Heliyon

Received:
7 September 2018
Revised:
26 March 2019
Accepted:
27 March 2019

Cite as:
Mengqiao Wang. A retrospective and predictive study of fertility rates in China from 2003 to 2018.
Heliyon 5 (2019) e01460.
doi: 10.1016/j.heliyon.2019.e01460

A retrospective and predictive study of fertility rates in China from 2003 to 2018

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Abstract

A retrospective longitudinal study was conducted on age-specific and birth-order-wise crude fertility rates and total fertility rates based on national sample surveys by the National Bureau of Statistics of China. Unexpectedly, such fertility datasets were officially deleted since 2016. A time-series predictive study was conducted based on the Holt's Exponential Smoothing models to restore the deleted fertility data for 2016 and beyond, allowing a comprehensive analysis of fertility rates in China from 2003 to 2018. In all, population structure was aging fast, fertility rates continued to decrease to a substantially low level, and three Northeastern provinces displayed notable socioeconomic issues associated with low-fertility trap. Adjustment is essential for China to timely remove its still-present birth limit and devise social policies to revert the fertility downtrend.

Keywords: Information science, Anthropology

1. Introduction

Presumably since as early as 221 B.C. when the First Emperor of Qin (*Qing Shi Huang*) conquered other warring states to establish a unified empire, China has been the most populous country on earth. In 2017, China ranks 1st worldwide with over 1.39 billion citizens, and it is still under an annual population growth of

https://doi.org/10.1016/j.heliyon.2019.e01460

6–7 million. However, history repeatedly demonstrated that with shifting dynamics such as growing economy [1], intensified social competition [2], enhanced gender equality and females' job participation [3, 4], any country would undergo an apparent decrease in fertility rates. In order to contain its large population, the country executed strict family planning, symbolized most notably by the "one-child" policy since 1980 allowing almost all couples only one child for their lifetime [5, 6]. After over three decades, the policy did undergo a few recent rounds of relaxations: allowing two children from 2011 for families of which both parents were themselves the only child, from 2014 for families of which at least one parent was an only child, and from 2016 finally for all families thus marking the end to the historic "one-child" social experiment and shifting to the current universal "two-child" policy [7]. Influences and consequences of the family planning policies on Chinese society were utmost and highly debated. Positive arguments included that more than 400 million births were averted by official estimation, the population control contributed significantly to economic development [8], and singleton daughters would no longer have to sacrifice their rights to the absent sibling sons, which was a common norm in societies with biased preferences to male offspring [9]. Meanwhile, counter-arguments against the above claims sufficed [10, 11], and concerns were present regarding sex-selective abortion as well as sex ratio imbalance [12], distortion of population structure [13], and side-effects as the behaviorally-unsatisfying "little-emperor generation" or the no-sibling "loneliest generation" [14, 15].

With factors as diverse as politics, socioeconomics, military, and religions, the "optimal" size of population is itself a controversial concept [16]. Two common parameters aim to describe the population-wise fertility level: crude fertility rate (CFR) refers to the number of live births among a female population (often normalized to per 1000 women) during a given period of time, and total fertility rate (TFR) refers to the number of children whom would be born for the lifetime of a theoretical woman if she were to pass her childbearing years (generally 15–49) following the current age-specific CFRs. Given the naturally imbalanced sex ratio at birth and the deaths of some females before reaching childbearing ages, a TFR of 2.1 denotes the replacement level in developed countries, under which on average a daughter could replace her mother inter-generationally and the long-term population would become stable in the absence of immigration or emigration. With sex ratio at birth and premature death rate both higher, developing countries including China may require TFR higher than 2.1 as the replacement level [17]. In summary, CFR describes the current cross-sectional fertility activity, and TFR reveals the hypothetical future fertility level. While it was commonly accepted that fertility rates in China were at sub-replacement level for over 20–25 years [18], a highly debated and controversial question remained on how low they were exactly [19, 20].

While detailed fertility data were largely absent for earlier years, national sample surveys by the National Bureau of Statistics (NBS) have published a table of *Age-*

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specific Fertility Rate of Childbearing Women by Age of Mother and Birth Order in annual *China Statistical Yearbook* since 2003, providing national raw data on annual CFRs for single-year ages or 5-year age groups, and even better grouping births by their birth order (1st, 2nd, and 3rd & beyond). The tables have been published until 2015, but unfortunately, such data for 2016 and 2017 were no longer available as the official yearbook publication mentioned that "*Of the chapter "Population", table named Age-specific Fertility Rate of Childbearing Women by Age of Mother and Birth Order is deleted*". Reasons were unavailable for the deletion of this table, and it was unclear if the deletion would be temporary or permanent, or whether such deletion would continue into future years. Given the autocorrelation of demographic parameters, time-series models, such as Holt's Exponential Smoothing [21, 22, 23], could learn the trend pattern from historic data and potentially forecast age-specific fertility rates missing for 2016 and beyond. Therefore, restoring the deleted tables would not only grant the continuity of fertility data, but would further reinforce the analysis on fertility trends.

Socioeconomic transformation in China has brought with it a structural decline in fertility [24], but what does the emergence and development of low fertility rates truly mean for the society? Riding through a four-decade period of demography dividend accompanying China's 1978 reform, previous family planning policies focused almost exclusively on controlling the total population but largely ignored on other important indicators such as population structure, social security, dependency ratio etc. [25] A lagging period naturally existed between low fertility and its multi-faceted implications, but by lying below the replacement level for over two decades, China, especially its administrative areas with the lowest fertility rates, could have already been struggling in the low-fertility trap, and if true, it was enough to toll the bells for the rest provincial areas on their fast-track to the similar "lowest-low" fertility [26].

2. Results

2.1. The population in China is aging fast

NBS sample surveys were conducted on "a stratified, multi-stage, systematic, Probability Proportional to Size (PPS) cluster sampling scheme" (*China Statistical Yearbook*), but no extra information was available for the details. A straightforward method of assuming simple random sampling and thus normalizing sample statistics by the sampling fraction resulted in accurate estimates of national demographic parameters, e.g. results matched well between annual population reported by the NBS (based on the real sampling scheme) and annual population inferred from simple random sampling (Fig. 1). The result validated the robustness of estimating national parameters from sample statistics assuming simple random sampling in replace of the original yet unknown sampling scheme. From 2003 to 2017, population in China

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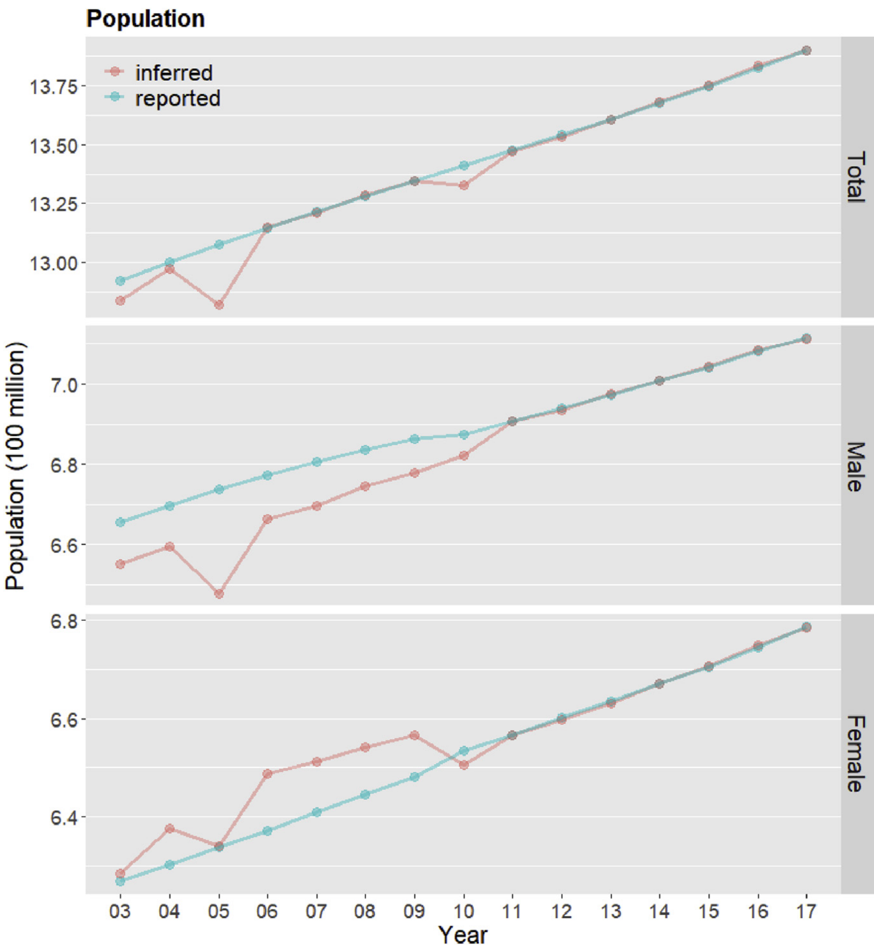

Fig. 1. Total or by-sex populations in China from 2003 to 2017 were compared between values directly reported by the NBS (cyan) and values inferred from sample population normalized by the sampling fraction (pink).

kept growing (Fig. 2A). For females, an obvious "aging" trend was observed: both the sub-population and the sub-proportion dropped sequentially for 0−14 age group (fertility-potential) and 15−49 age group (fertility-active), but in contrast steadily increased for the 50+ age group (fertility-completed) (Fig. 2B and C). Fertility-active females peaked at 383 million in 2011 but then started an annual decrease of 4−6 million. Comparison of female populations between the fertility-active group (15−49) and fertility-inactive group (0−14 and 50+ combined) revealed that while the former still constituted the majority, the gap became gradually narrower to a difference of 27.2 million in 2017 (Fig. 3A). Assuming the strong linear trends for both groups during 2011−2017 to persist, linear regression predicted that by the end of 2018, fertility-inactive females would be, for the first time ever in Chinese history, the majority group (Fig. 3A). In addition, population of the most fertile age group (20−29) stood at 101.9 million in 2017, but was predicted by the National Health and Family Planning Council (NHFPC) to drop to around 80 million in 2020

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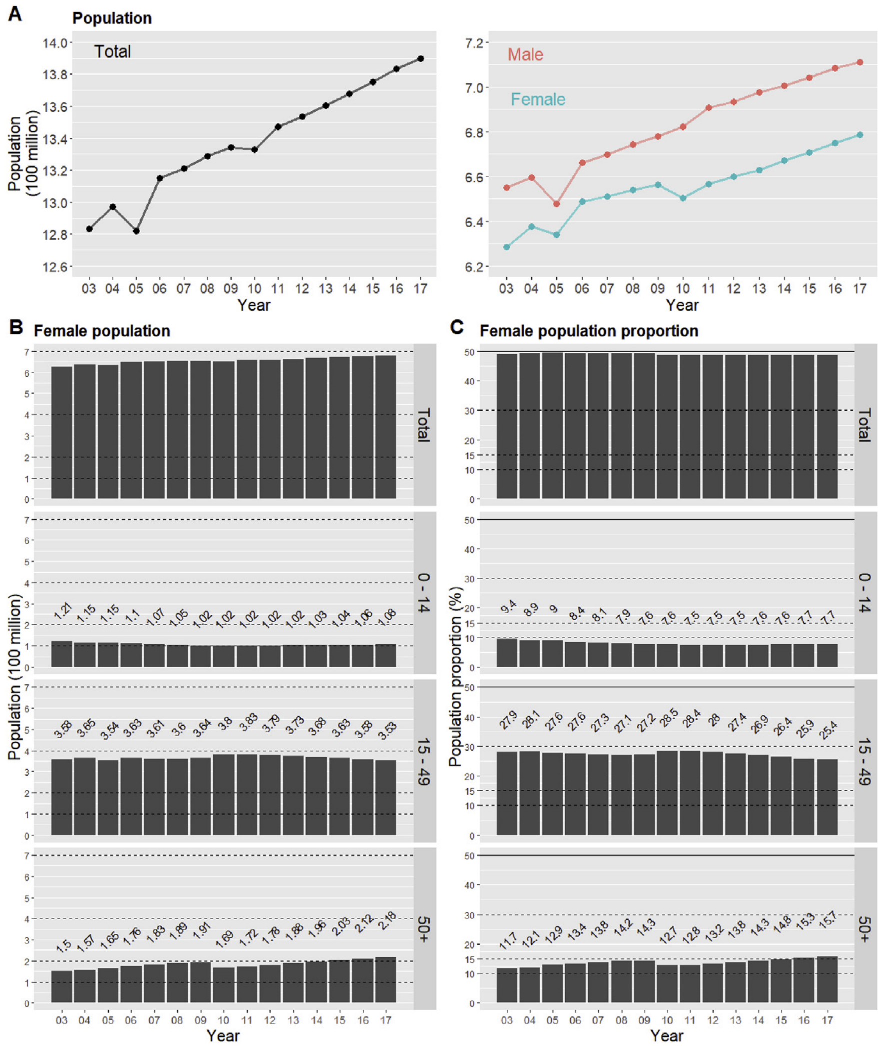

Fig. 2. Population in China from 2003 to 2017. A. Total or by-sex populations (inferred from sample population normalized by the sampling fraction). B and C. Female population count (B) and proportion (C) by age groups of fertility status (Total: all ages; 0−14: aged 0 to 14, fertility-potential; 15−49: aged 15 to 49, fertility-active; 50+: aged 50 and above, fertility-completed).

(Doc. 2016−38). Such shrinkage of about 22 million 20−29 females would alone translate to a decrease of 1.5 million annual births, which was more than 20% of the population growth of 7.4 million in 2017 (Fig. 3B). The similar "aging" trends were also observed in males, which could synergistically add to the decrease in future fertility (Fig. 4). The aging of Chinese population was well revealed by the dynamic shift in age pyramids (Movie 1).

2.2. Age-specific and birth-order-wise CFR and TFR

The table of *Age-specific Fertility Rate of Childbearing Women by Age of Mother and Birth Order* in *China Statistical Yearbook 2004−2016* reported CFRs for

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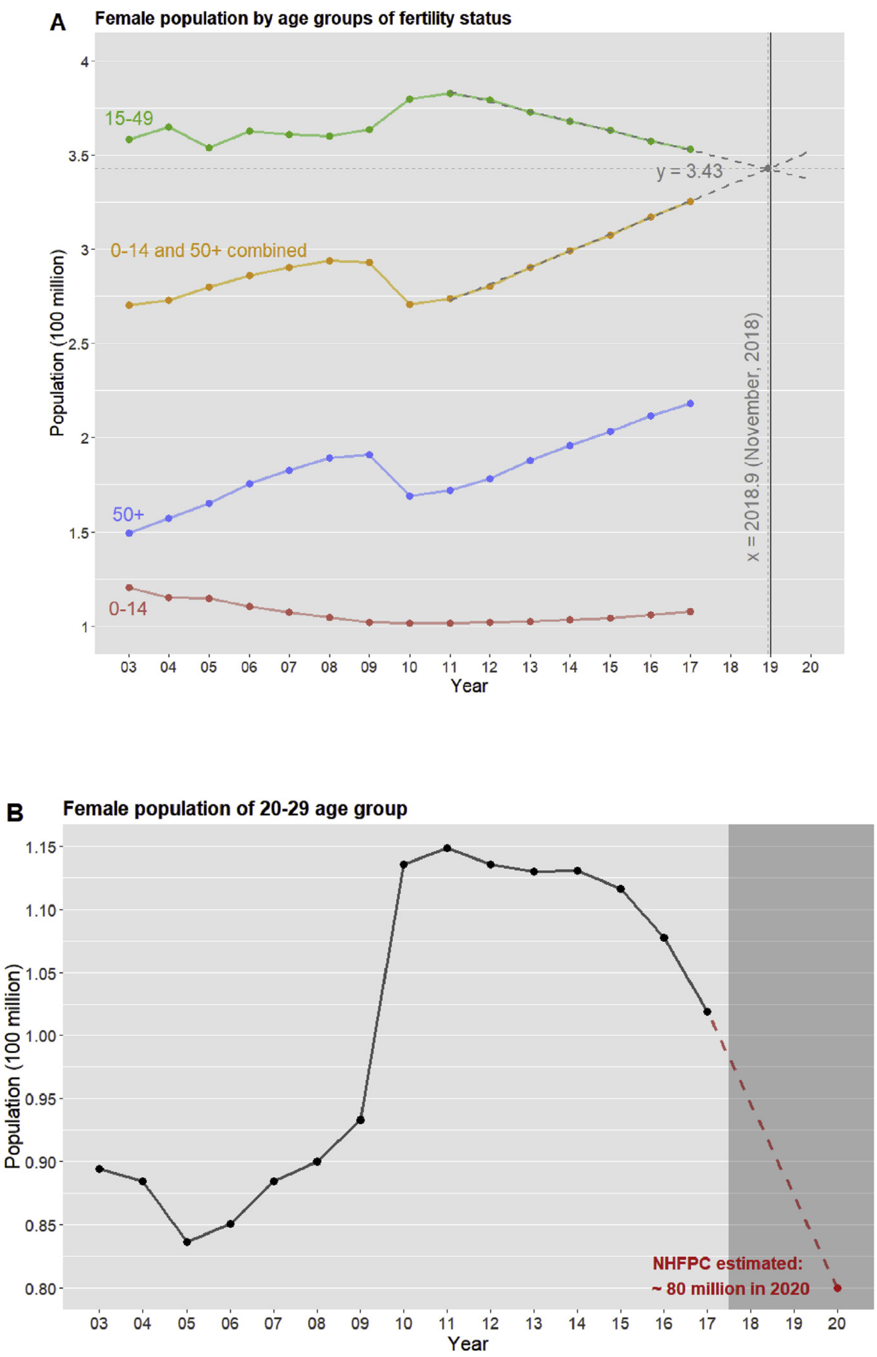

Fig. 3. Female population of age groups. A. Populations of fertility-active group (15−49) and fertility-inactive group (0−14 and 50+ combined). Population beyond 2017 were predicted using data of 2011−2017 based on linear regression models (adjusted R^2 of 0.997 and 0.998 respectively for the fertility-active and fertility-inactive groups). The intersection point was highlighted in grey. B. Population of the most fertile age group (20−29).

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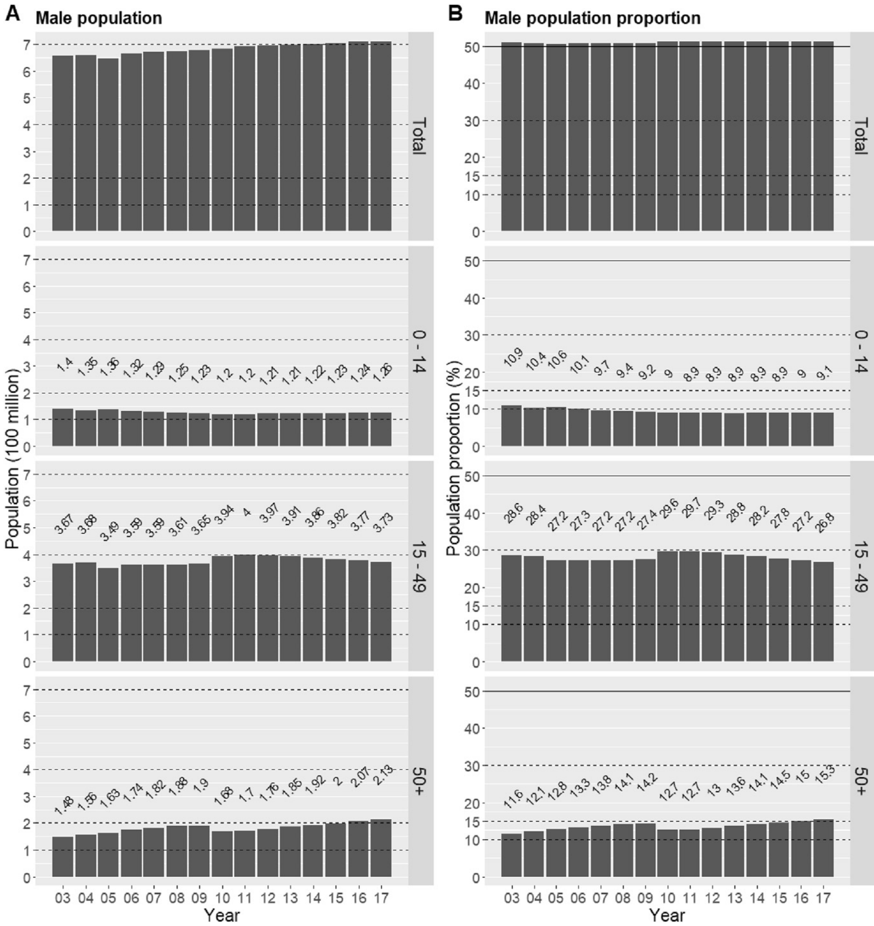

Fig. 4. Male population count (A) and proportion (B) by age groups of fertility status (Total: all ages; 0−14: aged 0 to 14, fertility-potential; 15−49: aged 15 to 49, fertility-active; 50+: aged 50 and above, fertility-completed).

single-year ages or 5-year age groups from 2003 to 2015. Corresponding visualization and tabulation revealed important insights (Figs. 5 and 6; Movie 2; Table S1): a). CFRs on the whole dropped sequentially due to a substantial decrease in 1st births and a partial offset of minor increase in 2nd births or 3rd & beyond births. b). while 1st births were the majority, the gap of CFRs in 1st births compared to 2nd births quickly shrank to a difference of 4.1‱ in 2015. c). downward trends in total CFR were apparently associated with the dynamic shift in age-specific fertility: both 20−24 and 25−29 age groups, presumably of the highest fertility, saw sharp drops in 1st-birth CFRs, while senior age groups generally displayed mild or no increase for all birth orders; notably, for the first time ever, 25−29 group surpassed 20−24 group in 2012 regarding peak CFR for 1st births, a representative reflection of the "delaying 1st birth" trend among young females. d). peak fertility ages remained largely unchanged as 22−25, 28−30 and 29−32 respectively for the 1st, 2nd and 3rd & beyond births. e). in accordance with the partial loosening of "one-child" policy since 2014, a mild spike appeared in 2nd-birth CFR, but the effect was not

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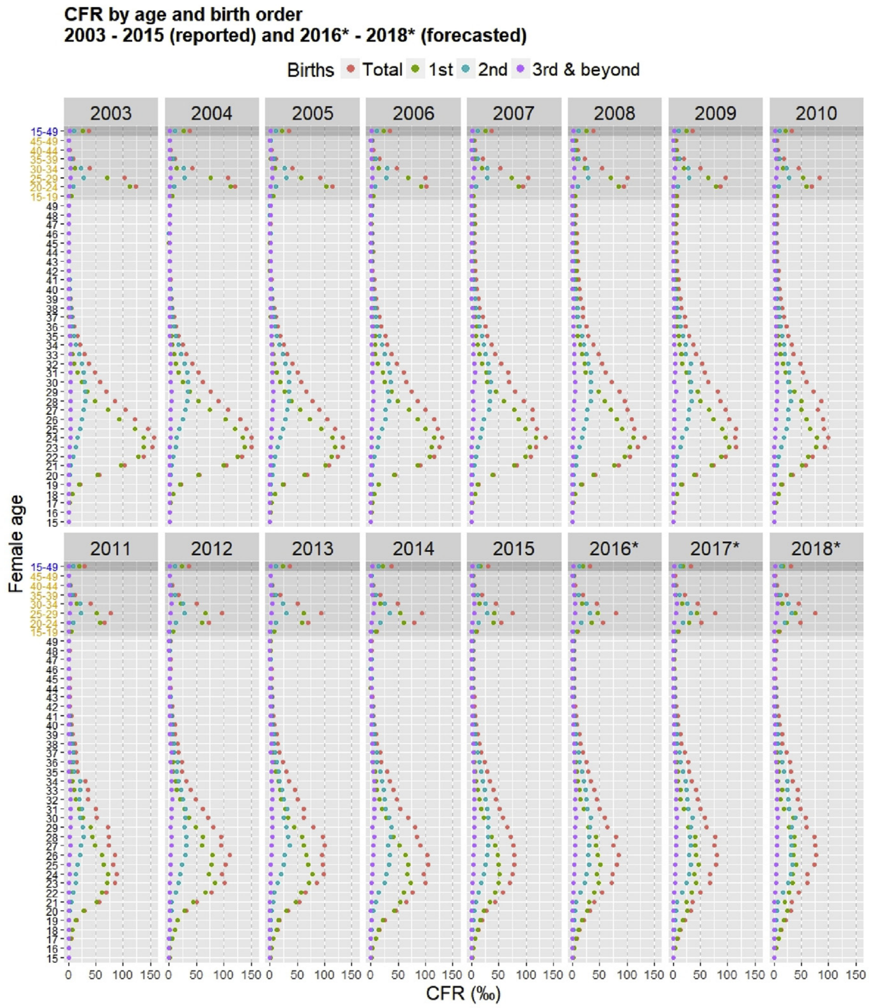

Fig. 5. Crude fertility rates by age and birth order for females. CFRs for 2003−2015 were reported in *China Statistical Yearbook 2004−2016* and for 2016−2018 were forecasted by the Holt's Exponential Smoothing models. Note: age-specific CFRs in 2016 and 2017 were deleted in *China Statistical Yearbook 2017* and *2018*.

sustainable as the parameter decreased again in 2015. In all, the above longitudinal observations reflected the "declining and delaying" fertility trends in China.

TFRs further validated the reality of low fertility (Figs. 7 and 8): far below the 2.1 replacement level, national TFR fluctuated around 1.4 since 2003, before dropping to around 1.2 since 2010 and finally reaching a low level of 1.05 in 2015. Any entity with TFR only half of the replacement level would watch its population theoretically halved in one single generation, although the lag effect might make it relatively longer for the extraordinary population decline to materialize. The sequential decrease in TFR was predominantly mirrored by the drop in 1st-birth TFR, arguing for females' inclination to delay or even avoid childbearing. With the "one-child"

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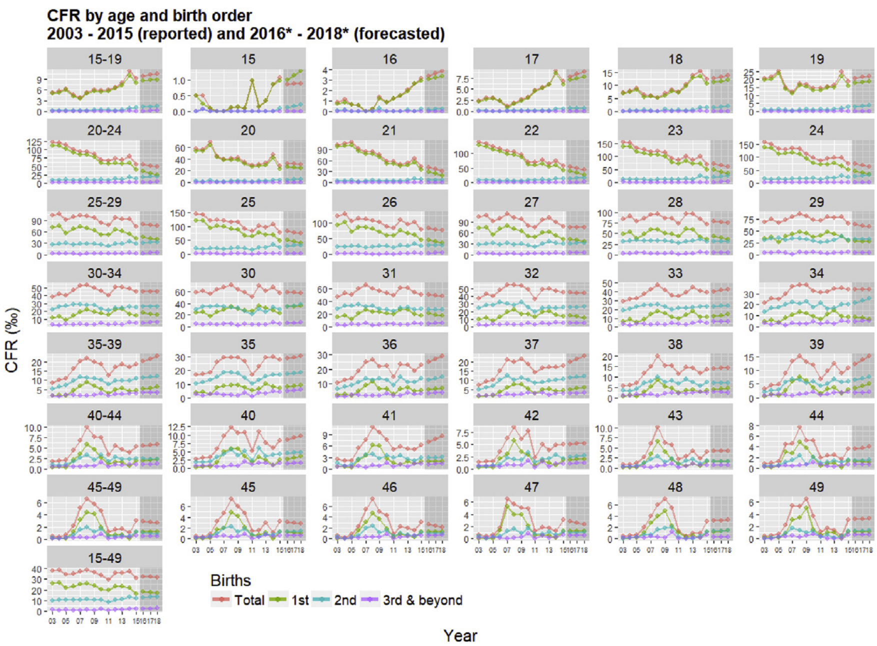

Fig. 6. Crude fertility rates by age and birth order for females from 2003 to 2015 (reported in *China Statistical Yearbook 2004−2016*) and from 2016 to 2018 (forecasted by the Holt's Exponential Smoothing models).

policy in effect, non-1st-birth TFRs remained largely stable at 0.40−0.45, but scored a mild increase to 0.5 since 2014 likely thanks to the loosening policy. The above results pointed out that not only birth limit but more importantly the unwillingness to even realize 1st births led to the plummet of TFR in China.

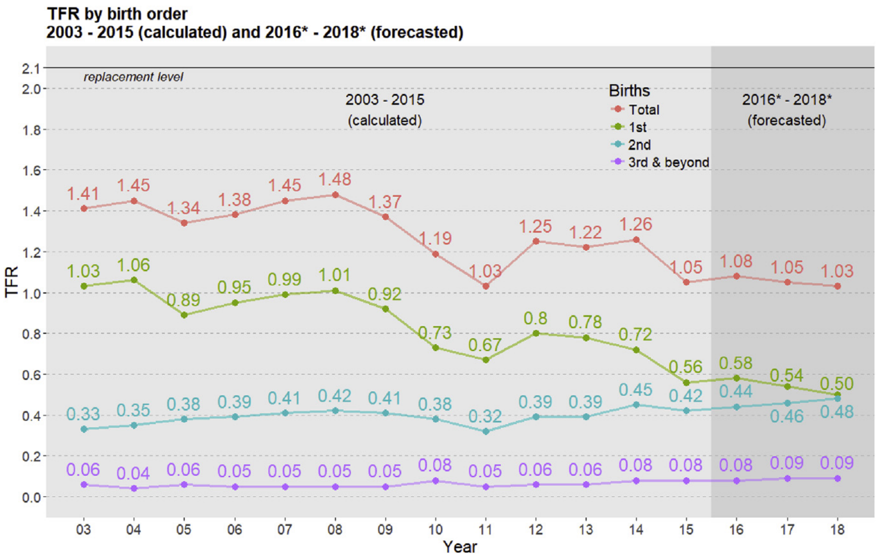

Fig. 7. Total fertility rates by birth order calculated from age-specific crude fertility rates for single-year ages. Results for 2003−2015 were based on CFRs for single-year ages reported in *China Statistical Yearbook 2004−2016*; results for 2016−2018 were based on forecasted CFRs for single-year ages in Table S2.

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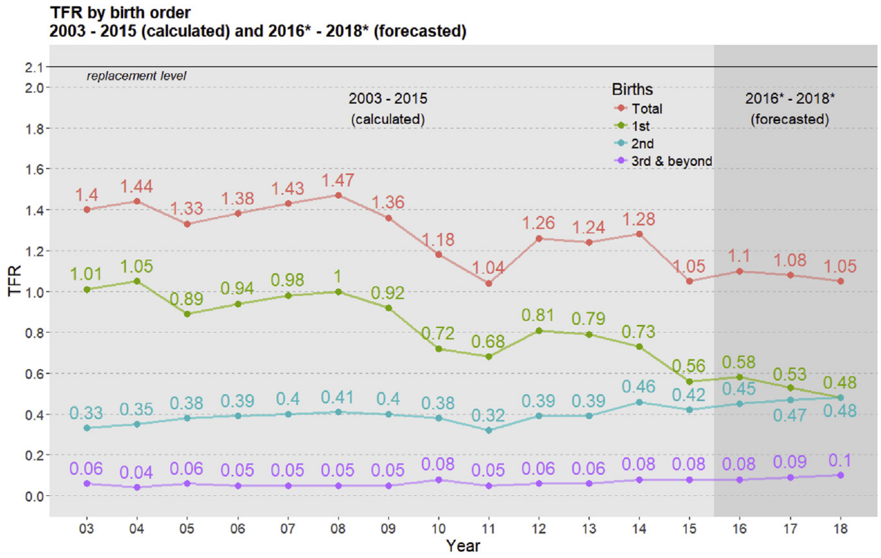

Fig. 8. Total fertility rates by birth order were calculated using age-specific crude fertility rates for 5-year age groups. Results for 2003−2015 were based on CFRs for 5-year age groups reported in *China Statistical Yearbook 2004−2016*; results for 2016−2018 were based on forecasted CFRs for 5-year age groups in Table S2.

2.3. Prediction of deleted fertility rates for 2016 and beyond

Efforts to monitor CFR and TFR in 2016 and 2017 were stalled by the unexpected issue that the fertility table was officially deleted in *China Statistical Yearbook 2017* and *2018*, thus making it impractical to track the fertility trends. To address this challenge, a time-series analysis was performed to build predictive models and forecast age-specific fertility rates missing for 2016 and beyond. Given that annual CFRs displayed no seasonal but non-stationary trends, Holt's Exponential Smoothing models were built using 2003−2015 CFR data conditioned on both females' age and birth order so that a total of 172 separate models applied respectively to each combination of specific ages (43 factor levels) and birth orders (4 factor levels) (see Methods). Residual diagnosis revealed that absolute residuals for 11-year training datasets (2005−2015) displayed no systematic overestimation or underestimation, and were mostly under 10‰ except for a few facets (Total births/1st birth, and ages of 20−34) (Fig. 9A). Such larger deviations were basically due to the high baselines of CFR in these most fertile facets, and indeed by scaling, relative residuals were mostly within 25% of the reported CFRs (Fig. 9B). Moreover, assumptions of the models held statistically: residuals displayed little evidence of non-zero autocorrelations at lags of 1−2 (3 out of 172 with the Ljung-Box test P value < 0.05, smaller than the random expectation of 8.6; Fig. 10A); residuals had no significant deviations from normality (11 out of 172 with the Shapiro test P value < 0.05, slightly over the random expectation of 8.6; Fig. 10B); all residuals had a mean of zero (the one-sample t test; Fig. 10C), and displayed little disobedience for the hypothesis

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of constant variances across years. Therefore, the Holt's Exponential Smoothing models built on 2003−2015 CFRs were accurate and robust for both point estimation and interval inference of age-specific CFRs in 2016 (Table S2A) and in 2017 (Table S2B). In case the deletion of CFR data would continue, such predictive analysis was further extended to 2018 (Table S2C).

The predictive models allowed diagnosing fertility trends beyond 2015 (CFR: Figs. 5 and 6, Movie 2; TFR: Figs. 7 and 8). It should be emphasized that China officially ended its "one-child" policy to replace with a universal "two-child" policy since the start of 2016. Such change was not incorporated into the models built on pre-2016 data, but the policy effect was likely only limited to 2nd births (1st births were always allowed, and 3rd & beyond births were still illegal). Therefore, forecasts of 2016−2018 fertility rates would undoubtedly underestimate 2nd births to some extent but should be accurate for 1st or 3rd & beyond births. Based on the forecasts, CFRs would continue both the decrease for 20−29 age groups and the mild increase for 30−39 age groups, and as well quickly narrow the fertility gap between 1st births and 2nd births. Considering the underestimation of 2nd births, it was reasonable to hypothesize that CFR for 2nd births would surpass that for 1st births by 2018. Indeed, the NHFPC announced that non-1st births (8.83 million) accounted for 51.2% of all newborns (17.23 million) in 2017, thus further validating the credibility of the predictive models. Meanwhile, TFRs were forecasted to remain at the low level of 1.0−1.1, and by 2018, TFRs for 1st births and 2nd births would become almost identical at 0.48−0.50, a milestone not only revealing a major shift in the fertility composition but also tolling the bell for the fast decline in 1st births.

2.4. Association of fertility rates and socioeconomic parameters at provincial level

While national fertility rates dropped sequentially, closer analysis at administrative levels offered a more defined look at the population trends in China. Rates of birth, death and growth from 2003 to 2017 were clustered hierarchically by rate pattern and visualized by color-gradient heatmaps (Fig. 11). Comparison among geographical areas offered several revealing insights: a). similar to the national trend, most areas observed sequential drops in birth and growth rates, with major exceptions of Shandong and Fujian. b). partly due to the less strict "one-child" policy implemented than other provinces, minority autonomous provinces such as Tibet and Xinjiang consistently had the highest birth and growth rates. c). megacities of Beijing and Shanghai returned to slow population growth after the initial decrease in 2003 but such change was likely due to the migration of young people into these cities thus temporarily lifting birth rates. d). three provinces (Liaoning, Heilongjiang and Jilin) notably clustered together as the "lowest birth rate, average death rate, lowest growth rate" pattern group, and starting from 2011, 2015, and 2016 respectively, they became

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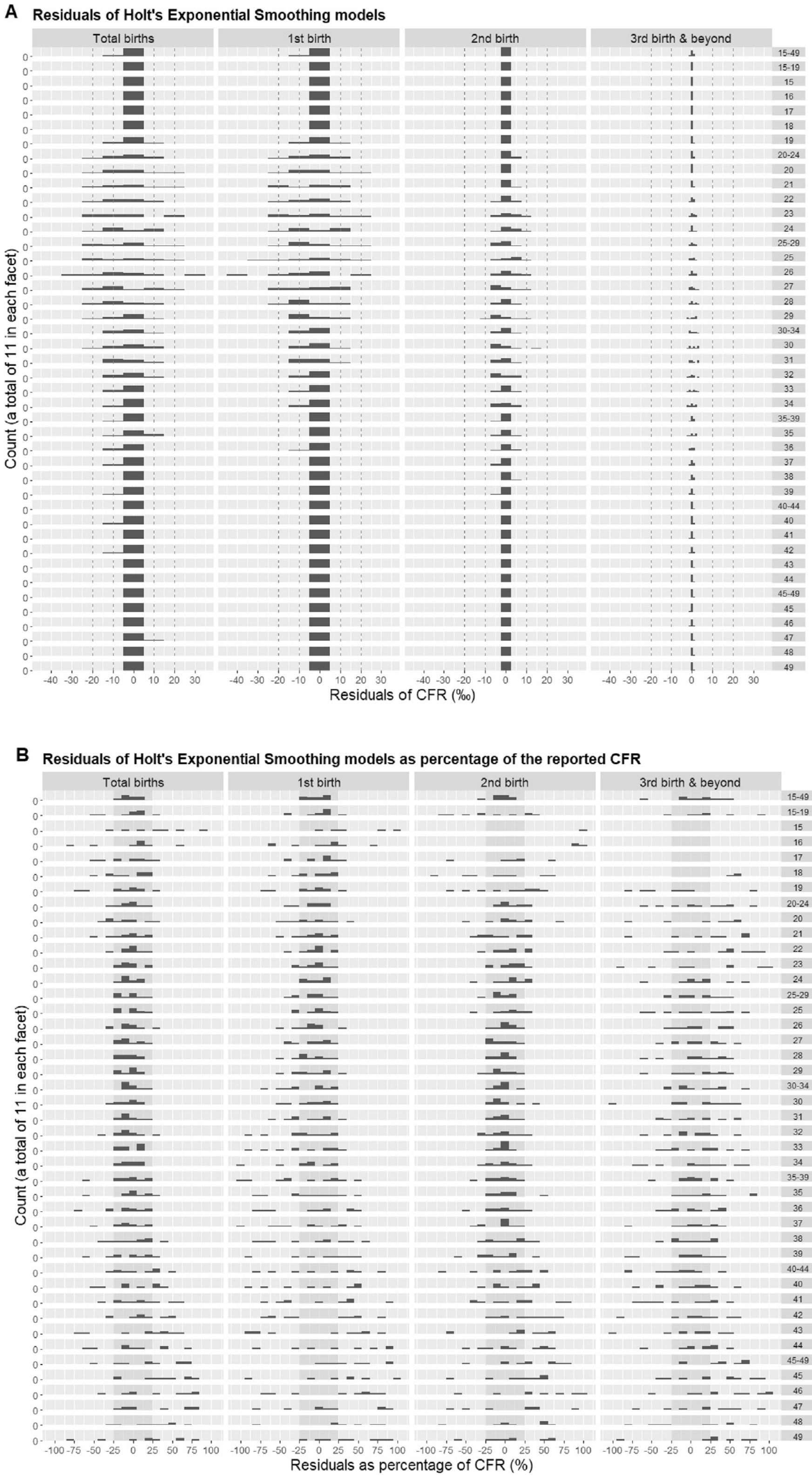

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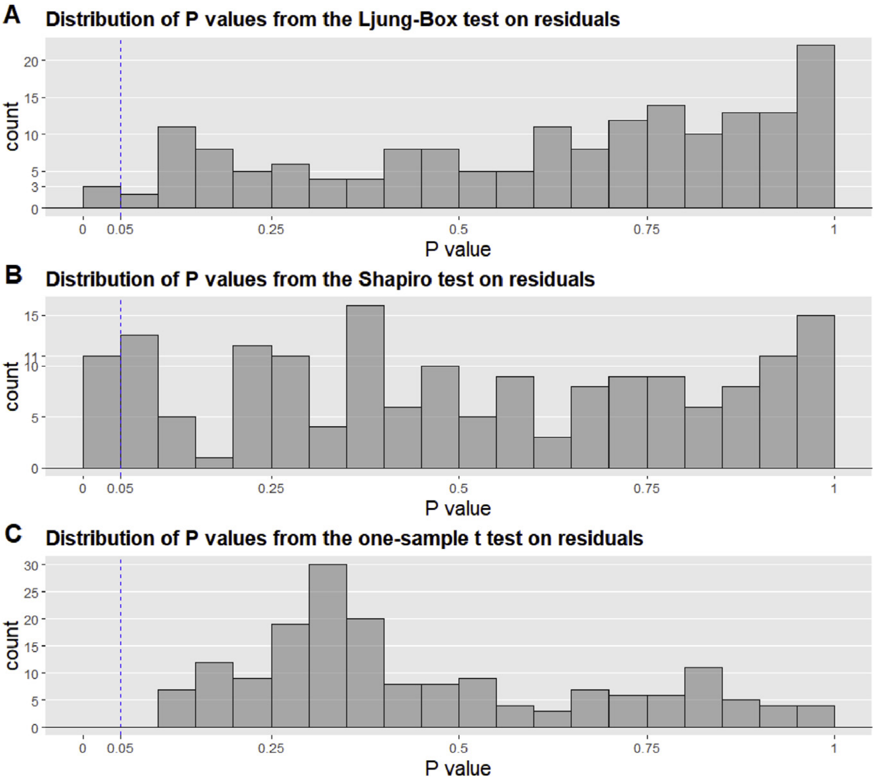

Fig. 10. Residuals of 172 Holt's Exponential Smoothing models (43 levels of females' age × 4 levels of birth order) were respectively diagnosed for autocorrelation by the Ljung-Box test (A), for normality by the Shapiro test (B), and for zero-mean by the one-sample *t* test (C). Distributions of *P* values from respective tests were visualized by histograms.

the only areas in China where natural growth rates turned negative and thus population underwent continuous decrease. Interestingly, the three provinces also clustered geographically in northwestern China (Fig. 12).

Comparison among administrative areas aimed to further investigate the association of low fertility with key socioeconomic parameters. Area-specific TFRs from the most recent 2010 census were consistent in identifying the three northeastern provinces as areas of the lowest fertility, with TFR at the extremely low level around 0.75 (Fig. 13A). Decrease of average family size applied to most areas but the

Fig. 9. Histogram for residuals of Holt's Exponential Smoothing models. Crude fertility rates from 2003 to 2015, conditioned on females' age and birth order, were modeled by the time-series method of Holt's Exponential Smoothing. A. 11 residuals of CFR for 2005−2015 were visualized by histogram for the respective conditional facets ($residual_{CFR} = CFR_{reported} - CFR_{forecasted}$). Note: residuals were not available for 2003 and 2004 given no predictions for the two time points due to the lack of enough lagging data. Bin-widths equal 10‰, 10‰, 5‰ and 1‰ respectively for the column-wise facets by birth order. B. 11 residuals of CFR for 2005−2015 were divided by the corresponding reported CFRs and the relative residuals were visualized by histogram for the respective conditional facets ($relative\ residual_{CFR} = \frac{CFR_{reported} - CFR_{forecasted}}{CFR_{reported}} * 100\%$). Note: relative residuals were not available for 2003 and 2004 as above. Bin-widths all equal 10%.

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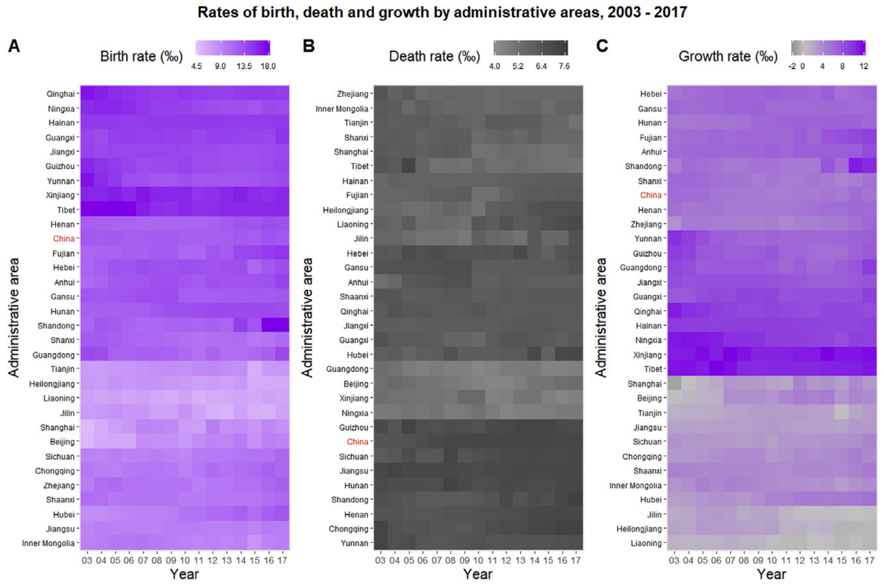

Fig. 11. Heatmaps of birth, death and growth rates (nation and 31 administrative areas). For each heatmap, rows were ordered using hierarchical clustering based on the *ward.D* agglomeration method and the Euclidean distance of rates from 2003 to 2017.

northeastern provinces were among those with the highest statistical significance, and since 2010, all of them were below 3 people per household, a low level almost comparable to that in megacities of Beijing and Shanghai (Fig. 14). In addition, the three northeastern provinces observed their growth rates in gross domestic product

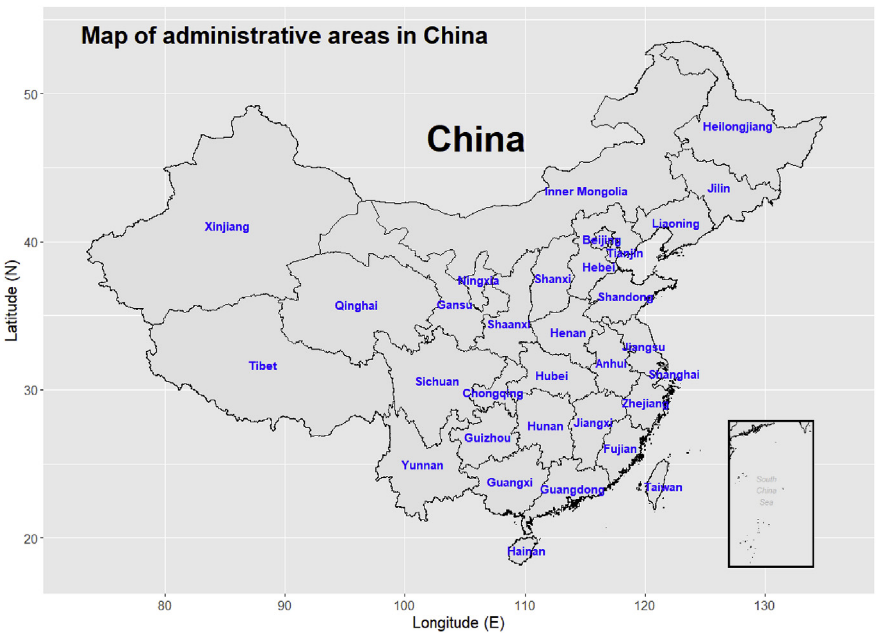

Fig. 12. Geographical map of China, with annotation of 32 administrative areas. Hong Kong and Macau are two special administrative regions to the south of Guangdong, not annotated here given their tiny sizes.

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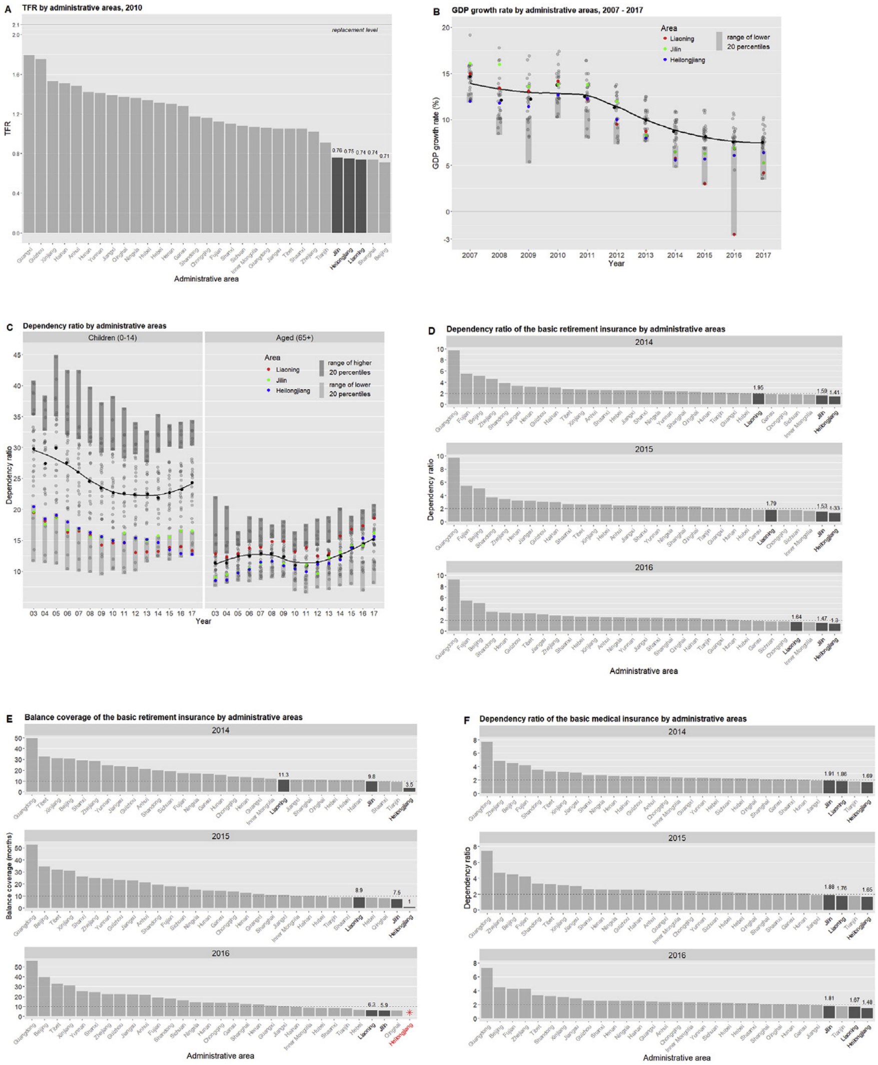

Fig. 13. Comparison of socioeconomic parameters by administrative areas, with focus on the three northeastern provinces of Liaoning, Jilin, and Heilongjiang. A. Total fertility rates by administrative areas from 2010 census. B. Growth rates of the GDP index by administrative areas from 2007 to 2017. For each year, rates of 31 administrative areas were plotted and a grey rectangle annotated the range of the lower 20% quantiles (the lowest 6 areas). Black dots referred to annual medians of 31 areas, based on which a black loess smooth line was fitted. Note: the rate of Liaoning was negative in 2016 as it was adjusted after the province got caught previously inflating GDP data. C. Dependency ratios of children (0−14) or the aged (65+) by administrative areas from 2003 to 2017. Dependency ratio is defined as the number of dependents per 100 working-age (15−64) adults. Two grey rectangles annotated the range of the higher and lower 20% quantiles (the highest and lowest 6 areas). Black dots referred to annual medians of 31 areas, based on which a black loess smooth line was fitted. D. Dependency ratio of the basic retirement insurance by administrative areas from 2014 to 2016. The indicator is defined as the number of premium-paying contributors for per pension-receiving retiree. E. Balance coverage of the basic retirement insurance by administrative areas from 2014 to 2016. The indicator is defined as the number of months able to be covered by the year-end cumulative balance of the program. Note: in 2016, the cumulative balance in Heilongjiang was a deficit thus unable to cover any future months (red marker). F. Dependency ratio of the basic medical insurance by administrative areas from 2014 to 2016. The indicator is defined as the number of premium-paying contributors for per non-paying retiree.

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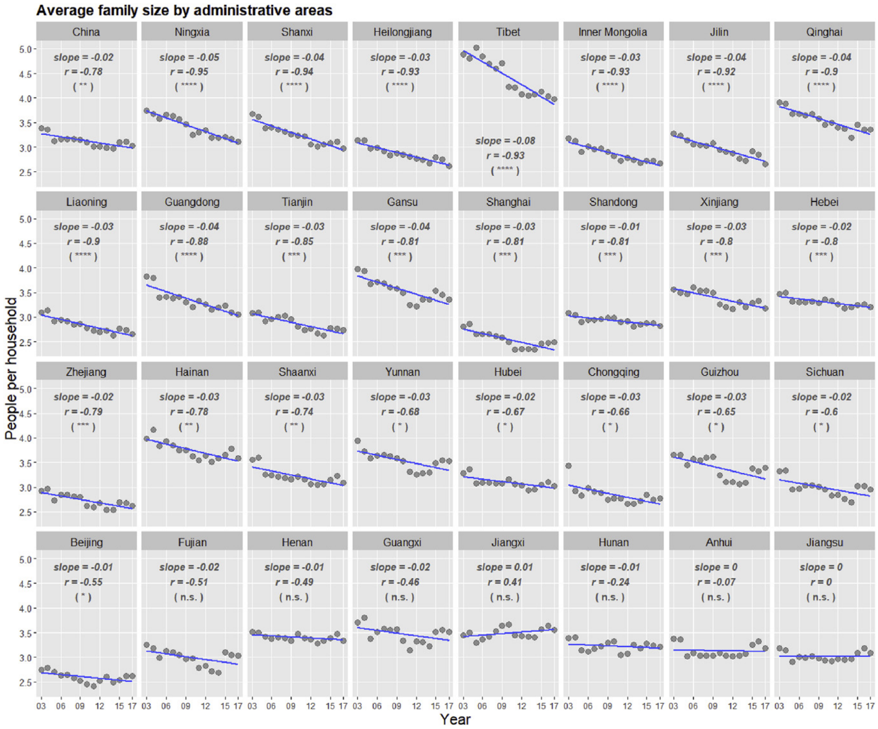

Fig. 14. Average family size (people per household) by administrative areas from 2003 to 2017. A linear regression line (blue) was fitted for each facet, with the linear coefficient (*slope*), *Pearson* correlation coefficient (r) and the significance of P value reported respectively. n.s.: not significant, $P \geq 0.05$; *: $P < 0.05$; **: $P < 0.005$; ***: $P < 0.0005$; ****: $P < 0.00005$. Facets of administrative areas were ordered by P values.

(GDP) slowing from around or above national average to the lowest 20% quantile group (Fig. 13B). Total dependency ratio is a parameter defined as the number of non-working-age (0−14 and 65+) people supported by per 100 working-age (15−64) adults. However, dependency ratios conditioned on the age status are more implicative for future support trend: a high dependency ratio of children (0−14) suggests a sufficient base of young generation that would eventually enter the working-age group within the next 15 years to empower the denominator; in contrast, a high dependency ratio for the aged (65+) suggests a large base of senior generation that could not possibly get back to the working-age group but remain as the numerator to be supported. The three northeastern provinces with the lowest fertility rates demonstrated dependency ratios low and dropping annually for the children but high and climbing yearly for the aged, an obvious sign of the deteriorating support load (Fig. 13C). In fact, dependency ratio of the aged was already significantly higher than that of children in Liaoning and Heilongjiang (Fig. 15). Population structure and fertility trends would also significantly influence social securities since such programs (pension, healthcare etc.) were financed by current contributions and would be sustainable only on the condition of a generalized revenue-expenditure balance between the contributing working generation and the non-

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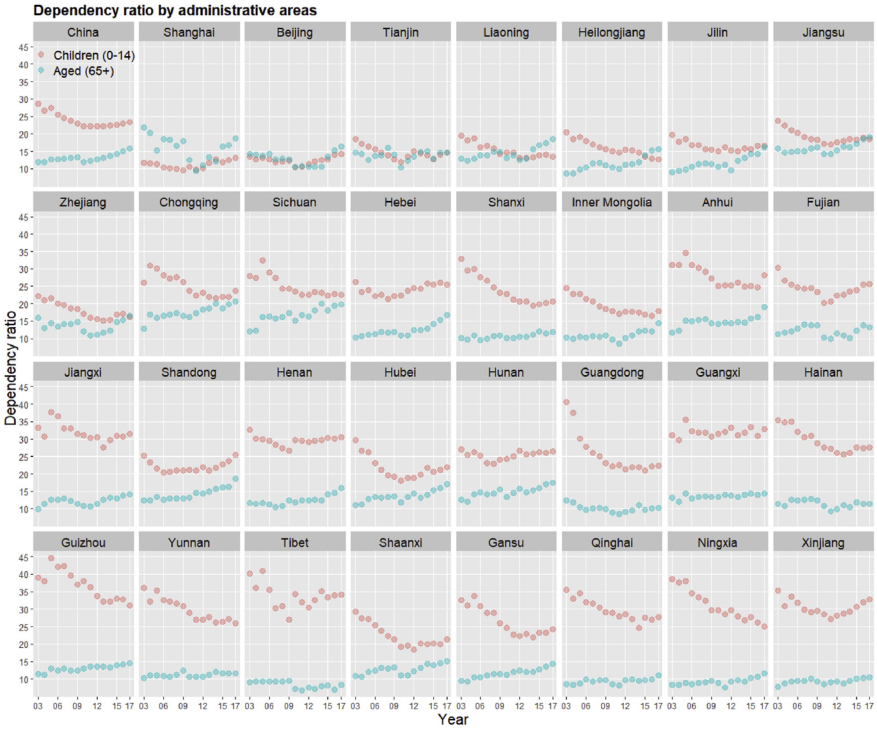

Fig. 15. Dependency ratios of children (0−14) and the aged (65+) by administrative areas from 2003 to 2017.

contributing senior generation. Data on social securities were not available until recently since 2014, but even within the limited 3-year period, the northeastern provinces ranked among the worst for the basic retirement insurance and the basic medical insurance (Fig. 13D and F). Their dependency ratios which evaluate the number of contributors for per non-contributor were all below 2. On another perspective, the northeastern provinces could barely cover half a year with the balance of basic retirement insurance (Fig. 13E). Remarkably, Heilongjiang had a negative cumulative balance of 23.2 billion RMB (3.51 billion USD) by 2016, becoming the first province to exhaust its basic retirement insurance fund and solely depend on the financial lending or credit from the central government to maintain full monthly payments. All of the above strong associations between deteriorating socioeconomic parameters and low fertility rates raised an unavoidable question of inference: with other areas of the country on their way to catch the three northeastern provinces with regard to very low fertility levels, will this challenge stall the transition of China from currently a developing country to in future a developed country? [27].

2.5. Adjustment of TFR, and the completed fertility rate

There has long existed the controversial debate on the precise value of TFR in China. The most-recent TFR in China was reported as 1.62 by the World Bank (2016) and 1.60 by the United Nations (2011−2015), all significantly higher than the NBS level

https://doi.org/10.1016/j.heliyon.2019.e01460

of 1.05 calculated for 2015 and 1.08 forecasted for 2016. The most critical argument against the raw TFRs calculated from age-specific CFRs was that the NBS sample surveys underreported births due to various potential reasons [28, 29, 30], e.g. respondents' unwillingness to report new births in fear of financial penalty, or difficulty to track the migrating groups. Assuming the surveys as simple random samples of the whole population, inference of annual births from the fertility and demography datasets indeed displayed a systematic underestimation compared to annual live births aggregate-reported by the NHFPC (Fig. 16A). The differences were 2−5.2 million in counts and 12%−32% in proportion from 2003 to 2015, and in 2016, the gap became bigger as the termination of "one-child" policy was not factored into the predictive model. Using the underestimation proportion in annual births as weights of adjustment, adjusted TFRs displayed a systematic lift of 0.2−0.5 compared to raw TFRs (Fig. 16B). Once adjusted, TFRs were in the

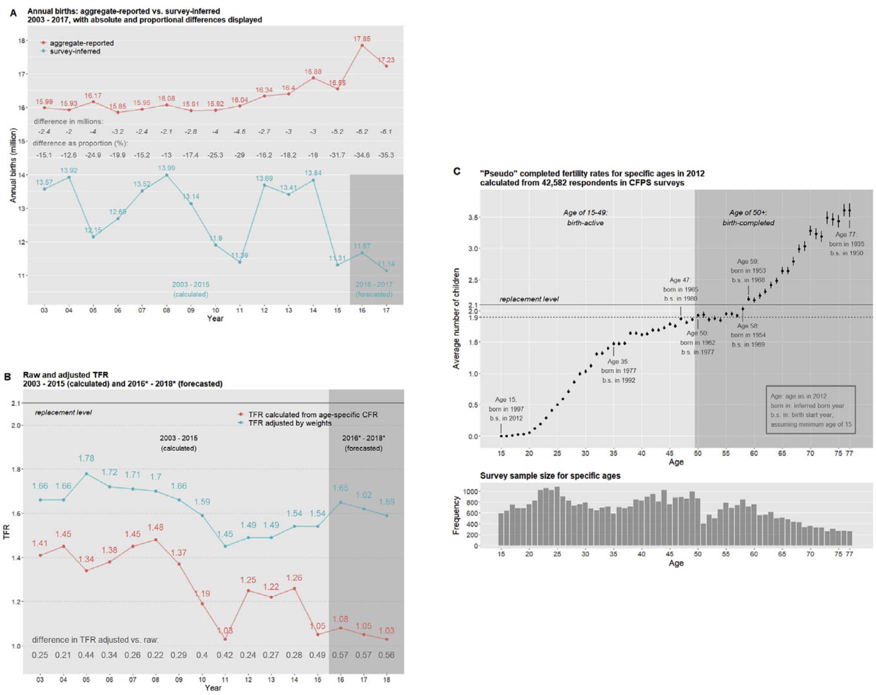

Fig. 16. Adjusted and completed fertility rates. A. Annual births reported by the NBS, and inferred from the fertility and demography tables of the sample surveys were compared, with differences displayed in both absolute and proportional values. Inferences for 2003−2015 and 2016 were respectively based on reported and forecasted age-specific CFRs. B. Total TFRs (as in Fig. 7) and TFRs adjusted by weights (underestimation proportion of annual births) were compared with differences displayed. Note: TFRs in 2017 and 2018 were adjusted with the weight for 2016. C. Confirmed the sex and age information of children, if any, match in both 2010 and 2012 surveys of China Family Panel Studies (CFPS), a total of 42,582 respondents were grouped into single-year ages and computed for the number of children per person [32]. Mean and standard error of such "pseudo" completed fertility rates were displayed as points and vertical bars. A few ages corresponding to some marker years were annotated; a histogram showing respondents' age-specific sample size was included. Note: respondents in CFPS were of both sexes; maximum age was set as 77 (born in 1935 and birth start in 1950) to account for completed fertility in P. R. China (founded on October 1, 1949).

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range of 1.6–1.8 during 2003–2010, and since then dropped to 1.45–1.55, matching the levels reported by the World Bank and the United Nations. Interestingly, adjusted TFR forecasted for 2016–2018 displayed a spike to 1.65 in 2016 but the temporary rise immediately reversed to a sequential decrease since 2017, arguing against the claim that terminating the "one-child" policy but keeping a "two-child" limit was sufficient in restoring replacement-level fertility.

A third parameter of the completed fertility rates longitudinally track a cohort of representative women up to the end of their fertility life, and sum age-specific CFRs of this defined cohort to reveal fertility at the materialized level. However, the requirement of longitudinal surveys on a single cohort made the task very challenging, especially in large and under-developed countries like China. To overcome the difficulty, this study used data from a large national survey in place of a cohort for displaying the number of children women have had by their ages. China Family Panel Studies (CFPS) is a comprehensive and nationally representative longitudinal social survey at the individual, family, and community levels, launched with baseline survey in 2010 and first follow-up survey in 2012 [31]. With a conservative quality-control standard of matching the sex and age of children in both 2010 and 2012 surveys, a total of over forty thousand respondents were analyzed for age-specific "pseudo" completed fertility in 2012 (Fig. 16C) [32]. For the birth-completed group (age 50+, born between 1935 and 1962), those born before 1953 displayed sequential drop in the average number of children from 3.61 to 2.19, all of which were above the replacement level of 2.1, but those born between 1954 and 1962 displayed largely stable level of 1.85–2.03, all below 2.1. Therefore, assuming 15–49 as fertility years, the fertile-active group had since 1969 shifted from replacement level to sub-replacement level, and by 2003 (those born in 1953 turning 50), there was no longer any fertile-active group with completed fertility rates over 2.1. Meanwhile, for the birth-active group (age of 15–49, born between 1963 and 1997), the "pseudo" completed fertility rates were still growing, but did not appear able to surpass a threshold of 1.90. Notably, people born in 1965 turned 15 in 1980 (when "one-child" policy officially started), and became the first wave under full fertility regulation; the group had on average 1.87 children as of 2012 (with 2 more years of fertility available), and this level likely stood as the upper threshold for all following generations. People born in 1977 turned 35 in 2012, and assuming all 1st births happen by the age of 35 and considering the limit of one birth per couple, their completed level of 1.47 would theoretically no longer rise beyond 2012, and thus presumably mark the true upper threshold of fertility in the "one-child" era.

2.6. The missing fourth peak

Similar to most worldwide entities, China observed a substantial decrease in fertility rates for the past six decades (Movie 3). Annual births displayed remarkable patterns

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since the nation's founding in late 1949 (Fig. 17). Around or above 20 million people were born annually during 1950−1957, marking the first fertility peak. With average annual births of 26.5 million in 1962−1973, self-delayed fertility during the 1958−1961 years of *Great Leap Forward* (an economic and social campaign in China, see https://en.wikipedia.org/wiki/Great_Leap_Forward) led to the earlier part of this second fertility peak, and the large base of *Peak 1* births contributed to the latter part. After *Peak 2*, birth count started to decrease again from 1974 to 1979 due to both fewer births during the 1958−1961 period and generally lower fertility rates. In 1980, the "one-child" policy was officially enacted to control population growth, and since then, annual births continued to increase and formed the third fertility peak of 1985−1991 averaging 23.8 million newborns annually. *Peak 3* arose simply as a result of the fertility of *Peak 2* generation. With the cyclical settings, fertile activity of *Peak 3* generation would predict a fourth peak around 2005−2015. However, such *Peak 4* was never present in reality given that annual births fluctuated around 16 million in 2003−2015, and this was for a large part because of two factors: the "one-child" limit for most families and a general decrease in fertility rates due to the changing socioeconomic dynamics (fewer and later marriages, higher costs in education, healthcare and housing, more job participation by females etc.). Additionally, after a temporary fertility jump to 17. 85 million births in 2016, total births in 2017 dropped to 17.23 million and in 2018 plummeted to 15.23 million, not only a sharp drop of 2 million from 2017, but also reaching a 7-decade low since the founding of P. R. China (only higher than 1960 and 1961). The missing fourth fertility peak and the newest low fertility data in 2018 both persuasively toll the bell for the urgency in quickly adjusting population policies.

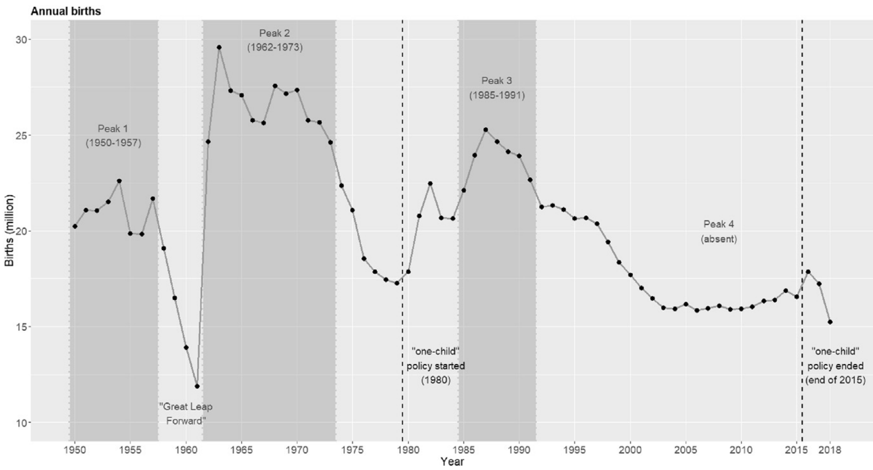

Fig. 17. Annual births in China from 1950 to 2018. Births from 1978 to 2017 were calculated using data from the NBS ($Annual\_births = Population_{mid-year} * birthrate$); births from 1950 to 1977 were retrieved from the Wikipedia[#1], with the original source potentially also from the NBS; births in 2018 were from preliminary report of the NBS. [#1] https://en.wikipedia.org/wiki/Demographics_of_China#Table_of_births_and_deaths_1950−2017, last accessed on July 8, 2018.

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3. Discussion

Family planning in China started in 1973 with a slogan of "later, sparser, fewer" but it remained largely as propaganda not strict regulations. An open letter on September 25, 1980 calling "only one child for each married couple" marked the start of the "one-child" era. Family planning became authorized as a fundamental national policy into the Constitution in 1982 and lasts until today to soon enter its fifth decade. After 30 years, stepwise adjustments of the "one-child" policy finally transformed into a universal "two-child" policy. By common definitions of aging society (over 10% of population 60+ or 7% of population 65+), China was already an aging country in 2003 with 12.2% 60+ and 8.5% 65+, and by 2017, the total population was 17.3% 60+ and 11.4% 65+. Several factors including longer life expectancy and low death rates contributed to the aging trend, but their effects were mild given the already good-enough levels (life expectancy of 76.3 years and crude death rate of 7.11‰ in 2015). Therefore, low-level fertility is likely the major culprit for aging China. Then how low is the low? Answer to this question has tremendous consequences in influencing fertility policies. This study demonstrated that TFR has been for long below 2.1 and reached 1.05 in 2015. Even adjustment of raw TFR by the underestimation coefficients led to the still low level around 1.5. Particularly, the three northeastern provinces serve as remarkable negative examples of the strong linkage between low fertility and unsatisfactory socioeconomics.

Switch to the current universal "two-child" policy was a major progress in fertility strategy, but TFR levels and population pyramids both argued that the change was essentially not enough. The real challenges for China are the plummet in 1st births and the fast decrease of future fertile-age citizens, as 2nd-birth increase is mild and far from enough to cover the loss in 1st births. It is likely that the forecast in this study would to some extent underestimate 2nd-birth CFR and TFR due to the policy change in 2016 but the training of predictive models using 2003−2015 data. However, such deviation seems minor and impossible to reverse the observed fertility downtrend. Indeed, the most recent fertility data argued against any potential hysteresis effect of the policy shift: annual births fell to 17.23 million in 2017 from 17.85 million in 2016, erasing almost half of the increase in 2016 due to the raise of birth limit, and in 2018, annual births further dropped 2 million to a 7-decade low at 15.23 million. Under the current "two-child" policies, 3rd & beyond births were still illegal as "out-of-policy" births, and would be not only prohibited but punished (Population and Family Planning Law Art. 6.41 and 6.42). In fact, this study has shown that 3rd & beyond births constituted a tiny portion of total births and in reality, few families would choose or afford to have 3rd & beyond births, so the restriction was not widely meaningful but mistakenly reinforcing the deluded impression of high fertility in China. Notably, citing anonymous sources, Bloomberg News reported in May 2018 on the possibility of China removing birth limit as early as 2019 [33]. Such

https://doi.org/10.1016/j.heliyon.2019.e01460

change, if materialized, should be welcomed as it is better later than never, and by that time, the focus of family planning in China would turn away from setting birth limit to letting citizens decide on their own childbearing and providing better fertility-related healthcare services.

Population monitor and forecast are essential duties of all governments, and relevant data should be open-accessible to the civil public. It was unfortunate for the table of age-specific fertility rates to be officially deleted in 2016 and 2017. While time-series modeling in this study restored the forecasted tables, it would be most valuable for the tables of real data to be available and help make data-driven decisions. In addition to data from national census and surveys, it is highly advisable to access and integrate multiple sources of data (including birth registration, marriage registration, pregnancy healthcare, children vaccination, social security etc.) on both the national and the provincial levels to scientifically monitor fertility levels and predict population trends. On the other aspect, it is most essential to include experts and the public in fertility policy planning so that all decisions would be objectively evidence-based rather than subjectively target-directed. In addition, policies such as tax credit and childcare benefits have been experimented in various countries to encourage fertility and support families, even though the effect was meaningful but not decisive. Thankfully, the government has finally started to offer some incentives since 2019 (e.g. monthly RMB 1000 (USD 150) tax deduction for each 3-year-old-plus child or teenager). Such policy direction is correct, but more and bolder social welfare incentives are needed, including more tax credit, affordable and accessible child care, equal employment opportunity for would-be mothers, holiday entitlement for new fathers etc.

Finally, a key factor often overlooked and unconsidered was the legality of births based on marriages. The Population and Family Planning Law clearly stated that parents must be married couples, suggesting that any births (even 1st births) of which parents were not married were illegal (thus qualified as “outside-policy” babies). Such regulations may have apparently negative influences on fertility: a). the Marriage Law requires males reaching 22 and females reaching 20 to be eligible for marriage (Art. VI), thus lifting the minimum age for 1st births; b). birth registration requires parents’ marriage certificate so the prerequisite would confer pressure and lead to more choices of involuntary abortion; c). similar to their peers in many developed countries, an increasing number of young people in China have embraced a “marry late or never marry” life track (average first marriage age estimated at 27.1 for males and 24.9 for females in 2015), and nationally more adults underwent divorces (crude divorce rates of 1.46‰ (2006), 2.13‰ (2011), and 2.79‰ (2015)), so the regulation would exclude such groups from fertility during their most fertile years. Taking the United States as an example, 11% of the 3.7 million total births were out-of-wedlock in 1970, but in 1990, the percentage rose to 30% out of the 4 million total births, and further climbed to 40% in 2007 [34]. Other western

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countries also had relatively high proportion of childbirths outside of marriage (in 2007, 50% in France, 44% in the U.K., and 30% in Germany) [35]. In contrast, while many factors contributed to the super-aging of Japanese society, one important aspect was that only 2% of total births were out-of-wedlock so marriage as an unofficial prerequisite for childbearing contributed to much lower fertility rates in Japan [35]. Undoubtedly, present are economic pressures and social stigmas associated with out-of-wedlock childbirths in many countries including China, but it is rational and appropriate to unlink marriage and fertility in legal terms, which would potentially boost fertility rates as in several Western countries.

4. Methods

4.1. Data sources

All NBS data used and analyzed in this study are publicly accessible either through the official website (http://www.stats.gov.cn/tjsj/ndsj/) or publications of *China Statistical Yearbook* (China Statistics Press). Particularly, data on fertility rates, demography, dependency ratio etc. were retrieved from annual *China Statistical Yearbook*; data on social security were retrieved from *Annual Report on China's Social Insurance Development* published by the Social Insurance Administration of the Ministry of Human Resources and Social Security (P. R. China); data on worldwide fertility rates were retrieved from the World Bank (https://data.worldbank.org/indicator); data on the number of children for women by age were retrieved from a *Technical Report* of China Family Panel Studies (CFPS). Other sources included the Wikipedia, news agencies etc. Cited government documents and law articles were annotated by the "Doc." and "Art." index respectively.

China Statistical Yearbook reported data for the previous year (e.g. *China Statistical Yearbook 2004* contained the related data for the year of 2003). The statistical window period was from previous November 1 to next October 31 (e.g. 2002/11/01−2003/10/31 for the year of 2003). All census and surveys covered 31 out of the total 34 administrative areas (excluding Taiwan, Hong Kong and Macau).

4.2. Data analysis

Key demographic parameters from the NBS were estimated in one of three sampling ways: a). every 10 years, a National Census was conducted (e.g. 2010) with a sampling fraction of 100% (for population) or 10% (for fertility); b). every 10 years, a Population Sample Survey was conducted (e.g. 2005 and 2015) with a sampling fraction of 1%; c). in other years, a National Sample Survey on Population Changes was conducted, with a sampling fraction between 0.8‰ and 1‰. CFR is calculated as: $CFR = \frac{\text{number of live births}}{\text{female population}_{\text{mid-year}}} * 1000‰$; depending on CFR reported for single-year

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ages or 5-year age groups, TFR is accordingly calculated as: $TFR = \sum_{i=15}^{49} CFR_i$ or $TFR = \sum_{i=''15-19''}^{''45-49''} 5*CFR_i$. With underestimation of annual total births by percentage of p, raw TFRs (calculated directly from summing age-specific CFRs) were adjusted by an adjustment coefficient of $\frac{1}{1-p}$. For null-hypothesis significance testing, α level of 0.05 and two-sided tests were used. All data analysis was performed in version 3.4.2 of the R statistical environment (R core team, 2017) [36], and data visualization was based on *ggplot2* and extended packages [37]. Time-lapse movies were created in VideoStudio (Corel Corporation).

4.3. Holt's exponential smoothing

Holt's Exponential Smoothing, also called Holt's Linear Model, is a method appropriate for series with trend but without seasonality. Estimate of the level for the time point (t) was a result of the level at previous time point (t-1) adjusted by a time-dependent trend component:

$$\widehat{y}_t = y_{t-1} + r_{t-1}$$

The model includes an α smoothness parameter for the base level and a β smoothness parameter for the trend component. Let $Holt_t$ denote an estimate of the series' level at time point t and r_t denote an estimate of the series' slope at time point t, then:

$$Holt_t = \alpha y_t + (1-\alpha)(Holt_{t-1} + r_{t-1}) \quad 0 \le \alpha \le 1$$
$$r_t = \beta(Holt_t - Holt_{t-1}) + (1-\beta)r_{t-1} \quad 0 \le \beta \le 1$$

Apparently, $Holt_t$ is a weighted average of observation y_t and the forecast for time point t; r_t is a weighted average of previous trend r_{t-1} and the estimated trend at time point t. Start value for the series' level could generally be set as y_1, while start value for the trend component could be set as the average trend in an initial h period $\left(\frac{y_h - y_1}{h-1}\right)$. The forecast for time point l ahead would thus be:

$$\widehat{y}_{t+l\,|\,t} = Holt_t + lr_t$$

In terms of statistical programming, with NBS data of age-specific CFRs by birth order in 2003−2015 (43 factor levels of females' age as Total, 7 5-year age groups, and 35 single-year ages of 15−49; 4 factor levels of birth order as Total, 1st, 2nd, and 3rd & beyond), the function of *HoltWinters*() in base R *stats* package was used to build a total of 172 (43 × 4) Holt's Exponential Smoothing models (argument of *gamma = FALSE*) with the default of minimizing the squared prediction error to estimate appropriate values for α and β parameters. All models were applied for predicting their corresponding 2005−2015 CFRs (training dataset; 2003−2004 forecasts not available due to setting an initial period of 2 for autodetecting the start value for parameters), and residuals were analyzed for checking the robustness and

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accuracy of the models. Specifically, the Ljung-Box test, the Shapiro test, and the one-sample *t* test were used to respectively test serial correlation, normality, and zero-mean of the residuals; line plots of residuals were applied to check the hypothesis of homoscedasticity across years. After quality check, the corresponding models were applied to forecast age-specific CFRs as well as the prediction intervals for 2016–2018. The core R codes of Holt's Exponential Smoothing modeling and prediction were submitted in the *holt_pred* script file.

Declarations

Author contribution statement

Mengqiao Wang: Conceived and designed the analysis; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Funding statement

Mengqiao Wang was supported by Sichuan University's Fundamental Research Funds for the Central Universities (20822041B4081), and Junior Faculty Grant (81800071) from National Natural Science Foundation of P. R. China.

Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2019.e01460.

Acknowledgements

The author appreciates the entities mentioned in the *Methods-Data sources* section for making relevant data open-accessible. The author would thank Dr. Jianzhang Liang for noting the deletion of the age-specific fertility rates table in *China Statistical Yearbook*.

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