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Abstract

China is expected to experience a rapid ageing process because of its low fertility rate, the ageing of the large baby boom generation and the improvement of mortality rates. Fertility and mortality rates are smaller for the urban than for the rural population, as a consequence of which the rapid urbanization will play an important role in changes in the age structure of the Chinese population. This paper estimates China's future population and labor force by developing a novel population forecast model that combines information about age-specific parameters on fertility and mortality for both rural and urban areas with information about rural-urban migration and transformation of rural areas into urban areas. We find that (i) the share of people aged 65+ in China's total population will double between 2010 and 2030, and the ageing problem in rural areas will be more serious than in urban areas; (ii) China's total labor force will decrease by 6% between 2010 and 2030, irrespective of potential relaxation of birth control policies; and (iii) China's urbanization rate will increase from 50% in 2010 to 71% in 2030. These projections deviate considerably from projections by the United Nations (2013).

Keywords: Population projection; Ageing; Urbanization; Labor force; China

1. Introduction

Ageing of the population will be an important concern for China in the upcoming decades. Basically, three causes can be distinguished. First, the fertility rate is low. After the one-child policy was launched in the 1980s, China's fertility rate declined substantially (Poston and Gu, 1987). According to the latest national population census data (NBS, 2012), China's fertility rate was 1.18 in 2010, which is clearly much lower than the replacement level of 2.10. If the current child control policy is not loosened, China's fertility rate is expected to remain at this low level. Second, China's large baby boom generation, which was born in the 1960s, will gradually retire in the following two decades, which will cause a substantial reduction in the share of the labor force in the total population. Third, the improvement of health care in China has led to an increased life expectancy, which contributes to the increase in the population share of the elderly. These three factors (i.e. the low level fertility rate, the ageing of the large baby boom generation, and the improvement of the mortality rates) will boost the ageing process of China in the following decades.

Another aspect is that ageing will affect rural areas different than urban areas. On the one hand, the fertility rate and the mortality rate are both significantly lower for the urban than for the rural population. This will increase ageing more in urban than in rural areas. On the other hand, ongoing urbanization should be taken into account. In the past two decades, many people migrated from rural to urban areas and the urban areas expanded. The urbanization rate (i.e., the share of the population living in urban areas) increased from 26.4% in 1990 to 50.0% in 2010, which is an annual increase of 1.2 %-point on average. This rapid urbanization trend is expected to continue in the future, given China's industrialization process (United Nations, 2012; Zheng, 2011). Characteristic for the urbanization process is that, in particular, young people migrate from rural to urban areas. This is likely to cause the ageing problem to be more serious in rural areas than in urban areas. The question is which of the two forces is stronger?

This paper projects the development of the age structure of the Chinese population until 2030, distinguishing between rural and urban areas and taking urbanization into full account. Such projections are relevant because many socio-economic issues arise with demographic changes. For instance, due to the retirement of the baby boom generation, the size of the labor force will decrease. This may have adverse effects on the long-run economic growth of China, which is highly dependent on the input of labor. It is thus important to know the future size of the labor force (i.e. the people in the age group 15-64). The reason for choosing 2030 as the projection year is that the effect of the retirement of the baby boomers will emerge around 2030. If the projection interval is shorter than 2010-2030, this effect would be neglected. A longer projection interval increases the uncertainty of the projection because assumptions for the long-term changes in China's fertility and mortality rates are required.

We develop a rural-urban population model that has the following characteristics. It is an age-sex specific model with a module for the rural population and a module for the urban population. This distinction allows for demographic heterogeneities between rural and urban areas, and for modeling the urbanization process by means of the rural-urban transition. We calibrate the model using data from the 2010 population census (NBS, 2012).

Recent projections for China's future population are United Nations (2013) and Mai et al. (2013). The projections by the United Nations (2013) are also based on the 2010 census data, whereas Mai et al. (2013) project China's population in 2050 based on China's 2000 population census data. Neither model distinguishes between rural and urban population. These projections thus cannot capture the unequal effects of ageing for the rural and urban populations, and cannot incorporate the effects of urbanization on countrywide ageing, as done in this study.

The remainder of this paper is organized as follows. Section 2 describes China's current population profile and the rural-urban demographic heterogeneity. The rural-urban population model is presented in Section 3 and Section 4 deals with the quantification of parameters through assumptions or estimates. Section 5 projects

China's population to 2030 under several fertility scenarios, Section 6 compares our findings with the other projections in the literature, and Section 7 concludes.

2. A sketch of China's population profile and the rural-urban demographic heterogeneity

According to the 2010 population census data (NBS, 2012), China's total population was around 1,340 million in 2010. The share of the population that was 65 years or older (age group 65+) was 8.9%, which was low when compared to developed countries. For example, the share of people aged 65+ was 13.1% in the US, 22.7% in Japan, and 20.4 % in Germany. However, when evaluated against the standard ageing line of 7% as set by the United Nations (United Nations, 1956), China actually had already become an ageing country.

Figure 1 depicts the age structure of the rural and urban population in 2010. It shows that a relatively large share of China's population was in the age group 35-49, both for the rural and the urban population. This age group consists of the baby boom generation born in the 1960s, when China just pulled out of the great famine. The age-group 20-24 covers a major part of the offspring of the baby boom generation and was also relatively large. A substantial proportion of the baby boom generation will survive the following two decades and contribute to China's ageing problem towards the end of this period.

Insert Figure 1

The age structures of the rural and urban population were quite different in 2010. The share of young people (i.e. aged 0-14) was clearly larger for the rural than for the urban population and the same was true (although to a lesser extent) for the share of old people (i.e. aged 65+). The opposite held for the share of the young labor force (i.e. aged 15-34), which was smaller for the rural than for the urban population. These different age structures are in line with the differences in fertility rates and the rural-urban migration, whereas different mortality rates seem to have dampened the disparities somewhat.

What factors underlie these differences? First, rural and urban areas faced different policies for child control, which led to different fertility rates. In the rural areas, the "one and a half" children policy was followed, which meant that rural couples were allowed to have a second child if their first child was female. In the urban areas, however, the "only one child" policy was executed, which allowed urban couples to have only one child. Figure 2 gives the age specific fertility rates for 2000 and 2010, for the rural and the urban population. It shows that the rural fertility rate was higher than the urban fertility rate for any age. This partly explains why the share of young people in the rural population was larger than in the urban population.

Insert Figure 2

Second, many young rural workers migrated to work in urban areas during China's industrialization process. Although the urban fertility rate was lower than the rural fertility rate, the urban population gained additional young workers via the immigration of rural people. This migration pattern led to a relatively large share of the young people in the urban population.

Besides fertility and migration, the rural and urban populations also had a large demographic disparity in their mortality rates. Figure 3 shows that the mortality rate of the rural population was larger than that of the urban population, in particular for newborn children (age 0) and for the population aged 65+. This has dampened the disparities. That is, if the rural and urban population would have had the same mortality rates, the difference between the rural and the urban population share for the young people (0-14) would have been larger than it actually was in 2010. The same holds for the age group 65+.

Insert Figure 3

3. The rural-urban population model

China's rural and urban population behave quite differently in many demographic aspects, such as fertility, mortality and migration. These demographic heterogeneities have caused different age structures and will play an important role in China's future population growth. In order to adequately project the dynamics of China's population, it is necessary to include these demographic heterogeneities in a rural-urban population model. The structure of our rural-urban population model is similar to the multiregional type of population projection model (Rogers, 1995; Wilson and Rees, 2005). It generates separate future profiles of the rural and the urban population and, by incorporating migration into the model, provides forecasts of the urbanization process in China.

The model is age-sex specific and includes two modules, a rural module and an urban module. Suppose the projection interval is one year and classify the rural and urban population in the following $h+1$ age groups. Age group 0 includes individuals who are aged 0 at the end of the year, age group 1 includes individuals aged 1 at the end of the year, …, age group h includes all individuals aged h or older. In what follows, we will use superscript r for rural and u for urban. Variables related to females will be indicated by italic letters (e.g. x), those for males will also include a tilde (e.g. $\tilde{x}$).

Definitions

n_{it}, $\tilde{n}_{it}$: the number of female and male individuals aged i at the end of year t.

f_{it}: the fertility rate of age group i in year t (assuming that birth takes place at the start of year t+1).[1]

p_t: the probability that a new birth in year t is female.

m_{it}, $\tilde{m}_{it}$: the mortality rate of female and male individuals in age group i in year t, i.e.

[1] Females from age 15 to age 49 are regarded to have reproduction ability. This means $f_i = 0$ for i = 0, …, 14 and $i > 49$.

the probability that an individual aged i-1 at the end of year t-1, dies in year t. m_{0t} gives the probability that a baby that is born at the start of year t dies before the end of the year.

$s_{it} = 1 - m_{it}$, $\tilde{s}_{it} = 1 - \tilde{m}_{it}$: the probability that a female and male individual of age group i survives in year t.

k_{it}, $\tilde{k}_{it}$: the rural-urban population transition rate of female and male individuals of age group i in year t (which is assumed to take place at the start of the year).

For each age-sex group, the rural-urban population transition rate equals the ratio of the net number of rural individuals who become urban individuals[2] and the total number of rural individuals. This transition stems from two causes. First, by migration. Second, rural areas may become urban areas. A rural individual then becomes an urban individual without physically moving but through the expansion of the urban areas. With the economic development of China, more and more rural areas have administratively (and thus statistically) become urban areas.

Rural females

For the rural population, equations are required for age-specific females and males. The female rural babies (who have age 0 at the end of the year t+1) are born at the start of the year t+1. Some of them will become urban (e.g. due to migration) and of those that remain rural some will die.

$$n_{0,t+1}^{r} = s_{0,t+1}^{r}(1 - k_{0,t+1})p_{t+1}^{r}\sum_{i=0}^{h} f_{it}^{r} n_{it}^{r}$$

where $\sum_{i=0}^{h} f_{it}^{r} n_{it}^{r}$ gives the rural babies born at the start of year t+1.

The number of rural individuals of age group i (= 1, …, h-1) at time t+1 equals the

[2] For a specific age group, the number of rural individuals who transit to urban individuals minus the number of urban individuals who transit to rural individuals yields the net number of rural individuals who transit to urban individuals.

survivors of the rural part (i.e. those that have not become urban) of the rural individuals who were in the previous age group *i*-1 at time *t*:

$$n^r_{i,t+1} = s^r_{i,t+1}(1-k_{i,t+1})n^r_{i-1,t}\,,\ \ i = 1,2,\ldots,h-1$$

The individuals of the last age group at the end of year *t*+1 are the survivors of those who remained rural and were *h*-1 years of age in year *t* or were already *h* or older.

$$n^r_{h,t+1} = s^r_{h,t+1}(1-k_{h,t+1})(n^r_{h-1,t} + n^r_{ht})$$

Rural males

The model for the male population is basically the same as for the female population, except the first age group, because reproduction is related to females.

$$\tilde{n}^r_{0,t+1} = \tilde{s}^r_{0,t+1}(1-\tilde{k}_{0,t+1})(1-p^r_{t+1})\sum_{i=0}^{h} f^r_{it} n^r_{it}$$

For the other age groups we have:

$$\tilde{n}^r_{i,t+1} = \tilde{s}^r_{i,t+1}(1-\tilde{k}_{i,t+1})\tilde{n}^r_{i-1,t}\,,\ \ i = 1,2,\ldots,h-1$$

$$\tilde{n}^r_{h,t+1} = \tilde{s}^r_{h,t+1}(1-\tilde{k}_{h,t+1})(\tilde{n}^r_{h-1,t} + \tilde{n}^r_{ht})$$

Urban females

The urban population model is basically the same as the rural population model. The difference is that part of the rural population becomes urban via the rural-urban population transition. The urban population receives these rural individuals at the start of the year, after which they may survive (or die) as urban people. The equations are as follows.

$$n^u_{0,t+1} = s^u_{0,t+1} p^u_{t+1} \sum_{i=0}^{h} f^u_{it} n^u_{it} + s^u_{0,t+1} k_{0,t+1} p^r_{t+1} \sum_{i=0}^{h} f^r_{it} n^r_{it}$$

$$n^u_{i,t+1} = s^u_{i,t+1} n^u_{i-1,t} + s^u_{i,t+1} k_{i,t+1} n^r_{i-1,t}\,, \quad i = 1,2,\ldots,h-1$$

$$n^u_{h,t+1} = s^u_{h,t+1}(n^u_{h-1,t} + n^u_{ht}) + s^u_{h,t+1} k_{h,t+1}(n^r_{h-1,t} + n^r_{ht})$$

Urban males

$$\tilde{n}^u_{0,t+1} = \tilde{s}^u_{0,t+1}(1 - p^u_{t+1}) \sum_{i=0}^{h} f^u_{it} n^u_{it} + \tilde{s}^u_{0,t+1} \tilde{k}_{0,t+1}(1 - p^r_{t+1}) \sum_{i=0}^{h} f^r_{it} n^r_{it}$$

$$\tilde{n}^u_{i,t+1} = \tilde{s}^u_{i,t+1} \tilde{n}^u_{i-1,t} + \tilde{s}^u_{i,t+1} \tilde{k}_{i,t+1} \tilde{n}^r_{i-1,t}\,, \quad i = 1,2,\ldots,h-1$$

$$\tilde{n}^u_{h,t+1} = \tilde{s}^u_{h,t+1}(\tilde{n}^u_{h-1,t} + \tilde{n}^u_{ht}) + \tilde{s}^u_{h,t+1} \tilde{k}_{h,t+1}(\tilde{n}^r_{h-1,t} + \tilde{n}^r_{ht})$$

4. Estimation of the parameters

The rural-urban population model consists of variables (n_{it}, $\tilde{n}_{it}$) and parameters (f_{it}, p_t, s_{it}, $\tilde{s}_{it}$, k_{it}, and $\tilde{k}_{it}$). The working of the model is fairly simple: given the values for the variables n_{it} and $\tilde{n}_{it}$ in *t* = 2010 and given estimates for the parameters, the population in *t* = 2011 can be projected, and so forth. This section describes how the estimates have been obtained and what assumptions have been made.

The probabilities that a new birth is female

For the probability that a new birth is female, we use the proportion of females in the number of newborn babies. In 2010, this proportion was 45.6% for rural newborn babies and 46.3% for urban newborn babies. The proportions were almost the same in 2000, namely 45.6% and 46.5%, respectively. Therefore, for our projections we assume that the probability that a new birth is female is fixed at the level of 2010.

Assumption 1. $p^r_t = p^r_{2010} = 0.456$ and $p^u_t = p^u_{2010} = 0.463$, for *t* = 2011, …, 2030.

The fertility rates

In 1980, the Chinese government launched the so-called one-child policy to control the rapid population expansion. After several adjustments, China's child policy differs nowadays across regions (i.e. rural and urban areas) as well as across nationalities. Urban couples are allowed to have only one child, rural couples, however, are allowed to have a second child if the first child is a girl. Couples from certain minorities in the population (e.g. couples with an Uygur nationality in Xinjiang province) are allowed to have two or more children. An adjustment that was implemented in 2014 is that couples are allowed to have a second child if one (or both) of the parents is an only child.

The strict policy of child control led to rather low and stable fertility rates for quite a long time. According to China's population census data (NBS, 2002; NBS, 2012), the total fertility rate (TFR)[3] of the rural population was 1.43 in 2000 and 1.44 in 2010, and the TFR of the urban population was 0.94 in 2000 and 0.98 in 2010. Both the rural and the urban TFR are significantly lower than the replacement rate of 2.10. Because the child control policy is much tighter for the urban population than for the rural population, the urban TFR obviously is lower than the rural TFR. From an age-specific fertility perspective, an obvious difference between 2000 and 2010 is that childbearing takes place at a later stage in life. Figure 2 shows that the hump in the graph shifted to the right (i.e. towards higher ages), which holds both for rural and for urban females. This means that the fertility rate of younger women is decreasing and that of older women increasing. More and more Chinese females plan to give birth at a later stage in their life. However, this shift in the timing of the childbearing has had very little effect on the TFR. The effect of the increased fertility rate of older women is canceled out by the effect of a decreased fertility rate of younger women. For our projections we make assumptions for the TFR. After the TFR for any year *t* has been set, the age specific fertility rates in *t* are obtained by proportionally adjusting the age specific fertility rates of 2010. In a sensitivity analysis we found that changes in the age

[3] The total fertility rate is the sum of the age specific fertility rates. It measures the average number of children a woman would bear if she survives through the reproductive age span and experiences at each age the age-specific fertility rate of that period.

specific fertility rates only had very minor effects as long as the TFR is the same.

It should be pointed out that the fertility level has been one of the most controversial issues in studies on China's population. Many researchers and also Chinese government officials believe that the TFRs derived from the census data are much lower than the true levels (see Zeng, 1996; Goodkind, 2004; Guo, 2004; Zhang and Zhao, 2006; Morgan et al., 2009; Cai, 2013). The underestimated fertility is mainly due to China's strict child control policy. On the one hand, strictly implementing child control policy is an important task for local governments. On the other hand, families with unauthorized births will be punished. Therefore, both families and local governments have a strong incentive to hide unauthorized births which are thus systematically underreported in census data. Studies have found that a large number of new births and children are missing in the 1990 and 2000 censuses (Zhang and Cui, 2002). Although some steps have been taken to address the underreporting problem in the 2010 census procedure, the TFR derived from the 2010 census data is still believed to be lower than the true level (Cai, 2013). The common opinion is that TFRs from the census data cannot be used directly and need to be adjusted.

For our projections we use two fertility scenarios so as to take possible future adjustments of China's child control policy into account. The baseline scenario assumes a constant fertility rate. We assume that China's child control policy will not change during the projection period (i.e. 2011-2030). The TFRs for both the rural and the urban population are fixed at the levels of 2010, which have been adjusted because of underreporting. The rate of underreporting can be estimated by taking the number of new births from the 2000 population census data, calculate how many would have statistically survived the period 2000-2010[4], and compare that with the number of 10 years old children in the 2010 population census data. We find that the number of 10 years old children in the 2010 population census data is 1.08 times the survivors of the new births in 2000. Considering the possibility that also the number of 10 year old children is underreported in the 2010 population census data, the TFR from the 2000 data seems to be underreported by at least 8%. We use this rate to adjust the TFR in

[4] The survivors during 2000-2010 of the new births in 2000 is calculated as $n_{0,2000} \times s_{1,2001} \times \ldots \times s_{10,2010}$.

2010 from 1.44 to 1.55 for the rural population and from 0.98 to 1.05 for the urban population.[5] The age specific fertility rates are thus magnified by the same proportion.

Assumption 2A. $f_{it}^{r} = \frac{1.55}{1.44} f_{i,2010}^{r}$ and $f_{it}^{u} = \frac{1.05}{0.98} f_{i,2010}^{u}$, for t = 2011, …, 2030.

The second scenario reflects the possibility that the Chinese government may adopt a relatively loose child control policy in the future. Many demographers believe that China's child control policy should gradually be relaxed. An option that has received widespread attention is the so-called "two children with late childbearing soft-landing" proposal by Zeng (2006, 2007). It suggests a smooth transition period of about seven years, after which all couples in China are allowed to have a second child. Zeng (2006) estimates the rural TFR to be 2.27 and the urban TFR to be 1.80, after the transition has been finished. Note that this is in line with the most recent adjustment by the Chinese government of the child control policy. Starting in 2014, couples are allowed to have a second child if at least one of the parents is an "only child".

For our projections, we adopt Zeng's proposal and assume for the years 2011-2013 that the rural and urban TFRs are fixed at the adjusted level of 2010 (i.e. 1.55 for the rural TFR and 1.05 for the urban TFR). The implementation of the two children policy starts in 2014 and the TFRs increase linearly in seven years to their 2020 levels. These are 2.27 for the rural population and 1.80 for the urban population. For the distribution of the increases in TFR over the age-specific fertility rates, it should be noted that the increased fertility is only due to an increase in the number of second children. The implicit assumption here is that family planning and thus the first child fertility rate is not affected by the implementation of the two children policy. For the distribution we use proportions based on the age-specific second child fertility rate in 2010.[6] The proportion for age group i (denoted by w_i^r for rural rates and w_i^u for urban rates) is calculated by dividing the second child fertility rate of age group i by the

[5] According to Cai (2013), the estimate of China's aggregate TFR in 2010 is around 1.5.

[6] For a specific age group i, the second child fertility rate is defined as the ratio between the number of females in age group i that give birth to a second child and the total number of females in age group i.

sum of the second child fertility rates across all age groups. The information on age-specific second child fertility rates can be obtained from the population census data. After 2020, the rural and urban TFRs are fixed at the level of 2.27 and 1.80 until 2030.

Assumption 2B.

$$f_{it}^{r}=\begin{cases}\frac{1.55}{1.44}f_{i,2010}^{r} & t=2011,\ldots,2013\\ \frac{1.55}{1.44}f_{i,2010}^{r}+\frac{2.27-1.55}{7}(t-2013)w_i^{r} & t=2011,\ldots,2013\\ \frac{1.55}{1.44}f_{i,2010}^{r}+(2.27-1.55)w_i^{r} & t=2011,\ldots,2013\end{cases}$$

$$f_{it}^{u}=\begin{cases}\frac{1.05}{0.98}f_{i,2010}^{u} & t=2011,\ldots,2013\\ \frac{1.05}{0.98}f_{i,2010}^{u}+\frac{1.80-1.05}{7}(t-2013)w_i^{u} & t=2011,\ldots,2013\\ \frac{1.05}{0.98}f_{i,2010}^{u}+(1.80-1.05)w_i^{u} & t=2011,\ldots,2013\end{cases}$$

Note that $\mathrm{TFR}_t^r=\sum_i f_{it}^r=2.27$ for $t=2020,\ldots,2030$, because $\sum_i f_{i,2010}^r=\mathrm{TFR}_{2010}^r=1.44$ and $\sum_i w_i^r=1$. In the same way, $\mathrm{TFR}_t^u=1.80$ for $t=2020,\ldots,2030$.

The mortality rates

Improvements in the living conditions and progress of medical technology have increased the life expectancy at birth of the Chinese population considerably, from 71.4 years in 2000 to 74.8 in 2010. Figure 3 showed that the decreases in the mortality rates between 2000 and 2010 were significant, in particular for newborn children and for the elderly (i.e. 65+). For instance, the 2010 census data shows that the infant mortality rates are 4.7‰ for the rural population and 2.5‰ for the urban population.[7] The substantial reduction of mortality rate suggested by the 2000 and 2010 census data confirms China's continued improvement in health, which is not unexpected for a country with rapid and persistent economic growth. Given that the current life

[7] It should be pointed out that China's mortality rates in the census data is also likely to be underestimated, especially for babies and young children (Cai, 2013). The reported infant mortality rates are very low. If the census data were accurate, China would be one of the countries with the lowest infant mortality rates in the world. Using these mortality rates for population projections implies that the survivals of babies and young children will—to some extent—be overestimated.

expectancy at birth in developed countries is around 80 years, China's mortality rate is expected to continue to decrease in the following two decades.

To forecast China's future age-specific mortality rates we use the Lee-Carter model (Lee and Carter, 1992). It is a leading statistical model for mid-term (around 50 years) forecasts of mortality rates and has been successfully applied to almost all countries that have reliable data and are in normal socioeconomic conditions (Booth, 2006; Li et al., 2013). Its main underlying assumption is that the future annual rate of decline of the age-specific mortality rates equals the average rate of decline in a past period for which data are available.

The Lee-Carter model has two characteristics that make it very appropriate for our case. First, only two years of historical data are sufficient to apply the model, which is attractive for countries with limited data availability, such as China. Second, the forecasts for age-specific mortality rates obtained from the Lee-Carter model always satisfy the desirable property that they are positive.

However, the Lee-Carter model also suffers from some limitations. It assumes that the historical average rate of decline in the age-specific mortality rates will prolong to the future. As Girosi and King (2008) point out, it may be reasonable to assume that the historical pattern continues in the short run. Over a longer time period, however, the model forecasts may diverge from empirical patterns. For instance, when the forecast period is very long, reversions in the rank order of the age-specific mortality rates may occur when the Lee-Carter model is used.[8] In this respect, Li et al. (2013) conclude that reversion of rank orders makes little or no difference for projections in most countries, except in countries with life expectancies above 80. As mentioned earlier in this section, the life expectancy in China is still far lower, so we believe it is plausible to assume that China's historical pattern of changes in age-specific mortality rates during 2000-2010 will continue also in the following two decades. In addition, the forecasts (which are shown later, in Figure 4) based on this assumption do not show serious problems in terms of reverted rank orders of the age-specific mortality rates. We therefore feel it is

[8] Reversion of the rank order means that the mortality rate of group *i* is larger than the mortality rate of age group *j* in time period *t*, whereas it is forecasted to be smaller in period *k*.

reasonable to forecast these mortality rates for China by using the Lee-Carter model.

The model assumes an exponential change in the age-specific mortality rates, which is specified as

$$\ln m_{it} = \alpha_i + \beta_i v_t + \varepsilon_{it} \quad (i = 0, 1, \ldots, h; t = 1, 2, \ldots, T) \tag{1}$$

α_i, β_i and v_t are parameters to be estimated and ε_{it} are random disturbances with mean 0 and variance σ^2. v_t represents the combined effects of exogenous factors (such as medical technology and economic growth) that have a systematic impact on the mortality rates of all age groups. Although v_t has an impact on the mortality rates of all age groups, the magnitude of the impact varies across age groups. Some age groups benefit more than other age groups and this difference is captured by β_i, which represents the effect of v_t on age group *i*. Equation (1) is estimated by using the singular value decomposition (SVD) approach (see the Appendix). This yields $\hat{\alpha}_i = \overline{\ln m_i} = \sum_{t=1}^{T} \ln m_{it} / T$, the average of $\ln m_{it}$ over time, and estimates $\hat{\beta}_i$ (i = 1, …, h) and $\hat{v}_t$ (t = 1, …, T).

In the forecasting procedure, we want to calculate $\hat{m}_{i,T+\tau}$. As Equation (1) indicates, the forecast depends on (*i*) the estimated parameters $\hat{\alpha}_i$ and $\hat{\beta}_i$, both of which are fixed over time, and (*ii*) the parameter $\hat{v}_{T+\tau}$ that is time varying. The forecast yields $\ln\hat{m}_{i,T+\tau} = \hat{\alpha}_i + \hat{\beta}_i \hat{v}_{T+\tau}$. Because the parameters $\hat{v}_{T+\tau}$ are time varying, they are obtained by specifying the following random walk with drift model.

$$\hat{v}_t = \theta + \hat{v}_{t-1} + \mu_t, \;\; \mu_t \sim N(0, \sigma_\mu^2)$$

This specification is used almost exclusively in practice (Girosi and King, 2008). The maximum likelihood estimate of θ is given by $\hat{\theta} = (\hat{v}_T - \hat{v}_1)/(T-1)$. Note that the estimate depends only on the values in the initial year and the final year. This implies that data for two years are sufficient to forecast age-specific mortality rates by means of the Lee-Carter model. The forecast for the parameters v now becomes $\hat{v}_{T+\tau} = \hat{v}_T + \hat{\theta}\tau$, for τ = 1, 2, …. Collecting all pieces of information and noting that in our case we only have census data for two years (2000 and 2010) yields the following.

Assumption 3. The forecast for the mortality rate is given by

$$\hat{m}_{i,2010+\tau} = \mathrm{e}^{\hat{\alpha}_i + \hat{\beta}_i \hat{v}_{2010+\tau}} = \mathrm{e}^{\overline{\ln m_i} + \hat{\beta}_i(\hat{v}_{2010} + \frac{\hat{v}_{2010} - \hat{v}_{2000}}{10}\tau)}$$

$$= \mathrm{e}^{\frac{\ln m_{i,2000} + \ln m_{i,2010}}{2} + \hat{\beta}_i(\hat{v}_{2010} + \frac{\hat{v}_{2010} - \hat{v}_{2000}}{10}\tau)}$$

for τ = 1, …, 20, where $\hat{\beta}_i$, $\hat{v}_{2000}$, and $\hat{v}_{2010}$ are parameters estimated with the singular value decomposition (see the Appendix).

We decided to estimate the Lee-Carter parameters based on Chinese census data for 2000 and 2010 only. In the middle of two census years (e.g. in 2005) a 1% sample survey is conducted and a 1‰ sample survey is conducted in other years. In these limited sample surveys, the mortality rates of the old population show large volatilities, because the number of surveyed old people is relatively small. Hence, there is no time series for China's age-specific mortality rates with a sufficient survey coverage. The 2000 and 2010 population census data are representative and obtained in a consistent way.

The annual forecasts up to 2030 for the age-specific mortality rates with the Lee-Carter model are given in Figure 4. Note that $\overline{\ln m_{it}} = (\ln m_{i,2000} + \ln m_{i,2010})/2$ in our case.

Insert Figure 4

The rural-urban transition rates

Data on age-specific transition rates of rural population becoming urban are not available and need to be estimated. As mentioned before, this transition is caused by two factors, migration and urban expansion. The age-specific impacts of these two factors are different. Whereas the migrants are mainly represented in the younger age groups, the transition due to urban expansion plays a role in a much wider range of ages.

We will estimate the age-specific rural-urban population transition in three steps. First, we estimate the aggregate rural-urban population transition. Second, we split this into the part that is due to urban expansion and the part due to migration. Third, we estimate the age structures for the two types of rural-urban population transition. The estimated aggregate rural-urban population transition due to urban expansion is then distributed over the age groups according to the corresponding estimated age structure, and the same is done for the transition due to migration, after which the rates are determined. Summarized, this yields the following.

Assumption 4. $k_{it} = k_i$ and $\tilde{k}_{it} = \tilde{k}_i$ for $t = 2011, \ldots, 2030$,

$$k_i = \frac{q_i^e e + q_i^g g}{n_i^r} \quad \text{and} \quad \tilde{k}_i = \frac{\tilde{q}_i^e e + \tilde{q}_i^g g}{\tilde{n}_i^r}$$

Here, k_i and $\tilde{k}_i$ are the female and the male rural-urban population transition rates of age group i; n_i^r and $\tilde{n}_i^r$ are the numbers of female and male rural persons in age group i; e and g are the aggregate rural-urban population transition due to urban expansion and due to migration; q_i^e and $\tilde{q}_i^e$ are the females and males in age group i as a share of the aggregate rural-urban population transition due to urban expansion; and q_i^g and $\tilde{q}_i^g$ are the females and males in age group i as a share of the aggregate rural-urban population transition due to migration. The details of the estimation procedure are discussed in what follows.

In the first step, the aggregate rural-urban transition is estimated. This is done by employing the decomposition approach of Zhang and Song (2003). The idea is that the actual growth of the urban population (for which data are available) is caused by natural growth and by net rural-urban population transition. The natural urban growth can be estimated using the fertility and mortality rates of the urban population. The aggregate rural-urban population transition can thus be estimated by deducting the natural urban population growth from the actual urban population growth.[9] NBS, only includes persons with permanent urban residence (those who have lived in urban areas for six months or more) in its urban population statistics.[10] Therefore, the temporary rural migrants to urban areas (who have migrated to urban areas for less than six months) are not considered as rural-urban migrants in the present study.

The results are given in Table 1 and show, for example, that the urban population increased from 645.12 million persons in 2009 to 669.78 million persons in 2010. The actual growth in urban population was thus 24.66 million persons. The natural growth in the urban population, as calculated with the urban fertility rates and mortality rates in 2010, was 3.27 million persons. The aggregate rural-urban population transition is therefore estimated as 24.66 – 3.27 = 21.39 million persons.

Insert Table 1

The second step splits the aggregate rural-urban population transition into the part due to urban expansion and the part due to migration. To this end, we estimate the part that is due to urban expansion. Because of data availability, this part is easier to estimate than the part due to migration. The transition due to migration is then obtained as a residual, by deducting the estimated transition due to expansion from the estimated aggregate rural-urban population transition.

The statistical standard that determines whether an area is rural or urban has changed several times in China (Zhou and Ma, 2003), the most recent of which occurred in 2006. According to this standard, the division takes place on the basis of residents' committees and villagers' committees. These are the smallest administrative

[9] The rural-urban population transition can also be estimated from the rural population growth. We find that the two results are almost the same.

[10] Persons with permanent residence in urban areas do not necessarily have local household registration (*hukou*). Instead, they may be issued residence permits.

units and are the basic autonomous organizations for urban and rural areas. That is, a residents' committee consists of and administers all urban households in its administrative area, and a villagers' committee consists of and administers all rural households in its administrative area. Due to urban expansion, many villagers' committees are administratively replaced by residents' committees, for example, because most of the workers in a villagers' committee are employed in non-agricultural industries. The rural-urban population transition from urban expansion is thus basically captured by the population in the newly created residents' committees, which can be calculated on the basis of information in the *China Civil Affair's Statistical Yearbook* (MCA, 2011).[11] Once the rural-urban population transition from urban expansion is calculated, the migration can be estimated as a residual. Continuing the example above, the aggregate rural-urban population transition was 21.39 million persons during 2009-2010, of which 13.71 million persons transited due to urban expansion. The estimated (net) migration therefore amounts to 21.39 – 13.71 = 7.68 million persons.

Table 1 gives the results for the period 2006-2010, i.e. the years after the last change in the statistical standard to determine the rural and urban population. The table shows that the growth in urban population is mainly caused by rural-urban population transition and that both migration and urban expansion are important factors in this. On average, urban expansion and migration effects have an equal size but the results fluctuate over the years (and in no particular direction). To eliminate the effect of fluctuations, the average values over 2006-2010 in Table 1 are used in Assumption 4. That is, e = 9.18 million persons and g = 9.30 million persons.

For the age-specific numbers of the rural population we use the 2010 population census data, which reflects the most recent state of the Chinese population. That is, $n_i^r = n_{i,2010}^r$ and $\tilde{n}_i^r = \tilde{n}_{i,2010}^r$. The third step estimates the age structures. The sex-specific age structure of the rural population in 2010 is used as an approximation for the age structure of rural-urban population transition due to urban expansion. Rural

[11] A similar approach was used by Hu (2003) to estimate the rural-urban population transition caused by urban expansion. In that study, data (from *China Civil Affair's Statistical Yearbook*) on newly created towns were used. Our study uses data on newly created residents' committees because of a more recent statistical standard to determine rural and urban areas.

population shares are used because rural areas become urban. We have $q_i^e = n_{i,2010}^r / \sum_{i=0}^{h} (n_{i,2010}^r + \tilde{n}_{i,2010}^r)$ and $\tilde{q}_i^e = \tilde{n}_{i,2010}^r / \sum_{i=0}^{h} (n_{i,2010}^r + \tilde{n}_{i,2010}^r)$.

There are no detailed data on the age structure of China's rural-urban migrants. China's population census data only report the age structure of total migrants, which includes urban-urban migrants and rural-rural migrants, next to rural-urban migrants. The age structure of total migrants (as reported in the 2010 population census) is thus used (after correction) as an approximation for the age structure of rural-urban migrants (i.e. q_i^g and $\tilde{q}_i^g$). This treatment is also used by other researchers when studying rural-urban migration issues in China (see e.g. Zeng and Vaupel, 1989). We exclude migrants for marriage from the total migrants, because it is difficult for rural people to migrate to an urban area just for marriage (Sun and Fan, 2011). The share of young people will be smaller after correction than before, because the excluded migrants for marriage are generally young.

The estimated age-specific rural-urban population transition rates are shown in Figure 5. They show a hump-shaped pattern, indicating a larger mobility of the young labor force (aged 15-49). Furthermore, the male population appears to be more mobile than the female population.

Insert Figure 5

For the pace of the urbanization process, Assumption 4 is relevant. It is assumed that the age-specific rural-urban population transition rates are kept fixed in the period 2011-2030. This assumption is in line with the recent past and the most recent plans. Historical data show that the speed of urbanization process has been steady in recent decades. The increase in the urbanization rate was around 1.4 percentage point each year during 2000-2010. The twelfth five-year plan (2011-2015) sets a target of a further 4 percentage points increase. This is the same as the target set in the eleventh five-year plan (2006-2010), which was actually exceeded. We therefore expect that the current fast urbanization process will continue in the following years.

5. The projections

Taking the 2010 population census data as a starting-point, we have projected China's population from 2010 to 2030 with the rural-urban population model, using two fertility scenarios. The population is divided into 91 age groups: 0, 1, 2 … and 90+. For convenience, the detailed results for all 91 groups have been aggregated to 19 groups when reporting the projection results in Table 2 (for the constant fertility rate scenario, i.e. Assumption 2A) and in Table 3 (for the two children policy scenario, i.e. Assumption 2B).

Insert Tables 2 and 3

Figure 6 graphs the projections for the total population under the two scenarios. It shows that China's population will first grow and will then gradually turn to decrease under the constant fertility rate scenario. The peak will be reached around 2027, with a population of 1403.5 million, and the total population in 2030 will be 1402.1 million. Under the two children policy scenario, China's population will continue to grow during the entire 2011-2030 period. The total population will reach 1458.4 million in 2030, which is 4% more than the projection under the constant fertility rate scenario.

Insert Figure 6

Figure 7 gives the projections for the total labor force and shows a decreasing pattern in the following two decades. In particular from 2025 onwards, China's labor force will experience a steep decline. This is because the Chinese baby boom generation born in the 1960s will start retiring in 2025. The total labor force will decrease between 2010 and 2030 with approximately 6% (from 998.8 million persons to 938.2 million persons under the constant fertility rate scenario and to 939.2 million persons under the two children policy scenario). Observe that the projections for the total labor force are exactly the same for both fertility scenarios in the years 2011-2028. The reason is that the labor force in this study is defined as the population aged 15-64 and that the total fertility rate in the two children policy scenario starts to increase in 2014. The policy adjustment starts to affect the labor force only when the first babies under the two children policy enter the labor at the age of 15, which is in 2029. To get some insight in the different effects of both scenarios on the labor force, we have extended our projections to 2050. Figure 7 shows that the labor force will continue to decrease, despite the effects of rising total fertility rate on the labor force from 2029 onwards. The two children policy cannot reverse the decreasing trend in China's labor force in the next 40 years, although it does slow down the decline. As Figure 7 shows, the gap between the results for the two fertility scenarios is widening from 2029 onwards.

Insert Figure 7

Table 2 gives the projections for each age group, assuming fertility rates that are fixed at the level of 2010. In the following two decades China will experience a rather fast ageing process. The share of the age group 65+ in China's population will increase from 8.9% in 2010 to 14.3% in 2020 and 21.5% in 2030. In 2010, there are almost twice as many young people in China (aged 0-14) than there are old people (aged 65+). In 2020, the sizes will be more or less the same. In 2030, however, there will be almost twice as many old people as there will be young people.

For the rural population, the share of the population aged 65+ increases from 10.1% in 2010 to 16.2% in 2020 and to 23.2% in 2030. The gap with the urban share of old people increases from 2.3 %-points in 2010 to 3.1 %-points in 2020, after which it shrinks somewhat to 2.5 %-points in 2030. This indicates that the ageing problem in China continues to be more serious in rural areas than in urban areas in the following decades. This is due to the fact that many young rural people will move to urban areas during the process of fast urbanization and industrialization. Meanwhile, the share of the labor force (aged 15-64) in China's total population will decrease from 74.5% in 2010 to 70.8% in 2020 and 66.9% in 2030.

If the current child policy is gradually loosened to a "two children" policy for all Chinese, Table 3 shows that the share of population aged 65+ reaches 20.6% in 2030. This is only 0.9 %-points lower than the projection for the constant fertility rate scenario (based on the situation in 2010, which was a "one-child" policy in urban areas and a "two children" policy in rural areas). Both fertility scenarios yield projections for the age group 65+ that are very close to each other also for the rural and urban population separately. This finding implies that at least in the following two decades the "two children" policy as recommended by several researchers cannot alleviate China's upcoming ageing problem very much.

Tables 2 and 3 show that also the projected urbanization rates in the two fertility scenarios are very close. Under the "two children" policy, the increase in the total fertility rates for the rural and urban population are basically the same, which leads to very similar effects on the growth of the rural and urban population. Because the rural-urban population transition rate is small for the infant group (see Figure 5) and because infants have a small share in the total rural population, transition only leads to a very minor increase in the urban population. The fertility rate changes in our scenarios therefore do not affect China's urbanization process. If the estimated rural-urban transition rates for 2010 are fixed in the following two decades, the projections show that China's fast urbanization process will continue. That is, China's urbanization rate will reach 62% in 2020 and 71% in 2030. For developed countries, the current urbanization rate is around 80%.[12] When compared with developed countries, China's urbanization level will still lag behind in the following two decades, even if it continues its current fast urbanization process.

6. A comparison of projections

[12] In 2011, the urbanization rates were 82% in the US, 91% in Japan, 74% in Germany, 86% in France, and 80% in Great Britain.

The United Nations (2013) recently revised its projections for the Chinese population on the basis of China's 2010 population census data. According to UN's result for the constant fertility rate scenario, the share of population aged 65+ will reach 11.7% in 2020 and 16.4% in 2030.[13] This is considerably lower than our projections, for which there are three reasons. First, although the UN revised its projection on the basis of China's 2010 population census data, we find that the 2010 population structure they report is quite different from the structure in the original data. According to UN (2013), the population in the age groups 0-14 is 18.1% of the total population in 2010, that in age groups 15-64 is 73.5%, and the share of the age group 65+ is 8.4%. However, the corresponding figures in the original 2010 population census are 16.6%, 74.5% and 8.9%, respectively. The share of the young population is 1.5% larger in the UN data than in the census data that we have used. The shares for the labor force and the old people are smaller. This difference in starting point will obviously affect the projections in later years. Second, the UN projection for China's future mortality pattern is obtained by using data from developed countries. Our projections use the future age-specific mortality rates as estimated by the Lee-Carter model. These estimates are based on China's development pattern of mortality rates between 2000 and 2010, using Chinese population census data. We believe that modeling China's mortality rates by using the country's own data is more realistic than using the data of developed countries.

Third, our model distinguishes between the rural and the urban population, and takes urbanization into account. As mentioned before, their demographic features of the two population groups are very different in terms of fertility, mortality and migration. The fertility rate and the mortality rate of the urban population are significantly smaller than those of the rural population. At the same time, a fast urbanization process will take place in the following two decades. If urbanization is taken into account the share of the urban (rural) population is larger (smaller) than in the case where urbanization is

[13] In its projection result with their medium fertility rate scenario, the share of population aged 65+ in 2020 and 2030 are 11.7% and 16.2%, very close to the projection result with constant fertility rate scenario. For the high fertility rate scenario, the share of population aged 65+ in 2020 and 2030 are 11.4% and 15.4%, 0.3 and 0.8 percentage points less than the constant fertility rate scenario. For the low fertility rate scenario, the share of population aged 65+ in 2020 and 2030 are 12.0% and 17.1%, 0.3 and 0.7 percentage points higher than the constant fertility rate scenario.

neglected. The average fertility and mortality rate of China's population as a whole (using the share of urban and rural population as weights) are thus smaller when urbanization is accounted for than in the case where urbanization is neglected. Smaller fertility and mortality rates (when urbanization is implemented in the model) yield a larger share of old people in the projections. That is, not taking urbanization into account will lead to a share of people aged 65+ that is smaller than when urbanization is accounted for in the model.

To quantify the effect of separating the rural and urban population, we have also made age-specific population projections with a version of the model where the rural/urban distinction is not built in. In the constant fertility rate scenario, the share of population aged 65+ in 2030 will be 21.0%. This is 0.5 %-points less than the result with our full rural-urban population model (see Table 2). The difference is comparable to the effect caused by the two children policy (0.9 %-points less than in the baseline scenario with constant fertility rate). Therefore, the rural and urban population need to be modeled separately when projecting the Chinese population. The effect of modeling them separately is of the same order as the effect one would like to investigate (i.e. the change in child control policy).

Another recent projection of China's population was presented by Mai et al. (2013). Their projection is for the period up to 2050 and they use 2000 population census data (because 2010 population census data were not published when they made their projections). They run several scenarios and the lowest total fertility rate they assume is 1.50, which is much larger than the 1.18 that the NBS published for 2010. Their model does not distinguish between the rural and urban population. With a total fertility rate of 1.50 and a medium pace of mortality improvement, their projections for the share of population aged 65+ are around 12% in 2020 and 17% in 2030, clearly lower than our projections. The different assumptions for the total fertility rate, the different approaches for modeling future mortality rates, the different base year data, as well as neglecting the rural-urban demographic heterogeneity will all have contributed to the differences in the projections.

Furthermore, forecasts for the urbanization rate of China in 2020 and 2030 have been published. For instance, the forecasts by the United Nations (2012) are 61.0% in 2020 and 68.7% in 2030, which is quite close to our own forecasts. This also holds for the forecasts by Zheng (2011), i.e. 60% in 2020 and 70% in 2030, which are obtained from a direct extrapolation of time series of past urbanization rates.

Summarizing, forecasts for the age-specific population shares (and thus ageing) appear to be sensitive to the underlying assumptions for fertility and mortality rates and to the inclusion of rural-urban demographic heterogeneities. Forecasts for the urbanization appear to be more robust.

7. Conclusions

China is expected to experience a fast ageing process in the following two decades, partly due to the ageing of the large baby boom generation born in 1960s. In order to make projections, we developed a rural-urban population model. The model takes into account (i) that fertility and mortality rates differ between rural and urban population, and (ii) that China's urbanization process reflects changes in the relative sizes of these two subpopulations.

Our projections have been conducted under two fertility scenarios. First, the constant fertility rate scenario assumes that the child control policy will not change. The total fertility rates and the age-specific fertility rates are fixed during the projection period at the levels of 2010. Second, the "two children" policy scenario reflects the possibility that the Chinese government may relax its current child control policy and will allow all couples to have a second child. The total fertility rates are fixed at the 2010 levels during 2011-2013, after which they increase linearly during 2014-2020 to 2.27 for the urban population and 1.80 for the urban population, which are the levels assumed for the period 2021-2030.

The population projections showed that in the fixed fertility scenario the peak of China's total population will occur in 2027 with 1404 million people (and 1402 in 2030). In the other scenario, the population will continue to grow which will yield an additional 56 million people in 2030. Further findings that held for both scenarios were the following. (1) China will experience a fast ageing process in the following two decades. The population aged 65+ as a share of China's total population will be above 20% in 2030. (2) The ageing problem will be more serious in the rural areas than in the urban areas due to rural-urban migration (which is an important factor in the urbanization process), mainly by young people. In 2030, the share of population aged 65+ will be more than 2 %-points larger for the rural population than for the urban population. (3) China will experience a fast urbanization process, also in the following two decades. The urbanization rate will increase from 50% in 2010 to 71% in 2030.

Our projections also showed that the size of the Chinese labor force will continue to decrease in the following two decades. The total labor force will decrease by 6% between 2010 and 2030. Because it takes at least 15 years before a new birth enters the labor force, the steady decline of the labor force cannot be reversed in our projection period (2011-2030) by loosening the child control policy from 2014 onwards. The decreasing size of the labor force may negatively affect China's long-run economic growth. It certainly indicates the importance of raising the labor productivity for China's future economic development.

Finally, we would like to point out that also our projections suffer from limitations. One of them is the exogeneity of the total fertility rates in our model, for which two scenarios were used. Future work might be devoted to endogenizing the total fertility rates. Economic growth, for example, has been proved to be an important determinant of age-specific fertility rates. Another limitation is that our forecasts of the mortality rates also do not take medical, social and economic growth into account. Endogenizing the fertility and mortality rates in our model would be an interesting future step. A similar line of reasoning applies to our treatment of rural-urban migration rates. We consider these to be constant over time for each age. It is well-known, however, that rural-urban migration rates are dependent on relative income levels in rural and urban areas (see, for example, Zhu, 2002; Zhang, 2012). The differences between rural and urban income levels can vary over time, for example as a consequence of positive agglomeration effects and negative congestion effects in urban economic activity. We do not have reliable indicators for future relative income levels, but our analysis could be enriched by endogenizing rural-urban migration under multiple scenarios with differential rates of economic growth in rural and urban areas.

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Appendix. Estimation of the Lee-Carter model

First, we would like to point out that the estimation result for Equation (1) is not unique. For instance, if (β_i, v_t) is a solution, then for any non-zero constant c, $(c\beta_i, v_t / c)$ is also a solution. The model in (1) is underdetermined and two constraints are required for unique identification of the parameters (Girosi and King, 2008).[14]

$$\sum_{i=0}^{h} \hat{\beta}_i^2 = 1 \text{ and } \sum_{t=1}^{T} \hat{v}_t = 0$$

Later, we will see that these two constraints are satisfied automatically in the estimation procedure. The constraint $\sum_{t=1}^{T} \hat{v}_t = 0$ immediately implies that $\hat{\alpha}_i$ equals $\overline{\ln m_i} = \sum_{t=1}^{T} \ln m_{it} / T$, the average of $\ln m_{it}$ over time for age group i.

Next, we estimate β_i and v_t. Let $\tilde{m}_{it} = \ln m_{it} - \overline{\ln m_i}$ (centered log mortality rate), then (1) can be rewritten as

$$\tilde{m}_{it} = \beta_i v_t + \varepsilon_{it} \qquad \text{(A 1)}$$

In matrix form:

$$\tilde{\mathbf{M}} = \boldsymbol{\beta}\mathbf{v}' + \mathbf{E} \qquad \text{(A 2)}$$

with $\tilde{\mathbf{M}} = (\tilde{m}_{it})_{h \times T}, \boldsymbol{\beta} = (\beta_i)_{h \times 1}, \mathbf{v} = (v_t)_{T \times 1}, \mathbf{E} = (\varepsilon_{it})_{h \times T}$.

The age-specific mortality rates (or actually their transformations $\tilde{m}_{it}$) in each time period (i.e. 2000 and 2010) are the observations used to estimate the parameters. As Lee and Carter (1992, p. 661) write: "The model cannot be fit by ordinary regression methods, because there are no given regressors; on the right side of the equation we have only parameters to be estimated and the unknown indexes v_t." Estimating the

[14] Lee and Carter (1992) use $\sum_{i=0}^{h} \hat{\beta}_i = 1$ as the constraint for $\hat{\beta}_i$, while Girosi and King (2008) use $\sum_{i=0}^{h} \hat{\beta}_i^2 = 1$ (i.e. $\hat{\boldsymbol{\beta}}$ is a vector with Euclidean length 1). We adopt the latter constraint because it simplifies some of the calculations in the singular value decomposition, whilst it has no bearing on the empirical applications.

parameters $\boldsymbol{\beta}$ and $\mathbf{v}$ in Equation (A 2) is to find two vectors $\hat{\boldsymbol{\beta}}$ and $\hat{\mathbf{v}}$, for which $\hat{\boldsymbol{\beta}}\hat{\mathbf{v}}'$ approximates the matrix $\tilde{\mathbf{M}}$ best. The estimates for the parameters can be obtained by applying the singular values decomposition (SVD) on matrix $\tilde{\mathbf{M}}$ (Lee and Carter, 1992; Girosi and King, 2008). $\tilde{\mathbf{M}}$ can be decomposed as

$$\tilde{\mathbf{M}}_{h\times T} = \mathbf{USP'} \qquad \text{(A 3)}$$

where $\mathbf{S}$ is a $h\times h$ diagonal matrix with nonnegative numbers $s_1, s_2, ..., s_h$ (which are ordered in a descending way and which are called singular values of $\tilde{\mathbf{M}}$) on the main diagonal. $\mathbf{U}$ is a $h\times h$ orthonormal matrix ($\mathbf{U}'\mathbf{U} = \mathbf{I}$) and its columns $\mathbf{u}_1, \mathbf{u}_2, ..., \mathbf{u}_N$ are called left-singular vectors of $\tilde{\mathbf{M}}$. $\mathbf{P}$ is a $T\times h$ matrix whose columns are mutually orthonormal if $T \geq h$ or whose first T columns are mutually orthonormal and the remaining columns are zeroes if $T < h$. The columns $\mathbf{p}_1, \mathbf{p}_2, ..., \mathbf{p}_h$ are called right-singular vectors of $\tilde{\mathbf{M}}$. If the rank of $\tilde{\mathbf{M}}$ is equal to *r*, then $\tilde{\mathbf{M}}$ has *r* positive singular values. Equation (A 3) can then be further rewritten as

$$\tilde{\mathbf{M}} = s_1\mathbf{u}_1\mathbf{p}_1' + s_2\mathbf{u}_2\mathbf{p}_2' + ... + s_r\mathbf{u}_r\mathbf{p}_r'$$

The matrix $s_1\mathbf{u}_1\mathbf{p}_1'$ corresponding to the largest singular value gives the best approximation to $\tilde{\mathbf{M}}$ in the least-squares sense (Girosi and King, 2008). Therefore, the estimate of $\boldsymbol{\beta}$ is obtained as $\hat{\boldsymbol{\beta}} = \mathbf{u}_1$ (i.e. the first column of matrix $\mathbf{U}$) and the estimate of $\mathbf{v}'$ is obtained as $\hat{\mathbf{v}}' = s_1\mathbf{p}_1'$ (the product of the first diagonal element of $\mathbf{S}$ and the first row vector of $\mathbf{P}'$). Alternatively, the estimate of $\mathbf{v}'$ can also be obtained as $\hat{\mathbf{v}}' = \hat{\boldsymbol{\beta}}'\tilde{\mathbf{M}}$ (because $\mathbf{U}'\tilde{\mathbf{M}} = \mathbf{SP}'$).

Since $\hat{\boldsymbol{\beta}}$ is the first column of the orthonormal matrix $\mathbf{U}$, its length is equal to 1. The constraint $\sum_{i=0}^{h} \hat{\beta}_i^2 = 1$is thus satisfied. In addition, because $\tilde{m}_{it} = \ln m_{it} - \overline{\ln m_\iota}$ the row sums (i.e. summing over *t*) of $\tilde{\mathbf{M}}$ is equal to 0. Therefore, we have $\hat{\mathbf{v}}'\mathbf{i} = \hat{\boldsymbol{\beta}}'\tilde{\mathbf{M}}\mathbf{i} = 0$ (where $\mathbf{i}$ is a column vector with ones), i.e. the constraint $\sum_{t=1}^{T} \hat{v}_t = 0$ is satisfied.

Table 1 The decomposition of urban population growth (unit: million persons)

Year	Urban population	Growth in persons	Natural growth in persons	Rural-Urban population transition	
				Urban expansion in persons	Net immigration in persons
2006	582.88				
2007	606.33	23.45	3.12	7.46	12.87
2008	624.03	17.70	3.40	8.15	6.16
2009	645.12	21.09	3.23	7.39	10.47
2010	669.78	24.66	3.27	13.71	7.68
Average		21.73	3.25	9.18	9.30

Table 2 The Chinese population projection result under the constant fertility rate scenario (%)

Age group	2010			2020 (Projected)			2030 (Projected)		
	Rural	Urban	Aggregate	Rural	Urban	Aggregate	Rural	Urban	Aggregate
0-4	6.7	4.6	5.7	5.2	4.2	4.6	4.3	2.9	3.3
5-9	6.1	4.5	5.3	5.8	4.4	4.9	4.7	3.5	3.8
10-14	6.4	4.9	5.6	6.9	4.5	5.4	5.5	4.2	4.5
15-19	7.0	8.0	7.5	6.0	4.6	5.1	5.9	4.5	4.9
20-24	8.5	10.7	9.6	5.8	5.1	5.4	6.5	4.9	5.3
25-29	6.5	8.7	7.6	6.0	7.8	7.1	5.2	5.0	5.1
30-34	6.2	8.4	7.3	7.4	10.2	9.1	5.1	5.3	5.3
35-39	8.0	9.7	8.8	5.6	8.3	7.3	5.4	7.7	7.0
40-44	9.2	9.5	9.3	5.6	7.8	7.0	6.8	9.8	8.9
45-49	7.8	8.0	7.9	7.6	8.7	8.3	5.4	7.9	7.2
50-54	6.0	5.8	5.9	8.8	8.8	8.8	5.6	7.3	6.8
55-59	6.6	5.6	6.1	7.3	7.4	7.4	7.6	8.1	8.0
60-64	4.9	3.9	4.4	5.9	5.1	5.4	8.9	8.2	8.4
65-69	3.5	2.7	3.1	6.2	4.9	5.4	7.0	6.9	6.9
70-74	2.7	2.2	2.5	4.3	3.4	3.7	5.6	4.5	4.9
75-79	2.0	1.6	1.8	2.7	2.1	2.3	5.2	4.3	4.6
80-84	1.1	0.9	1.0	1.7	1.5	1.6	3.1	2.6	2.8
85-89	0.5	0.4	0.4	0.9	0.8	0.9	1.5	1.3	1.4
90+	0.2	0.1	0.1	0.4	0.4	0.4	0.9	1.0	1.0
0-14	19.2	14.0	16.6	17.9	13.2	14.9	14.5	10.5	11.6
15-64	70.8	78.2	74.5	66.0	73.7	70.8	62.3	68.8	66.9
65+	10.1	7.8	8.9	16.2	13.1	14.3	23.2	20.7	21.5
Urbanization rate			50.0			62.2			71.3

Table 3 The Chinese population projection result under the two children policy scenario (%)

Age group	2010			2020 (Projected)			2030 (Projected)		
	Rural	Urban	Aggregate	Rural	Urban	Aggregate	Rural	Urban	Aggregate
0-4	6.7	4.6	5.7	5.5	4.7	5.0	6.0	4.7	5.1
5-9	6.1	4.5	5.3	5.9	4.4	5.0	6.6	4.5	5.1
10-14	6.4	4.9	5.6	6.9	4.5	5.4	5.5	4.5	4.8
15-19	7.0	8.0	7.5	6.0	4.5	5.1	5.7	4.4	4.8
20-24	8.5	10.7	9.6	5.8	5.1	5.3	6.2	4.7	5.1
25-29	6.5	8.7	7.6	6.0	7.8	7.1	5.0	4.8	4.9
30-34	6.2	8.4	7.3	7.3	10.1	9.1	4.9	5.1	5.1
35-39	8.0	9.7	8.8	5.6	8.2	7.2	5.2	7.4	6.8
40-44	9.2	9.5	9.3	5.6	7.7	6.9	6.5	9.4	8.6
45-49	7.8	8.0	7.9	7.5	8.7	8.3	5.1	7.6	6.9
50-54	6.0	5.8	5.9	8.8	8.7	8.7	5.4	7.0	6.6
55-59	6.6	5.6	6.1	7.3	7.4	7.3	7.3	7.8	7.7
60-64	4.9	3.9	4.4	5.8	5.1	5.4	8.5	7.9	8.1
65-69	3.5	2.7	3.1	6.1	4.9	5.4	6.7	6.7	6.7
70-74	2.7	2.2	2.5	4.3	3.3	3.7	5.4	4.4	4.7
75-79	2.0	1.6	1.8	2.7	2.1	2.3	5.0	4.1	4.4
80-84	1.1	0.9	1.0	1.7	1.5	1.6	2.9	2.5	2.7
85-89	0.5	0.4	0.4	0.9	0.8	0.8	1.4	1.3	1.3
90+	0.2	0.1	0.1	0.4	0.4	0.4	0.8	1.0	0.9
0-14	19.2	14.0	16.6	18.3	13.6	15.3	18.1	13.7	15.0
15-64	70.8	78.2	74.5	65.7	73.4	70.4	59.7	66.3	64.4
65+	10.1	7.8	8.9	16.1	13.1	14.2	22.2	20.0	20.6
Urbanization rate			50.0			62.2			71.1

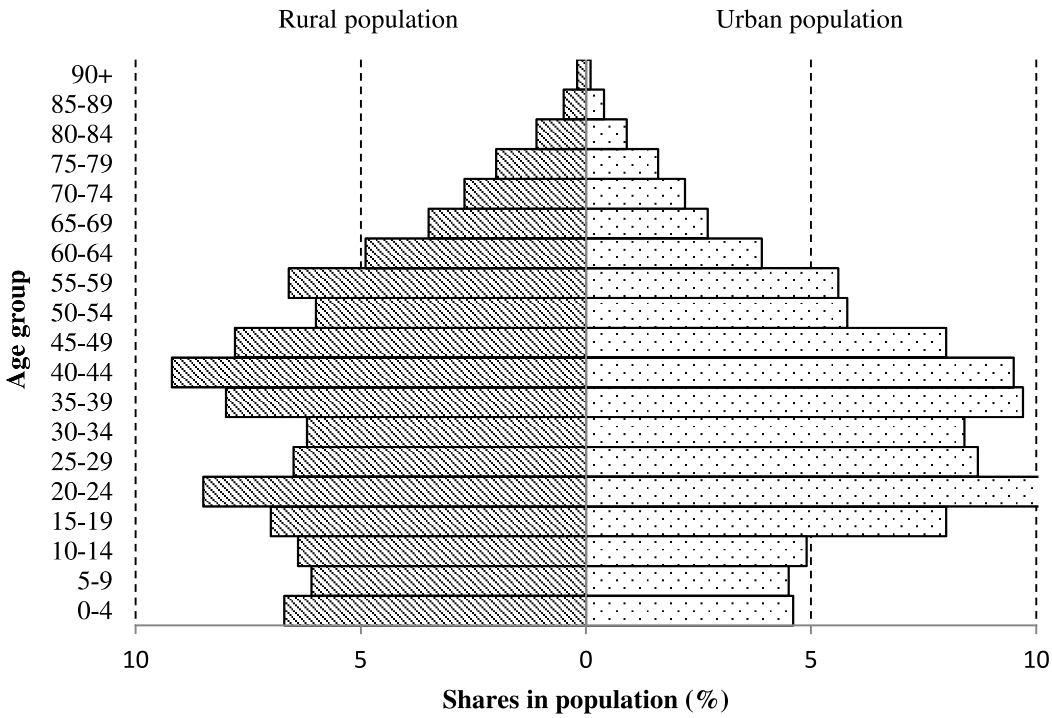


Figure 1. The age structure of the rural and urban population in 2010

(Source: China 2010 national population census data, NBS, 2012.)

Note: The percentages in Figure 1 refer to the shares of each rural age group in the total rural population (left hand-side) and the shares of each urban age group in the total urban population (right hand-side).

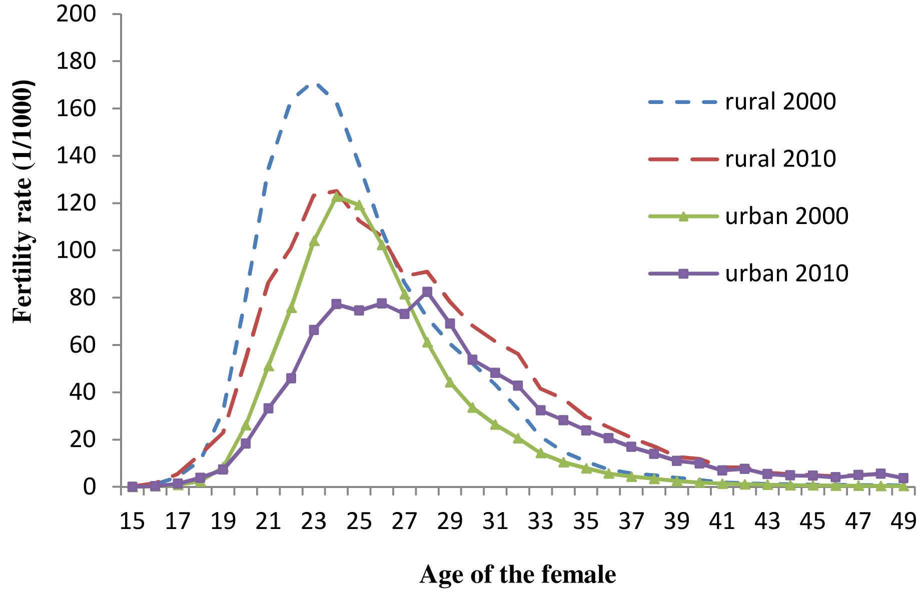


Figure 2. The rural and urban age specific fertility rates in 2000 and 2010
(Source: 2000 and 2010 population census; NBS, 2002, 2012)

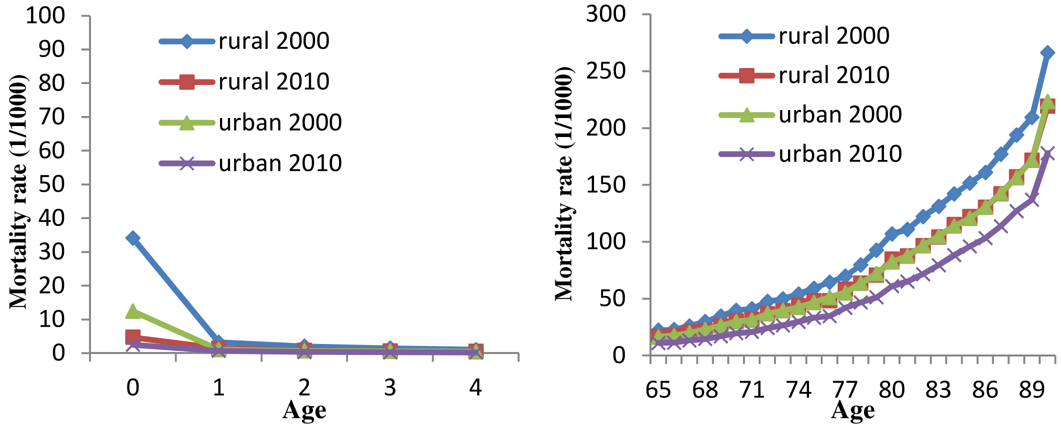
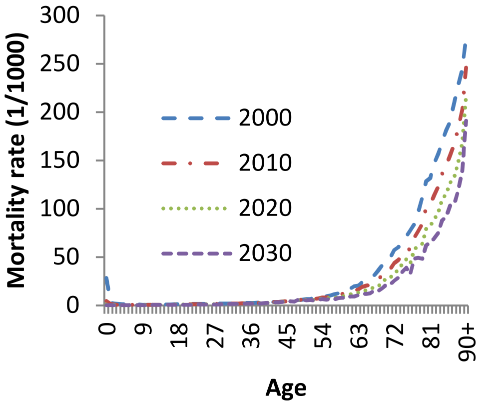


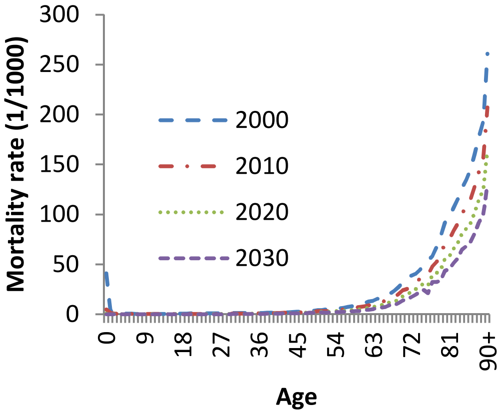
Figure 3. The age specific (aged 0-4 and 65-90+) mortality rates in 2000 and 2010

(Source: 2000 and 2010 population census; NBS, 2002, 2012.

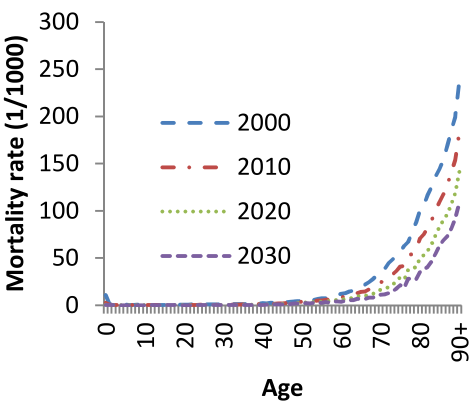
Note that the two figures use different scales.)



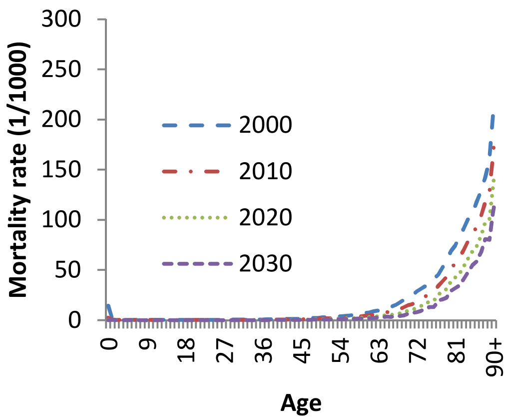
Rural male



Rural female



Urban male



Urban female

Figure 4. The age-specific mortality rates in 2000, 2010, 2020 and 2030

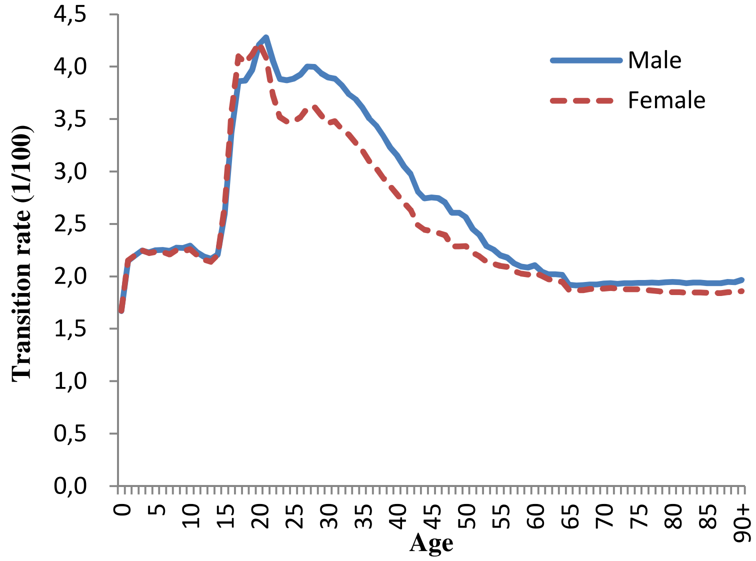


Figure 5. The age-specific rural-urban population transition rates

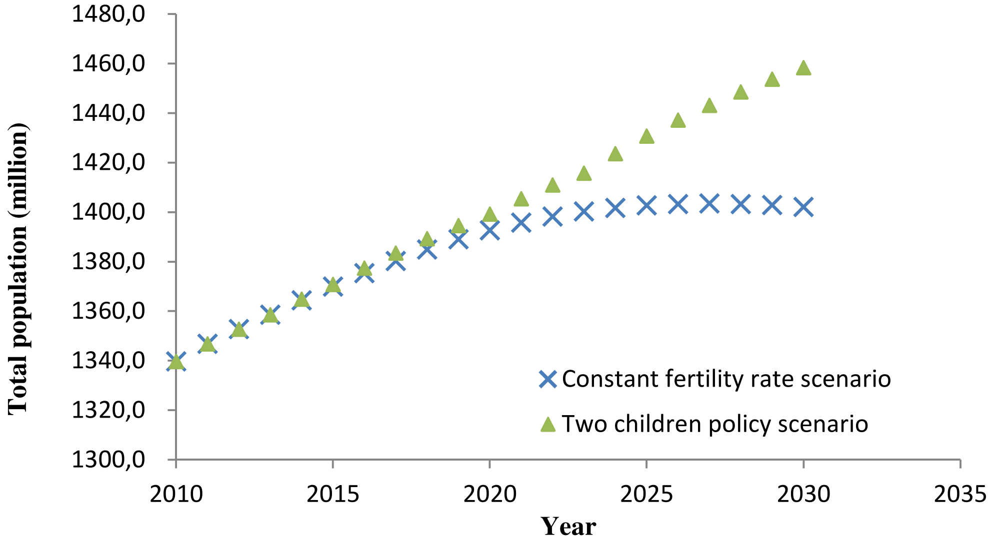


Figure 6. Total population (2010-2030)

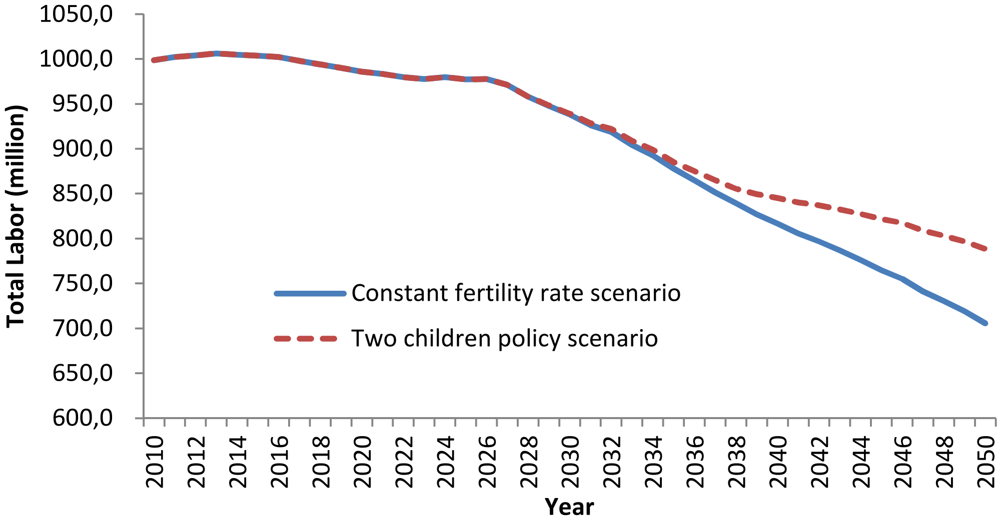


Figure 7. Total labor force (aged 15-64, 2010-2050)

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