Bayo and Faber, 1983; Kestenbaum, 1992). Accordingly, Andreev and Gu (2017) showed that mortality declines after age 100 disappeared in the United States by 2001–2011.

With regard to China, Gu and Dupre (2008) showed that observed mortality rates continued to increase with age beyond age 100 in the 1998, 2000, and 2002 waves of the Chinese Longitudinal Healthy Longevity Survey (CLHLS). In the 2000 Chinese census, however, death rates decreased after age 95 (Gu and Dupre, 2008). The CLHLS is a nationwide survey focusing on oldest-old adults and includes approximately 2,500–3,000 centenarians in each wave. Death rates were further calculated in later waves of the CLHLS (in 2005, 2008, and 2011) and it was shown that death rates continued to increase after age 95 to age 110 and beyond. The discrepancy is because age validation in the CLHLS is much more restricted than in the Chinese census (Gu and Dupre, 2008); and therefore, death rates calculated from the CLHLS are more reliable than those from the Chinese census.

Our results revealed that eastern-coastal provinces had relatively lower rates of underestimation on average and less distortion in age trajectories of mortality compared with provinces in western China. Several reasons may explain these regional differences. First, eastern-coastal provinces are the most developed and urbanized areas in China; and where death registration is relatively complete compared to other areas in western China (Huang and Poston, 2000; Wang, Wang, Cai *et al*., 2011). In the Chinese Disease Surveillance Point system, eastern coastal provinces generally had less underestimation of death than in provinces in other parts of China (Wang, Wang, Cai *et al*., 2011). Second, the population is primarily Han ethnicity in eastern China; whereas in some western provinces ethnic minorities accounted for a relatively large share of total population. Because Han Chinese use a lunar calendar (i.e., animal years) to remember his/her birth date and other important life events — such as marriage — age misreporting is relatively lower than among ethnic minorities in China (Zeng and Gu, 2008; Zeng and Vaupel, 2003). It is also possible that less steep slope of mortality at very old ages in less developed western provinces may be due to mortality selection that dropped those frail persons out, leaving more robust ones in the cohort, a common phenomenon at very old ages in general populations (Zheng, 2014).

The underestimation of mortality at older and oldest-old ages was more pronounced in the 2010 census than in the 2000 census. However, the age trajectory of mortality was more accurate in 2010 census than in the 2000 census. These seemingly counterintuitive findings are not unreasonable. First, improved age-trajectories of mortality in the 2010 census likely reflects less age-exaggeration in the 2010 census than in the 2000 census. Indeed, this is consistent with recent improvements in the household registration system (or *hukou* system) in China (Zhai, Chen and Li, 2015). Second, the higher rates of underestimated mortality after age 70 in the 2010 census (vs. the 2000 census) may be attributable to higher rates of underestimated mortality at ages 60 to 70 in the 2000 census. The higher underestimation of mortality in the 2000 census for ages 60 to 70 (i.e., lower observed mortality rates) likely produced artificially lower estimates for mortality after ages 70. In other words, it is possible that actual rates of underestimated mortality were smaller in the 2010 census than in the 2000 census. Third, underreports of death were more severe in the 2010 census than in the 2000 census. It has been reported in China many families either do not report the deaths of their older parents or relatives within the required time-period following their deaths (or "postpone" the actual dates of death) to continue receiving pensions or other social benefits (Liu, 2011; Wang and Liu, 2016; also see Appendix A: Note 4 for more information). Such underreports may be more serious in the 2010 census because of possible increased motivations for higher pensions and more social benefits at older ages due to improvements in social security and other social welfare systems in both urban and rural areas in China after 2000.

Gender differences in the underestimation and age-trajectories of mortality are also noteworthy. In almost all cases, females matched the age trajectory of the Kannisto model better than males, yet females had higher rates of underestimation than males. Again, this seemingly counterintuitive finding is not entirely unexpected. Males may have a greater underestimation of mortality at ages 60 to 70 than females, which in turn, may produce an artificially lower underestimation of mortality at ages 70 or older in males. According to the 2009 DSP assessment survey by the China Center for Disease Control and Prevention for in the 2006, 2007, and 2008 DSP regular surveys, males had a higher rate of underestimation than females in all age groups except at ages 0 to 5 (Wang, Wang, Cai *et al*., 2011). Therefore, it is possible that females had a lower rate of underestimated mortality at ages 70 and older relative to males. It also may be possible that underreports of death are more prevalent at all ages in females than in males. More research is clearly warranted to better understand gender differences in the underestimation of mortality at oldest-old ages in the Chinese census(es).

Results also demonstrated crossovers between the observed death rates at some ages in several provinces in the 2000 and 2010 censuses and the observed death rates in Japanese females in the 2000s. Such crossovers are not likely due to mortality selection — in which frail people exit the cohort before reaching oldest-old ages, leaving more robust individuals in the cohort. Instead, we believe that these crossovers are due to significant undercounting of death or age misreporting at ages 90 and older. Considering the relatively smaller discrepancies between the observed and fitted death rates, underestimations were also prevalent at ages 60 to 70. As a result, the Kannisto curve was fit at a very low level, creating a crossover in death rates with Japanese females. Also considering that Japanese females have the world's highest life expectancy, it is highly implausible that these Chinese provinces (relatively undeveloped areas in China) would have life expectancies at older ages comparable to older Japanese females. Of course, it is possible that very low mortality in Hainan Province (in South China Sea) may be because it has attracted many older migrants from other provinces seeking the favorable climate during winter months (Xia, 2016). In turn, these seasonal migrants/retirees may have been enumerated as a part of de facto population counts in Hainan Province at the time of the censuses (November 1). However, these older adults may ultimately die in their residence of origin — which brought down death rates in the censuses for Hainan Province. Nevertheless, more empirical research is needed to validate these arguments.

Our findings on age-trajectories of mortality are consistent with previous research on Chinese oldest-old showing mild to substantially lower age-trajectories of mortality after age 97 compared with the Kannisto curve among Han Chinese (Zeng and Vaupel, 2003). Considering that Han Chinese have more accurate age-reporting than ethnic minorities and that discrepancies from the classical age-trajectory remains prevalent after 20 years, we conclude that age exaggerations exist not only among ethnic minorities, but also among Han Chinese, especially after age 90. The rates of underestimation for mortality at ages 70 and older are also generally consistent with recent findings by Wang (2013).

Underestimations of mortality — in terms of the level and shape of age trajectories — in the 2000 and 2010 Chinese censuses may be attributable to age exaggeration/misreporting, underreports of deaths, and/or incomplete death registration. In China, the prestige associated with old age in traditional Confucian culture may motivate individuals to overstate their age (Chou, Ju, and Huang, 2013). Indeed, several studies have documented age exaggerations in enumerated population counts in the Chinese censuses (Liu, 1991; Wang, 2012; Yang, 1988). In cases of age exaggeration, death rates computed from death records will be biased downwards relative to true death rates; and the discrepancy with true data would progressively widen with advancing age (Andreev and Gu, 2017). Furthermore, in Chinese censuses, death counts are primarily collected from reports gathered from household family members — which can lead to possible misreporting and/or underreporting for purposes of receiving social benefits.

We recognize the need for caution when interpreting our findings. First, we did not provide exact levels of underestimation in mortality. Instead, we only explored possible rates of underestimation from regression-based models (strict criterion) and from confidence ellipses (lenient criterion). These two scenarios can be interpreted as the high and low boundaries, respectively, for underestimation. Furthermore, because data were not available for calculating age-sex-province-specific underestimations, we assumed that rates of underestimation were the same for China and its provinces at ages 60–70 (or at ages 70–80) when we estimated rates of underestimation at ages 70–95 (or at ages 80–95). However, these assumptions may not be true (Wang, Wang, Cai *et al*., 2011). Alternatively, our findings would be more robust if province-age-sex-specific rates of underestimation are applied when data become available. Therefore, we encourage more research on the levels of mortality underestimation at oldest-old ages in the 2000 and 2010 censuses.

Second, although some provinces had age trajectories that matched the Kannisto curve, it does not mean that there were no (or low) rates of underestimation in these provinces. The Kannisto model does not produce adjusted estimates for mortality at advanced ages (Andreev and Gu, 2017). Instead, it only smoothes the age trajectory of mortality and extrapolates death rates at very old ages (e.g., age 110 or beyond). All ages (80 or older) may be systematically or proportionally underreported even though the observed death rates match the Kannisto model. Nevertheless, if age-specific death rates do not follow the Kannisto function, these age rates are likely very distorted and proper adjustments should be used before applying them.

Third, the accuracy of mortality beyond age 100 was not assessed in this study due to the limited availability of data. However, we suspect that the underestimation of mortality among centenarians is at the least same (or greater) than that for adults ages 80 to 99. Indeed, Zeng and Vaupel (2003) showed that the age trajectory of mortality after age 100 was mildly below the Kannisto curve for Han centenarians in the 1990 census.

A final limitation is that we assumed that migration had no effect on the relationships between ${}_{10}q_{60}$ and ${}_{25}q_{70}$ and between ${}_{10}q_{70}$ and ${}_{15}q_{80}$; and had no effect on age-specific death rates. However, it is likely that migration may increase or decrease population exposures and number of deaths, thereby affecting mortality at these ages — especially before age 70. In provinces with relatively large percentages of in- or out-migration, the effects of migration should be taken into account to obtain more robust estimates.

Despite these limitations, our findings have important implications. To obtain reliable and meaningful age-specific estimates of death at oldest-old ages in China, appropriate adjustments are needed and the Kannisto model should be applied after adjustment. Additional research is needed to further understand how to assess the underestimation and how to obtain factors for adjustment. In estimating mortality at old and oldest-old ages, the Brass relational logit system (Brass, 1971), the modified logit system for linking to a model or a standard life table (Murray, Ferguson, Lopez *et al*., 2003), or flexible two-dimensional mortality model (Wilmoth, Zureick, Canudas-Romo *et al*., 2012) can be used to estimate age-specific mortality if accuracy in the selected mortality indicators in the linking function of the relational logit system can be ensured.

Age misreporting and death underreporting are challenging to demographic research and aging studies (Zeng and Vaupel, 2003). Therefore, it is important to recognize and minimize data errors in population estimates. Given the rapid growth of oldest-old populations, the accuracy of death counts will not only impact demographic analysis, but will also have important implications for the distribution and equity of social welfare systems. Currently, China has several systems to collect data on deaths (see Liu, Li, Wei *et al*., 2016). Greater harmonization of these different collection systems would help establish a more reliable system that would be more cost-effective than several unintegrated systems. Fortunately, the China Center for Disease Control and Prevention has established an internet-based nationwide cause-of-death reporting system since 2004 (Zhou, Wang, Zhu *et al*., 2016). As of 2015, more than 93% of counties throughout China have been covered by this system (Zhou and Yin, 2016). With further development of this system, we can expect that there will be further improvements in the completeness of death registration and reductions in age misreporting and the underestimation of deaths. It will also be possible for researchers to better assess the accuracy of mortality at oldest-old ages in the census (or other surveys) and establish more robust age-trajectories of mortality at old and oldest-old ages.

5. Conclusions

Based on the 2000 and 2010 Chinese censuses, this study examined (i) the possible underestimation of mortality at age 70 and older and (ii) age trajectories of mortality after age 80. We found sizeable rates of underestimated mortality at old and oldest-old ages for most provinces and for both sexes. We also found that the age-patterning of mortality after age 90 in most provinces was not reliable — even when an overall adjustment for old ages or the oldest-old ages as a whole were applied. Overall, provinces in eastern coastal areas (mainly with relatively high socioeconomic development)had higher data quality; whereas provinces in western China had more problematic data. Age-sex-specific adjustments by province and/or the application of some classic models should be simultaneously used to obtain robust estimates; otherwise, direct estimates of mortality at oldest-old ages — especially beyond age 95 in the Chinese censuses — should not be used. Improvements in the death registration system may provide opportunities in the near future to further assess rates of underestimation of mortality and construct reliable age-trajectories of mortality at oldest-old ages in China.

Authors' Contribution

DG designed the study, performed the analysis, drafted and revised the manuscript. RH was involved in the design, revised the manuscript, and interpreted the results. KA was involved in performing the analyses, revised the manuscript, and interpreted the results. MED revised and interpreted the results. YZ and HL collected and prepared the data and interpreted the results.

Conflict of Interest and Funding

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Ethics Approval

N/A—this study used secondary aggregated data from publicly available census tabulations.

Disclaimer

The views expressed in this paper are solely those of the authors and do not reflect those of the United Nations, Nanjing Normal University, Duke University, or the China Population and Development Research Center.

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Appendix A

Notes:

1. The observed infant mortality rate for China in the 2010 census was less than 4‰, lower than the level of the UK in the same year (which is not plausible) and more than 70% lower than that observed in the Maternal and Child Mortality Surveillance System in China (http://www.childmortality.org/index.php?r=site/graph#ID=CHN_China).
2. To calculate the observed ${}_{10}q_{60}$, ${}_{25}q_{70}$, ${}_{10}q_{70}$, ${}_{15}q_{80}$ for Chinese data, we first estimated the average number of person-years lived in a given five-year age group using the following approximation of the Greville formula: ${}_{n}a_{x} = \frac{n}{2} - \frac{n^2}{12}\left({}_{n}m_{x} - \frac{\ln({}_{n}m_{x+n} / {}_{n}m_{x-n})}{2n}\right)$ (Greville, 1943), where ${}_{n}a_{x}$ is the number of person-years lived in age group $[x, x+n)$, n is the age interval (herein n=5) and ${}_{n}m_{x}$ is the death rate of that age group. This formula is also used in the MortPak package (United Nations, 2003). However, we found that when ${}_{5}m_{x}$ is greater than 0.5, there is a noticeable bias. We thus added an error term E in the formula, where the error term was estimated using HMD data from the earliest date available to the latest date available until 2015. We finally obtained $E = b_1 * ({}_{n}m_{x})^3 + b_2 * ({}_{n}m_{x})^2 + b_3 * {}_{n}m_{x} + b_4$, where b1= –0.020359672, b2=0.771687846, b3= –0.221638614, and b4=0.017067167. Once the ${}_{n}a_{x}$ was obtained, the probability of dying for any given five-year age group could be calculated. We also tried alternative approaches to de-group mortality into single-age mortality, including the piecewise cubic Hermite interpolating polynomial plus smoothness and constraints that was used by the United Nations (2013), and a relational technique for estimating the age-specific mortality pattern from grouped data (Kostaki, 2000; Kostaki and Lanke, 2000). We then re-grouped them. These alternative results were very close to those presented in the text.
3. The China Center for the Disease Control and Prevention has been conducting evaluation surveys every three years for its disease surveillance point (DSP) system. According to the 2012 evaluation survey, which assessed the DSP regular surveys in 2009, 2010, and 2011, there was an approximately 12-15% underestimation in death counts among the population aged 60 and older in the regular annual DSP surveys in these three years (Zhou and Yin, 2016). The age-specific death rates in the 2010 DSP data largely matched the 2010 census' unadjusted figures (not shown). This suggests that there was an approximately 12-15% underestimation in death counts above age 65 in the 2010 census. Because the age-specific percentages of underestimation in death rates from the DSP were not available, we applied the overall underestimation rate among older persons to all age-specific death rates and re-calculated the probabilities of dying presented in Figure 1 (see Appendixes B1, B2, and C).
4. For example, in a county in Sichuan Province, the local government audited 803 suspected cases of underreported deaths for possible pension fraud in 2015 (the number of newly filed fraud cases was 234 for those who died in 2015; and the remaining 570 cases were for those who died before 2015), accounting for more than 83% of audited cases in that county in 2015 (http://www.scsi.gov.cn/tszs/shownews.php?lang=cn&id=3116).

Appendix B

Table B1. Average five-year age-specific rate (%) of underestimation in the probability of dying at ages 70-95 under the assumption that there was a 15% underestimation in death rates at ages 60-70

Regions	Provinces	2000 census				2010 census			
		Males		Females		Males		Females	
		A	B	A	B	A	B	A	B
China		0.4	15.1	9.2	25.7	5.9	20.4	12.2	28.4
North	Beijing	0.0	11.5	0.0	19.1	0.0	13.1	0.0	18.5
North	Tianjin	0.0	13.4	6.8	22.9	6.7	25.0	7.7	28.3
North	Hebei	0.0	1.0	4.7	18.7	0.0	7.8	5.5	18.8
North	Shanxi	0.0	2.3	0.0	13.7	1.5	15.2	12.8	24.8
North	Neimeng	0.0	6.3	0.0	12.3	14.9	28.1	17.7	32.0
Northeast	Liaoning	0.0	10.4	1.2	18.7	2.3	17.8	5.4	22.8
Northeast	Jilin	17.3	28.3	24.7	34.2	25.9	37.4	32.2	42.6
Northeast	Heilongjiang	18.6	29.6	25.2	36.2	28.1	38.6	37.8	46.8
East	Shanghai	0.0	5.4	0.0	12.1	0.0	6.8	0.0	7.5
East	Jiangsu	0.0	11.5	0.0	19.6	0.0	9.6	0.0	16.6
East	Zhejiang	0.0	1.8	0.0	10.5	0.0	6.3	0.0	6.3
East	Anhui	9.0	23.0	9.9	28.1	4.0	19.7	7.8	27.3
East	Fujian	0.7	16.2	4.4	25.8	1.0	16.7	0.0	18.7
East	Jiangxi	2.1	15.5	10.1	25.4	2.8	16.5	12.7	27.6
East	Shandong	0.0	5.0	0.0	19.6	0.0	12.8	4.7	22.9
South Central	Henan	2.7	16.4	15.6	30.1	10.2	23.0	26.8	38.6
South Central	Hubei	0.0	13.2	12.4	26.6	9.5	23.9	11.4	28.5
South Central	Hunan	5.1	19.4	13.6	28.9	7.7	22.9	17.9	33.1
South Central	Guangdong	0.0	14.8	2.4	25.6	7.6	22.3	7.4	27.0
South Central	Guangxi	9.6	24.5	16.3	35.8	18.8	30.4	24.8	40.7
South Central	Hainan	14.0	29.0	17.1	38.1	25.0	38.1	26.6	44.7
South Central	Chongqing	6.7	20.2	13.0	26.7	12.3	27.1	11.9	29.8
Southwest	Sichuan	9.8	22.5	18.7	31.8	11.6	25.5	17.4	31.9
Southwest	Guizhou	1.1	15.1	9.6	24.1	9.5	22.7	15.0	28.8
Southwest	Yunnan	0.0	9.3	4.7	17.5	5.6	17.2	15.8	25.7
Southwest	Tibet	36.5	42.1	47.6	49.7	35.2	40.3	52.4	52.8
Northwest	Shaanxi	0.0	12.4	8.0	21.1	8.5	22.0	19.9	31.1
Northwest	Gansu	9.5	21.0	7.1	17.7	12.2	23.9	21.5	31.0
Northwest	Ningxia	28.3	36.8	29.9	37.1	23.2	32.1	29.0	36.6
Northwest	Qinghai	0.0	14.0	6.5	21.7	0.0	8.4	2.4	14.6
Northwest	Xinjiang	32.7	43.6	45.5	52.4	36.2	45.0	48.2	54.3

Note: (1). A: The average five-year age-specific rate of underestimation was calculated as (100*(1− ${}_n\bar{q}_x$ / ${}_n\hat{\bar{q}}_x$), where ${}_n\bar{q}_x$ represents the observed average probability of dying over the five-year age group in the entire age group [*x*, *x*+*n*) (i.e., ${}_{25}\bar{q}_{70} = 1 - {}^{1/5}\sqrt{(1 - {}_{25}q_{70})}$) and ${}_n\hat{\bar{q}}_x$ represents the corresponding average probability of dying derived from the fitted estimates of the lower boundary of the confidence ellipse in Appendix C. (2). B: ${}_n\hat{\bar{q}}_x$ was estimated from linear regression models between logit-transformed probabilities of dying at ages 70-95 and at ages 60-70. The R^2 was 0.86 for males and 0.88 for females (see Appendix C). (3) These average rates of underestimation for five-year age group were mildly lower than those for singe years of age.

Table B2. Average five-year age-specific rate (%) of underestimation of probability of dying at ages 80-95 under the assumption that there was a 15% underestimation in death rates at ages 70-80

Regions	Provinces	2000 census				2010 census			
		Males		Females		Males		Females	
		A	B	A	B	A	B	A	B
China		5.8	12.6	11.6	18.6	10.4	17.6	18.0	23.1
North	Beijing	0.3	9.8	5.5	14.6	0.6	10.7	8.4	17.4
North	Tianjin	3.7	11.5	9.1	16.4	16.9	25.2	20.5	26.4
North	Hebei	0.0	1.0	7.4	13.2	3.8	8.5	14.6	17.0
North	Shanxi	0.0	3.9	3.1	8.4	8.9	14.5	16.5	19.9
North	Neimeng	0.7	5.9	3.5	8.1	18.2	24.8	23.2	27.4
Northeast	Liaoning	0.0	6.8	4.3	11.9	5.9	13.9	13.3	18.0
Northeast	Jilin	19.1	25.3	21.1	27.2	27.9	34.2	33.1	37.3
Northeast	Heilongjiang	19.7	26.1	22.7	29.1	30.6	36.3	37.8	41.8
East	Shanghai	0.0	3.5	0.0	7.8	0.0	7.3	0.0	10.2
East	Jiangsu	0.0	8.7	1.3	12.0	0.0	6.8	4.9	12.3
East	Zhejiang	0.0	0.0	0.0	4.6	0.0	2.7	0.0	4.3
East	Anhui	13.3	20.4	13.6	21.7	12.0	18.6	18.9	24.5
East	Fujian	2.8	11.0	7.0	17.1	5.6	13.4	7.3	14.4
East	Jiangxi	8.0	14.1	12.5	19.6	10.1	15.6	19.3	23.9
East	Shandong	0.0	3.7	4.1	12.8	3.9	10.8	14.2	19.5
South Central	Henan	9.4	15.1	18.3	24.8	16.2	21.7	30.8	34.5
South Central	Hubei	6.3	12.1	14.7	20.9	16.6	23.0	19.6	24.6
South Central	Hunan	10.7	17.4	13.2	21.2	12.4	19.9	22.6	27.4
South Central	Guangdong	3.1	11.2	7.7	17.9	13.0	19.8	16.3	22.2
South Central	Guangxi	11.6	20.1	19.7	29.2	18.3	25.4	29.4	35.1
South Central	Hainan	17.3	25.5	21.9	32.0	24.7	32.4	29.8	37.7
South Central	Chongqing	9.8	16.8	11.7	19.1	15.5	23.3	18.1	23.7
Southwest	Sichuan	11.7	18.9	17.8	24.5	14.5	21.4	20.9	25.6
Southwest	Guizhou	6.3	12.8	10.8	17.2	13.0	19.2	19.2	23.2
Southwest	Yunnan	1.9	7.6	4.8	10.6	8.6	13.9	15.7	18.9
Southwest	Tibet	37.7	41.7	38.2	42.7	32.5	36.6	46.0	47.6
Northwest	Shaanxi	8.5	13.8	12.3	17.0	13.8	20.1	22.0	25.4
Northwest	Gansu	19.1	23.1	9.4	13.3	16.6	22.1	22.8	25.7
Northwest	Ningxia	32.7	37.1	29.0	33.0	22.6	28.1	28.5	31.0
Northwest	Qinghai	8.0	14.5	16.1	20.6	3.3	8.8	9.2	11.2
Northwest	Xinjiang	35.7	41.9	43.1	48.1	30.5	37.4	43.6	47.5

Note: (1). A: The average five-year age-specific rate of underestimation was calculated as (100*(1− ${}_n\bar{q}_x / {}_n\hat{\bar{q}}_x$), where ${}_n\bar{q}_x$ represents the observed average probability of dying over the five-year age group in the entire age group [*x*, *x*+*n*) (i.e., ${}_{15}\bar{q}_{80} = 1 - \sqrt[1/3]{(1 - {}_{15}q_{80})}$) and ${}_n\hat{\bar{q}}_x$ represents the corresponding average probability of dying derived from the fitted estimates of the lower boundary of the confidence ellipse in Appendix C. (2). B: ${}_n\hat{\bar{q}}_x$ was estimated from linear regression models between logit-transformed probabilities of dying at ages 80-95 and at ages 70-80. The R^2 was 0.87 for males and 0.93 for females (see Appendix C). (3) The average underestimation rates for five-year of age were mildly lower than those for single years of age.

Appendix C

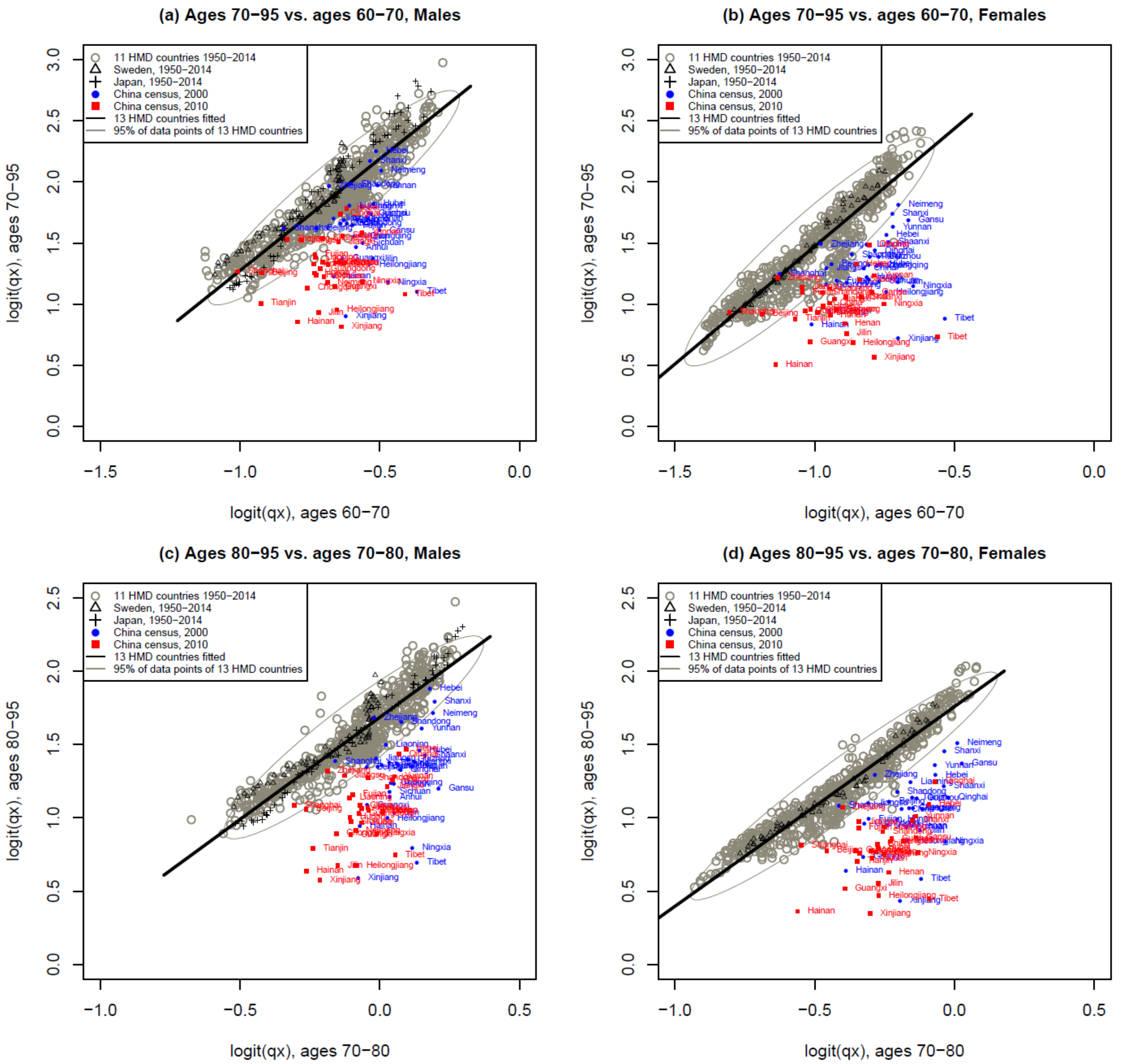

Figure C. Logit-transformed probabilities of dying at ages 60-70 against ages 70-95 and ages at 70-80 against ages 80-95 in Chinese censuses by sex and province in comparison with those 13 HMD countries

Note: Figures C(a) and C(b) assumed that death rates at ages 60-70 had a 15% of underestimation for China and its all provinces. Figures C(c) and C(d) assumed that death rates at ages 70-80 had a 15% of underestimation for China and its all provinces.