GeoHealth

RESEARCH ARTICLE
10.1029/2024GH001058

Ozone Mortality Burden Changes Driven by Population Aging and Regional Inequity in China in 2013–2050

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Key Points:

- Ozone-related mortality burden are increasing in the future except for the SSP1 scenario
- The mortality burden increases were mainly driven by the population aging in China
- The O_3 mortality burden per capita, are inequitably distributed, with more severe effects in developed regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Chen, X., Jiang, Z., Shen, Y., Wang, S., Shindell, D., & Zhang, Y. (2024). Ozone mortality burden changes driven by population aging and regional inequity in China in 2013–2050. *GeoHealth*, *8*, e2024GH001058. https://doi.org/10.1029/2024GH001058

Received 31 MAR 2024
Accepted 10 JUL 2024

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Abstract Air pollution exposure is closely linked to population age and socioeconomic status. Population aging and imbalance in regional economy are thus anticipated to have important implications on ozone (O_3)-related health impacts. Here we provide a driver analysis for O_3 mortality burden due to respiratory disease in China over 2013–2050 driven by population aging and regional inequity. Unexpectedly, we find that population aging is estimated to result in dramatic rises in annual O_3 mortality burden in China; by 56, 101–137, and 298–485 thousand over the periods 2013–2020, 2020–2030, and 2030–2050, respectively. This reflects the exponential rise in baseline mortality rates with increasing age. The aging-induced mortality burden rise in 2030–2050 is surprisingly large, as it is comparable to the net national mortality burden due to O_3 exposure in 2030 (359–399 thousand yr^{-1}). The health impacts of O_3 pollution, shown as mortality burden per capita, are inequitably distributed, with more severe effects in less developed provinces than their developed counterparts by 23.1% and 21.5% in 2019 and 2030, respectively. However, the regional inequity in O_3 mortality burden is expected to be mitigated in 2050. This temporal variation reflects evolving demographic dividend characterized by a larger proportion of younger individuals in developed regions. These findings are critical for targeted improvement of healthcare services to ensure the sustainability of social development.

Plain Language Summary Air pollution exposure is closely linked to the age distribution and socioeconomic status of the population. The ongoing process of population aging and the pronounced disparities in regional economic growth across China are thus anticipated to have substantial implications for the health effects stemming from ozone (O_3) exposure. Our finding reveals that population aging is projected to lead to a significant upsurge in annual O_3 mortality burden; the health impacts of O_3 pollution, measured in terms of mortality burden per capita, exhibit significant disparities, with more severe effects in less developed provinces than their developed counterparts. These results hold critical implications for the targeted improvement of healthcare services, ensuring the sustainable development of society in China over the coming decades.

1. Introduction

Long-term exposure to ambient ozone (O_3) is associated with increased risk of respiratory mortality (Jerrett et al., 2009; Turner et al., 2016). The increase in O_3 pollution in China (X. Chen et al., 2021; Li et al., 2019; Zhu et al., 2023) has resulted in rapid rises in annual O_3-related premature deaths, ranging from 48.8 to 84.6 thousand yr^{-1} (L. Chen et al., 2023; Xiao et al., 2022). Previous studies have indicated that elderly people are more susceptible to air pollution exposure, implying a possible disproportion increases over recent years depending on the O_3 metrics used and period analyzed (Beard et al., 2016; Ding et al., 2019). Global modeling studies have shown the important impacts of the shifting in age structure on fine particle ($PM_{2.5}$) related mortality burden (Southerland et al., 2022; H. Yin et al., 2021). Several studies have also been carried out in China with similar conclusions drawn (Niu et al., 2022; S. Yin, 2022; Yue et al., 2020). Aging has been an emerging societal issue in China, with 18.7% of the total population over 60 years old in 2020 (approximately 264 million) (NBS, 2021), with this expected to continue to evolve to 26.7% (approximately 400 million) in 2030 and 36.7% (approximately 500 million) in 2050 (Y. Chen et al., 2020). However, less attention has been paid to the effects of aging on O_3-related health impacts due to respiratory disease in China, except for one recent study that evaluated the

Writing – review & editing:
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contribution of different factors including aging on the O_3-related mortality from 2013 to 2030 (L. Chen et al., 2023).

Air pollution exposure is influenced by the socioeconomic status of populations. Recent studies have demonstrated disproportionately high exposure to $PM_{2.5}$ for lower-income population groups in the United States (Colmer et al., 2020; Jbaily et al., 2022). Similarly, Huang et al. (2019) found that populations with lower socioeconomic status encountered more severe $PM_{2.5}$ pollution in Beijing, China; and L. Liu (2019) indicated a higher mortality burden in rural than urban residents in China in 2002–2015 because of discrepancies in economic conditions and $PM_{2.5}$ exposure. However, few studies focus on the effects of population socioeconomic status on O_3-related health impacts. Furthermore, beyond the economic condition of individual people, residents in developed and less developed provinces in China, as a whole, may experience inequity in socioeconomic status, and this inequity could be modulated by the migration of population between developed and less developed regions (Zhan et al., 2021). This prompts the question if the imbalance in regional economic growth results in an inequity in O_3 mortality burdens between residents in developed and less developed provinces in China.

In this study, we aim to estimate the O_3-related mortality burden changes due to respiratory disease in China in both historical (2013–2020) and future periods (2020–2050), and distinguish the contributions from changes in population magnitude, aging, O_3 concentration and baseline mortality rates. We also discuss the changes in regional inequity in O_3 health impacts between developed and less developed provinces during the same period. The O_3 mortality burden changes from 2013 to 2020 are first assessed by combining data fusion surface O_3 concentration data (Xiao et al., 2022; Xue et al., 2020), provincial age-specific baseline mortality rates (Zhou et al., 2016) and population data at high spatiotemporal resolution. The future O_3 mortality burden changes from 2020 to 2050 are then evaluated by considering both population and O_3 concentration changes under four shared socioeconomic pathways (SSP) scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6) projections. Changes in future baseline mortality rates are also considered. The analysis undertaken in this work provides critical insights into how population aging and regional inequity contribute to O_3 mortality burden changes, which is important to ensure the sustainability of social development in China.

2. Methods

2.1. Ozone Concentration Data

High-resolution maximum daily 8h average (MDA8) O_3 concentrations during 2013–2020 over China are provided by the Tracking Air Pollution in China (TAP) platform (http://tapdata.org.cn/), which fuses ground and satellite measurements, chemical transport model simulations, meteorology fields, and land-use information with multilayer machine learning models (Xiao et al., 2022; Xue et al., 2020). The TAP O_3 data set has a horizontal resolution of $0.1° \times 0.1°$ with complete spatiotemporal coverage and good consistency by comparison with in-situ observations and model simulations. Future O_3 concentrations are taken from the CMIP6 UKESM1-0-LL model simulations (https://esgf-node.llnl.gov/search/cmip6/) under different SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) as UKESM1-0-LL model includes hourly surface O_3 concentrations and full coverage over 2015–2050 under different SSP scenarios. All available ensembles (Table S4, see Supporting Information S1) from the UKESM1-0-LL model have been included in the study. We use the 10-year mean O_3 concentrations to represent the projected O_3 concentrations in 2030 and 2050, for example, the mean MDA8 O_3 concentration during 2025–2034 is used to represent the O_3 concentration in 2030 (Figure S3, see Supporting Information S1).

Following Wang et al. (2024), the future CMIP6 model O_3 data was corrected by using the relative changes to the TAP data in the baseline period:

$$O_{3\,\mathrm{Future}}^{\mathrm{Calibrated}} = O_{3\,\mathrm{Baseline}}^{\mathrm{TAP}} + O_{3\,\mathrm{Baseline}}^{\mathrm{TAP}} \times \left[\frac{O_{3\,\mathrm{Future}}^{\mathrm{Model}} - O_{3\,\mathrm{Baseline}}^{\mathrm{Model}}}{O_{3\,\mathrm{Baseline}}^{\mathrm{Model}}}\right] \tag{1}$$

where $O_{3\,\mathrm{Future}}^{\mathrm{Calibrated}}$ represents the future O_3 concentration after calibration; $O_{3\,\mathrm{Baseline}}^{\mathrm{TAP}}$ represents the TAP O_3 during the baseline period (2019); $O_{3\,\mathrm{Baseline}}^{\mathrm{Model}}$ represents the O_3 concentration from CMIP6 models during the baseline period (2015−2019); and $O_{3\,\mathrm{Future}}^{\mathrm{Model}}$ represents the CMIP6 model-derived O_3 concentration in the future. The spatial distribution of O_3 concentration after the correction can be seen in Figure S4 of Supporting Information S1, which demonstrates a good consistency with the observations. The future O_3 data are regridded to $0.1° \times 0.1°$ to match the resolution of other data sets.

2.2. Population Data

We use provincial grid-based population data at 30 arc-seconds spatial resolution from 2010 to 2100, which considered fertility-promoting policies and population ceiling restrictions of megacities under different SSPs. The population data were obtained at https://doi.org/10.6084/m9.figshare.c.4605713.v1 and were regridded to $0.1° \times 0.1°$ resolution to maintain consistency with the O_3 data. The provincial age-specific grid-based population with a 5-year interval from 25 years old to age >95 years old (i.e., 25–29, 30–34, …, 80–84, 95+) was generated by:

$$\text{Pop}_{i,j,\text{yr},a,\text{pro}} = \text{Pop}_{i,j,\text{yr},\text{pro}} \times \frac{\text{Pop}_{\text{yr},a,\text{pro}}}{\text{Pop}_{\text{yr},\text{pro}}} \tag{2}$$

where $\text{Pop}_{i,j,\text{yr},a,\text{pro}}$ is the age-specific population in each grid; $\text{Pop}_{i,j,\text{yr},\text{pro}}$ is the total population in each grid; and the factor $\frac{\text{Pop}_{\text{yr},a,\text{pro}}}{\text{Pop}_{\text{yr},\text{pro}}}$ represents age structure. The population data were evaluated by comparison with other population data, such as WorldPop and Gridded Population of the World v4 (Y. Chen et al., 2020). The population data over 2030 and 2050 are calculated based on corresponding future scenarios (SSP1-2.6, SSP2-4.5, SSP3-6.0, SSP5-8.5).

2.3. Baseline Mortality Rate

Annual national age-specific baseline mortality rate data of chronic obstructive pulmonary disease (COPD) from 2013 to 2019 were obtained from the Global Burden of Disease (GBD) database (https://vizhub.healthdata.org/gbd-results/). Provincial baseline mortality rates are variable among different provinces due to different socioeconomic, geographic and climatic differences (S. Yin, 2022). The baseline mortality rates at the province level are only available in 2013 (Zhou et al., 2016). We derive the annual age-specific baseline mortality rates at the province level in China for each year following S. Yin (2022):

$$y_{0\,\text{yr},a,\text{prov}} = \frac{\text{ZBM}_{\text{prov}}}{\text{ZBM}_{\text{nation}}} \times \text{GBM}_{\text{yr},a,\text{nation}} \tag{3}$$

where $y_{0\,\text{yr},a,\text{prov}}$ is the baseline mortality rate of COPD for age group (a) in a year (yr) for a province (prov); ZBM_{prov} and $\text{ZBM}_{\text{nation}}$ are age-standardized mortality rates of COPD for the province (prov) and nation, respectively, obtained from Zhou et al. (2016); and $\text{GBM}_{\text{yr,a,nation}}$ is the annual baseline mortality rate for age group (a) of COPD in China obtained from the GBD data set.

The data of future baseline mortality rates are obtained from International Futures (IFs) model version 7.89 basic scenario prediction (http://pardee.du.edu/access-ifs). The IFs data includes specific death rates for each disease up to 2100. The annual age-specific baseline mortality rates at the national level in China in 2030 and 2050 are calculated as:

$$\text{IF\_BM}_{\text{yr},a,\text{nation}} = \frac{\text{IF\_BM}_{\text{yr},\text{nation}}}{\text{IF\_BM}_{2019,\text{nation}}} \times \text{GBM}_{2019,a,\text{nation}} \tag{4}$$

where $\text{IF\_BM}_{2019,\text{nation}}$ and $\text{IF\_BM}_{\text{yr},\text{nation}}$ are IF's age-standardized baseline mortality rate in 2019 and in years 2030 and 2050 (yr), respectively. $\text{GBM}_{2019,a,\text{nation}}$ is GBD's age-standardized baseline mortality rate in 2019. The age-specific baseline mortality data in 2030 and 2050 are then obtained by using Equation 3.

2.4. Health Impact Assessment for Long-Term Ozone Exposure

To estimate the premature respiratory mortality attributable to long-term O_3 exposure, we apply the relative risk from various epidemiological studies, baseline mortality rates, population, and exposure concentrations as follows:

$$\mathrm{Mort}_{\mathrm{yr}} = \sum_{a} \left[y_{0\ \mathrm{yr},a} \times \mathrm{AF} \times \left(\mathrm{Pop}_{\mathrm{yr}} \times \mathrm{Age}P_{\mathrm{yr},a} \right) \right] \tag{5}$$

where $\mathrm{Mort}_{\mathrm{yr}}$ is the mortality burden attributed to long-term O_3 exposure in that year, $\mathrm{Pop}_{\mathrm{yr}}$ is the exposed population with ages greater than 25 years old, and $\mathrm{Age}P_{\mathrm{yr},a}$ is the proportion of the population with age group a. $y_{0\ \mathrm{yr},a}$ is the baseline mortality rate of COPD. AF is the attribution fraction of mortality associated with air pollution exposure, which is defined as $1 - \frac{1}{\mathrm{RR}}$ (RR signifies relative risk). The RR for long-term O_3 exposure is retrieved from Turner et al. (2016), which reports an RR of 1.12 (95% confidence interval (CI): 1.08, 1.16) for respiratory disease, and the theoretical minimum risk exposure level for O_3 exposure assessment is 26.7 ppb. Exposure-response functions play a crucial role in health impact assessment. Therefore, we also conducted sensitivity analyses by using Chinese population-based exposure-response functions, which report an RR of 1.093 (95% CI: 1.046−1.142) and 1.18 (95% CI: 1.13−1.23) for cardiovascular disease (CVD) and all-causes (Niu et al., 2022; Yuan et al., 2023). The theoretical minimum risk exposure level for O_3 exposure assessment is 82 and 110 $\mu g/m^3$, respectively. In addition, to evaluate the individual contributions of four factors (population growth, age structure, baseline mortality rate and O_3 concentration), we performed the decomposition analysis (Yue et al., 2020), as shown in Figure S1 of Supporting Information S1. The difference between each consecutive step provides an estimate of the relative contribution of each factor. Then we used the same method recalculate in reverse, and finally obtained the average relative contribution of each factor.

3. Results and Discussion

3.1. O_3-Related Mortality Burden Changes in 2013–2020

Figure 1 shows the spatial and temporal changes in O_3 mortality burden in China from 2013 to 2020. The average mortality burden is higher in Sichuan, Shandong, Henan, Jiangsu and Guangdong provinces (Figure 1a) by more than 10 thousand yr^{-1} (Table S1, see Supporting Information S1) due to dense population density and high O_3 concentrations (Figure S2 in Supporting Information S1). Figure 1b further shows the spatial changes in mortality burden from 2013 to 2020. Seven provinces demonstrated stronger rises in annual mortality burden by more than 3 thousand in 2013–2020 (Table S2, see Supporting Information S1): Shandong, Henan, Jiangsu, Anhui, Sichuan, Gansu and Guangdong. The national O_3 mortality burden, as shown in Figure 1c, rose from 161 thousand yr^{-1} (95% CI: 112–205) in 2013 to 240 thousand yr^{-1} (95% CI: 169–303) in 2020. We find good agreement between our analysis with L. Chen et al. (2023). For example, the mean mortality burdens are 183 and 176 thousand yr^{-1}, and the increases in annual mortality burden are 80 and 85 thousand in 2013–2019 in our analysis and L. Chen et al. (2023), respectively. There are noticeable differences in magnitude as well as the trend after 2017 between our study and the GBD2019, which are partially associated with the different estimate indicators, such as population, baseline mortality rates, and ozone data sets (Seltzer et al., 2018). Additionally, the population-weighted O_3 changes with a 0.6 ppb drop in 2013–2019 in the GBD2019 (2020). Although the estimation in our study is much higher than the GBD2019, the derived O_3 mortality burden in our analysis could still be underestimated due to the lack of consideration of the important effect of CVD. As shown in Figure S5 of Supporting Information S1, the mean mortality burdens are 882 and 907 thousand yr^{-1} in 2013–2019 by using Chinese population-based CVD and all-causes exposure-response model, compared with 183 thousand yr^{-1} by using U.S. population-based respiratory exposure-response model.

As shown in Figure 2 (in 2013–2020), the population increased by 4.7% from 1.36 to 1.42 billion; the population over 60 years old increased by 23.8% from 15.1% to 18.7% of the total; the age-standardized baseline mortality rate decreased by 21.4% from 83.65 to 65.73 (per 100 thousand population); and the population-weighted O_3 increased by 15% from 40.78 to 47.58 ppb in 2013–2020. The contributions of individual factors to mortality burden changes are then decomposed as described in the methods. As shown in Figure 3a, the changes in O_3 concentrations and population age structure resulted in increases of 59 and 56 thousand annual premature deaths over the entire period 2013 to 2020, respectively; the change in population magnitude had a smaller impact on annual mortality burden, increasing it by 9 thousand; and the change in baseline mortality rate led to a decrease in annual mortality burden by 45 thousand over this time. At the provincial level (Figures 3b–3e and Table S2 in Supporting Information S1), changes in age structure resulted in increases in annual mortality burden by more than 8 thousand in Sichuan province and by 3–4 thousand in the provinces of Henan, Shandong, Hubei and Jiangsu; changes in baseline mortality rate led to decreases in annual mortalities by more than 6 thousand in the

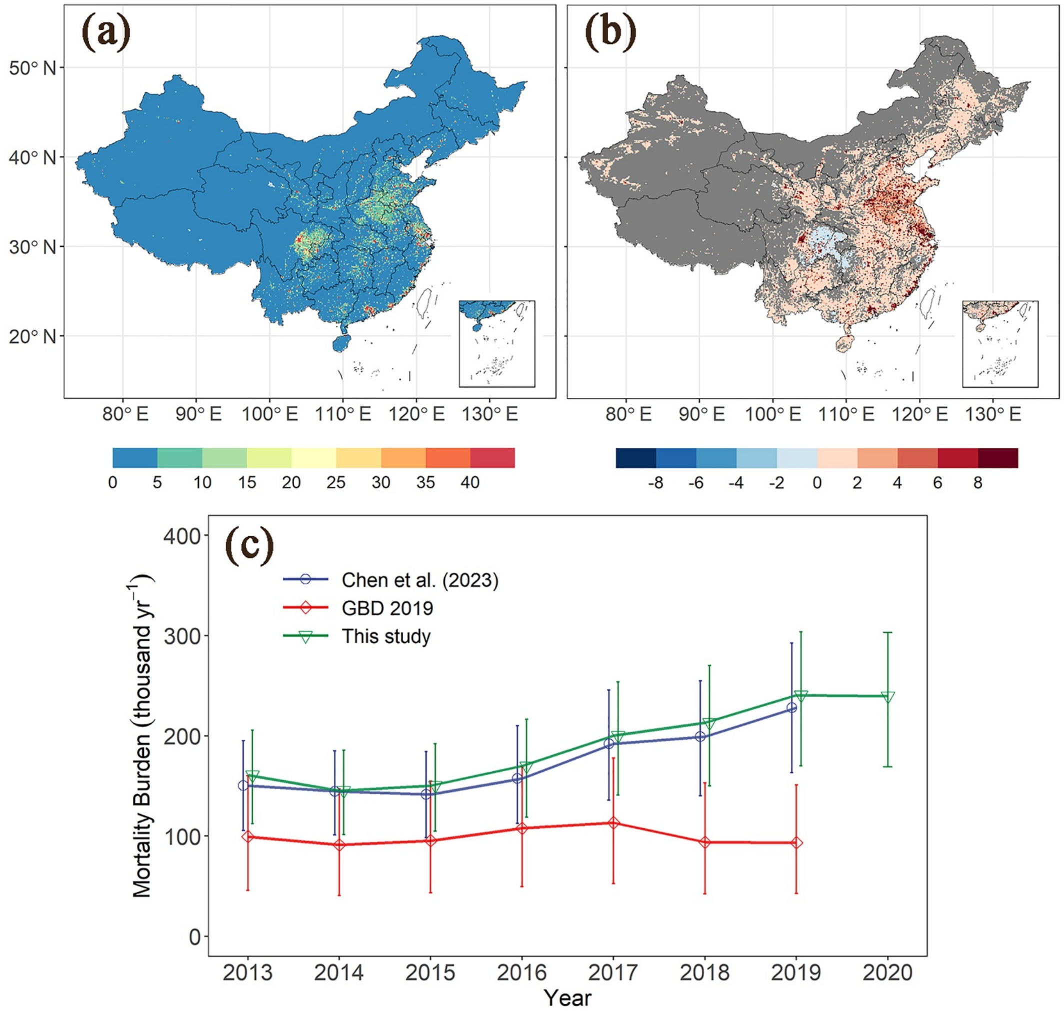

Figure 1. Spatial patterns of O_3-related mortality burden (unit: thousand yr^{-1}) in 2013–2020 for (a) multi-year average, (b) the difference between 2013 and 2020, (c) national total from our studies and two other studies from L. Chen et al. (2023), and GBD2019 results. The error bars are the 95% confidence interval.

Sichuan province and by 3–4 thousand in the provinces of Henan, Shandong and Jiangsu; and changes in O_3 concentrations resulted in increases in annual mortality burden by more than 4 thousand in the provinces of Shandong, Jiangsu, Henan and Anhui.

3.2. Projected Changes in Mortality Burden in 2020–2030

As shown in Figure 2, we expect a slowed rate of decrease in the age-standardized baseline mortality rate in 2020–2030, that is, a decrease by approximately 8.1% from 65.73 to 60.82 (per 100 thousand population) over 2020–2030; in contrast, the population over 60 years old is expected to increase rapidly, by approximately 38.0%–46.5% from 18.7% to 25.8%–27.4% over 2020–2030. The 10-year mean O_3 concentrations from CMIP6 Model (see Table S4 in Supporting Information S1 for details) are adopted in our analysis to represent O_3 concentrations in the future (Griffiths et al., 2021) to reduce the possible uncertainty and bias in the analysis. As shown in Figure 2c, the projected population-weighted O_3 concentrations are 49.3, 49.9, 49.7 and 51.7 ppb in 2030 in SSP1-2.6 (strong climate change mitigation scenario), SSP2-4.5 (middle-of-the-road scenario), SSP3-7.0 and SSP5-8.5 (weak climate change mitigation scenarios, though SSP3-7.0 includes substantial air pollution mitigation), respectively.

Figure 4 shows the projected changes in mortality burden due to O_3 exposure and the contributions from individual factors under different SSP scenarios. Comparing annual values in 2030 with those in 2020, the changes in

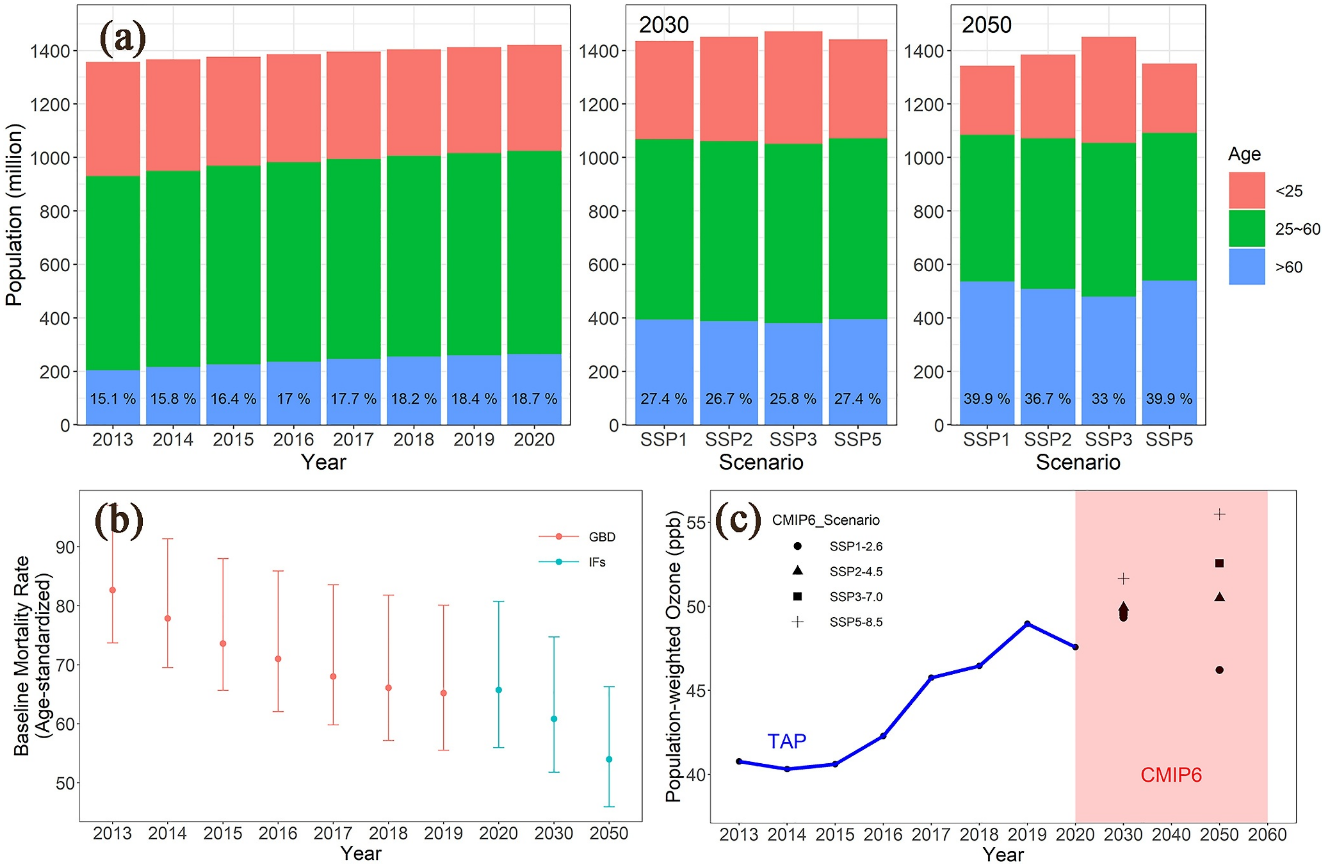

Figure 2. The time series changes of (a) historical population and age structures from 2013 to 2020 and future population and age structures in 2030 and 2050 under the four different SSPs scenarios; (b) annual age-standardized baseline mortality rate from 2013 to 2019 from the Global Burden of Disease, and the future (2030 and 2050) from International Future; (c) population-weighted O_3 concentration in 2013–2050, which includes ensemble model mean for future results.

age structure, O_3 concentrations and population magnitude are suggested to result in increases in annual mortality burden by 101–137, 12–43 and 4–11 thousand, respectively, and the changes in the baseline mortality rate can lead to a decrease in the annual mortality by 23–24 thousand. The slower decline in baseline mortality rates (−8.1%) is unable to offset the combination of changes in population aging (38.0%–46.5%) and O_3 concentrations (3.7%–8.6%), which results in rises in projected annual mortality burden from 240 to 359–399 thousand over 2020–2030. We find broad consistency between our analysis and recent studies; for example, the contributions from population aging are 101–137 thousand (2020–2030) in our analysis, compared with 138–160 thousand (2019–2030) in L. Chen et al. (2023). There are differences in the contributions from baseline mortality rate and O_3 concentrations, which could be associated with the different CMIP6 models between these analyses as well as the discrepancy in the baseline mortality rate data, for example, province-based data in this work and national-averaged data in L. Chen et al. (2023), which may affect the derived health impacts (Southerland et al., 2022).

It should be noted that the annual mortality burden from 2020 to 2030 will continue to increase by 12 thousand even though the national population-weighted O_3 concentration is lowest under the SSP1-2.6 scenario (Figure 2c). This is caused by the projected increase in O_3 concentrations in western China (Figure S8f, see Supporting Information S1) accompanied by higher baseline mortality rates. The disproportional O_3 changes in eastern and western China are consistent among all the SSPs in 2030 (Figure S8f in Supporting Information S1), contributing to the significant annual mortality burden changes from O_3 concentration only, ranging from 12 thousand in SSP1-26 to 43 thousand in SSP5-8.5 respectively (Figure 4).

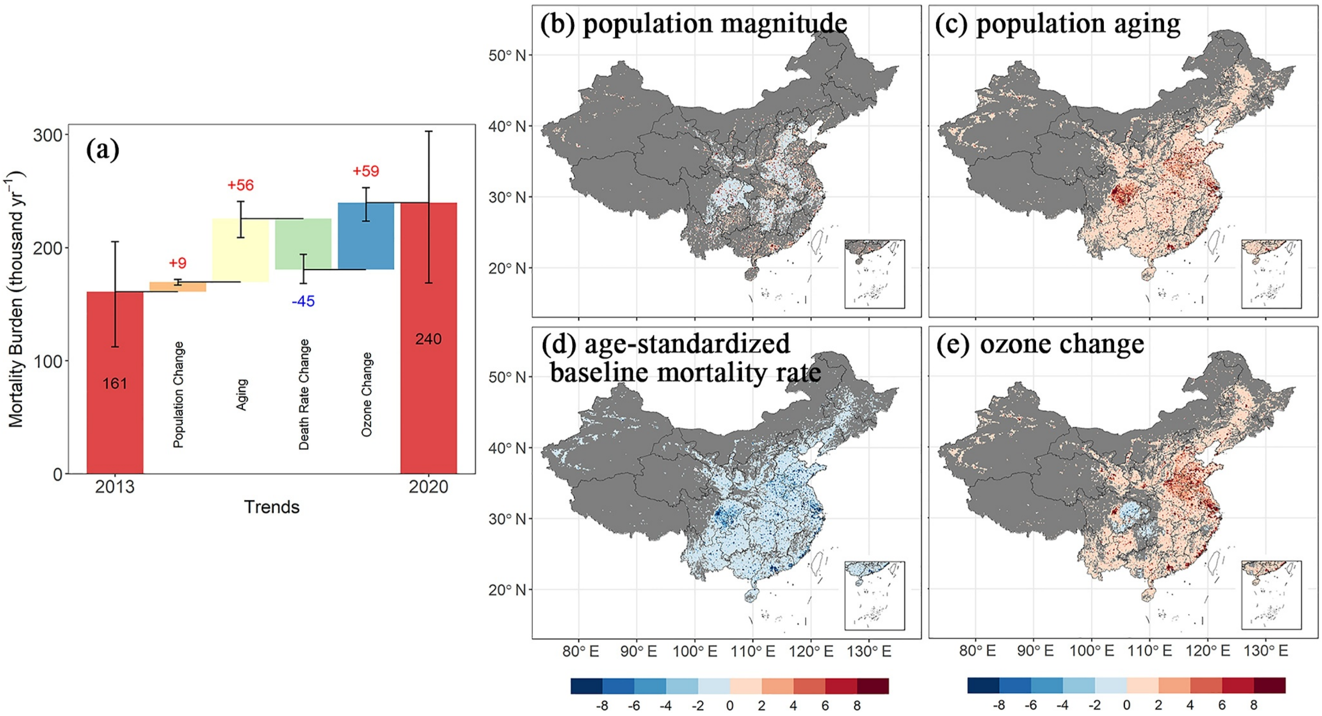

Figure 3. The changes in O_3-related mortality burden (a), and the contributions from changes in (b) population magnitude, (c) population aging, (d) age-standardized baseline mortality rate, and (d) O_3 concentration in 2013–2020.

3.3. Exponential Rise in Mortality Burden Driven by Population Aging

The population over 60 years old is expected to increase by 27.9%–45.6% in China from 25.8% to 27.4% in 2030 to 33.0%–39.9% in 2050. People may thus assume a comparable increase in the aging-induced mortality burden in 2030–2050 to that in 2020–2030. However, as shown in Figure 4, the aging-induced annual mortality burden increase is 298–485 thousand over 2030–2050, which is higher than the aging-induced annual mortality burden increase in 2020–2030 (i.e., 101–137 thousand) by approximately 200%–300%. The increase in aging-induced mortality burden in 2030–2050 is surprising, as it is comparable with the net national mortality burden due to O_3 exposure in 2030 (359–399 thousand yr^{-1}) and is 25%–100% higher than that in 2020 (240 thousand yr^{-1}). The exponential rise in aging-induced annual mortality burden, that is, 56, 101–137 and 298–485 thousand in response to changes in population aging by 23.8%, 38.0%–46.5% and 27.9%–45.6% in 2013–2020, 2020–2030, and 2030–2050, respectively, reflects the exponential rise in the baseline mortality rate with increasing age: the baseline mortality rate (per 100 thousand population) increases exponentially from 70 in 60–64 years old to 381 in 70–74 years old and 1592 in 80–84 years old (Figure S6, see Supporting Information S1). The accumulated intensification in population aging and the shift of the age structure to a more elderly population is thus finally resulting in the increase of O_3-related mortality in 2030–2050.

Furthermore, as shown in Figure 2, the age-standardized baseline mortality rate is expected to decrease by 11.3% from 60.8 to 54.0 (per 100 thousand population) in 2030–2050, and the projected population-weighted O_3 concentrations are 46.2, 50.5, 52.6 and 55.5 ppb (Table S4 in Supporting Information S1) in 2050 under different scenarios. Change in O_3 concentrations in 2030–2050 is thus suggested to result in a decrease in annual mortality burden by 86 and 7 thousand under SSP1-2.6 and SSP2-4.5, an increase in the annual mortality burden by 51–73 thousand under other scenarios; change in population can lead to a decrease in annual mortality by 7–42 thousand; and change in the baseline mortality rate can lead to a decrease in annual mortality by 59–73 thousand. The national mortality burden due to O_3 exposure can reach 569–842 thousand yr^{-1} in 2050 driven by the rapid population aging, which is approximately 60%–110% higher than the national mortality burden in 2030 and 150%–250% higher than that in 2020. It should be noted that the projected mortality under SSP1-2.6 (strong-mitigation scenario) is expected to be 10.2%–48.0% lower than those in other scenarios because of the expected decrease in O_3 concentrations under SSP1-2.6.

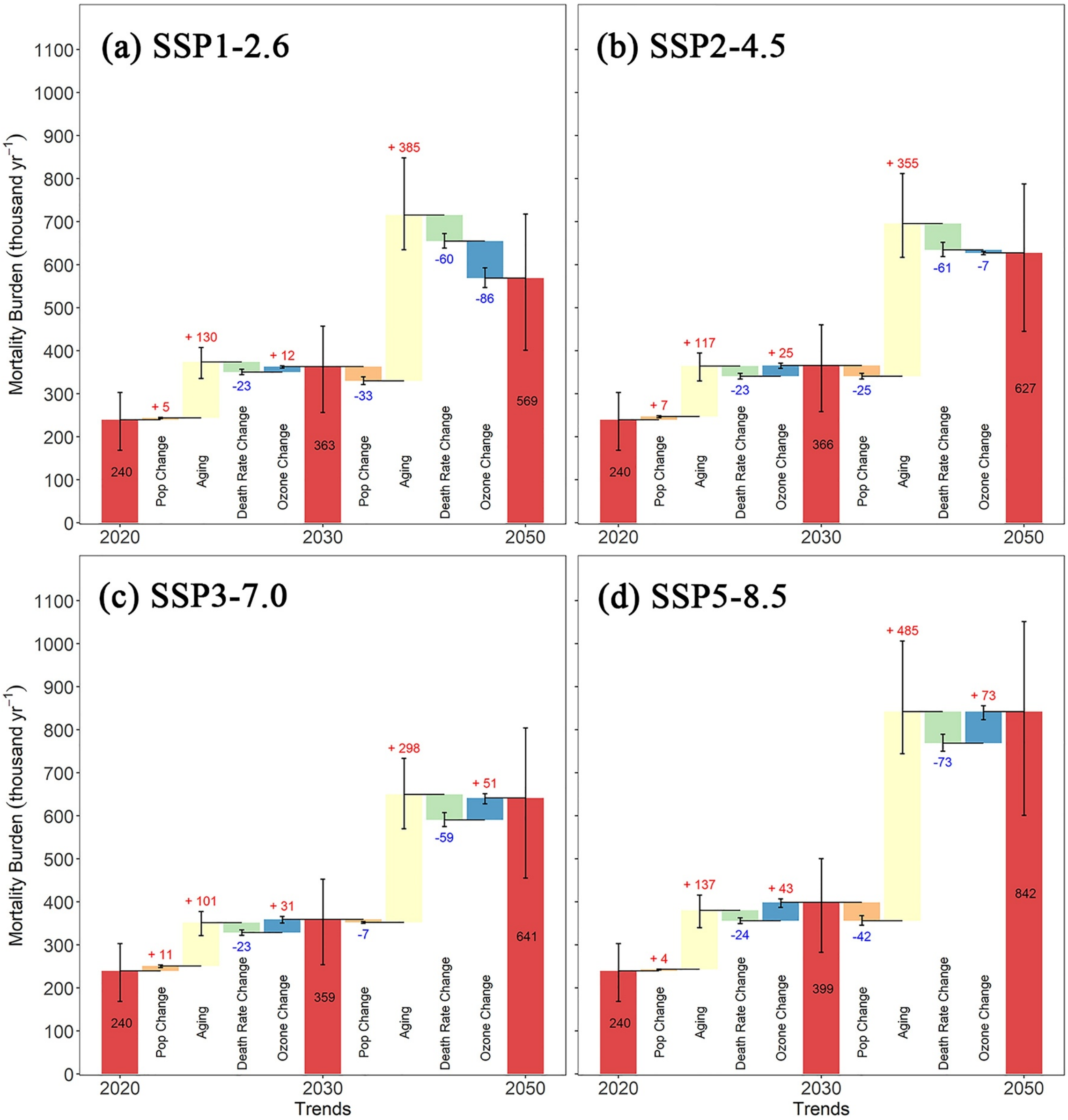

Figure 4. Changes in O_3-related mortality burdens and the contributions from population magnitude, population aging, age-standardized baseline mortality rate and O_3 concentrations in 2020–2030 and 2030–2050 for the four different SSPs (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP3-7.0, and (d) SSP5-8.5.

3.4. Regional Inequity in Mortality Burden in 2013–2050

Finally, we evaluate the regional inequity in O_3 mortality burden between residents in developed and less developed provinces. The provinces with the top 20% of Gross Domestic Product (GDP) per capita in 2013 are defined as the developed provinces, which include Beijing, Shanghai, Jiangsu, Tianjin, Zhejiang, Fujian, Guangdong, and the remaining 24 provinces (excluding Taiwan, Hong Kong and Macau) are defined as less developed provinces. There is a negative correlation between mortality rate and GDP in 2013 and 2019 (Figure S10, see Supporting Information S1). As shown in Figure 5a, the average mortality rates of different scenarios (per 100 thousand population) are 14.9, 20.2, 30.2 and 63.0 in the developed provinces, and 18.1, 24.9, 36.7 and 62.0 in less developed provinces in 2013, 2019, 2030, and 2050, respectively. The average mortality rates in less developed provinces are higher than those in the developed provinces by approximately 21.5%, 23.1% and 21.5% in 2013, 2019, and 2030, respectively. It is partially associated with inequity in medical conditions; for example,

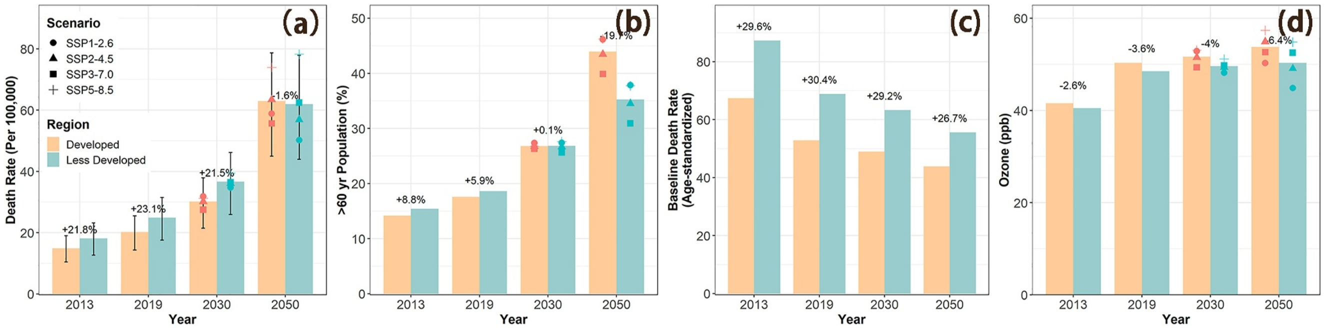

Figure 5. (a) O_3-related mortality rate; (b) population aging (i.e., population over 60 years old); (c) age-standardized baseline mortality rate; and (d) population-weighted O_3 concentrations in 2013, 2019, 2030, and 2050 in the developed and less developed provinces. The values on top of the column are the differences between developed and less developed provinces.

the baseline mortality rate in less developed provinces is higher than that in the developed provinces by approximately 30% (Figure 5c).

However, the regional inequity in O_3 mortality burden is expected to be mitigated from 21.5% in 2030 to −1.6% in 2030–2050. As shown in Figure 5b, the population over 60 years old are expected to be 14.2%, 17.6%, 26.8%, and 43.9% in developed provinces, and 15.4%, 18.6%, 26.8% and 35.3% in less developed provinces in 2013, 2019, 2030, and 2050, respectively. The temporal variability in the population over 60 years reflects the evolution of the demographic dividend in the developed regions, that is, young people are expected to flow into developed regions, which leaves more severe population aging issues in less developed regions in 2013–2019; in contrast, slower population mitigation and better medical conditions are expected to result in the fading of the demographic dividend and more severe population aging issues in developed regions by 2050 (Figure S7, see Supporting Information S1). Furthermore, the O_3 concentrations in less developed provinces is 6.4% lower than that in developed provinces in 2050. Consequently, the lower proportion of population over 60 years old (−19.7%) and O_3 concentrations (−6.4%) in less developed provinces offset the higher baseline mortality rates (26.7%), alleviating regional inequity compared to developed provinces in 2050.

4. Conclusion

The deterioration in O_3 pollution poses significant risks to human health in China. There is currently much effort focused on O_3-related health impacts in China (L. Chen et al., 2023; Dang & Liao, 2019; H. Liu et al., 2018; Lu et al., 2020; Yao et al., 2023; Zhang et al., 2021). Our work estimates an average of 190 (95% CI: 133–241) thousand O_3-related annual premature deaths in China during 2013–2020 and an increase of 79 (95% CI: 57–98) thousand from start to end of 2013–2020 due to respiratory disease, consistent with previous findings. However, given the large population (more than 1.4 billion) and continuous or even accelerating population aging in China it is critical to evaluate the long-term effects of population aging on O_3 health impacts. Furthermore, the imbalance in economic growth may result in inequity in socioeconomic status for residents in the developed and less developed provinces in China. A better understanding of regional inequity in O_3 health impacts between developed and less developed provinces is important for making effective environmental regulation and public health policies targeting the following decades.

To our knowledge, we show for the first time that the accumulated intensification in population aging and the shift of age structure to the more elderly population can result in an exponential rise in the O_3-related mortality burden in China. The increases in aging-induced annual mortality burden are estimated to be 56, 101–137 and 298–485 thousand in response to changes in the population aging by 23.8%, 38.0%–46.5%, and 27.9%–45.6% over the intervals 2013–2020, 2020–2030, and 2030–2050, respectively, reflecting the exponential rise in baseline mortality rate with the increase in age. The increase in the aging-induced mortality burden in China in 2030–2050 is surprising, as it is comparable with the net national mortality burden due to O_3 exposure in 2030 (359–399 thousand yr^{-1}) and is approximately 25%–100% higher than that in 2020 (240 thousand yr^{-1}). The national mortality burden due to O_3 exposure can reach 589–842 thousand yr^{-1} in 2050 driven by the rapid population aging, which is approximately 60%–110% higher than that in 2030 and 150%–250% higher than that in 2020. Furthermore, we find a noticeable inequity in O_3 health impacts between the developed and less developed provinces. The average mortality rates in less developed provinces are higher than those in the developed provinces by approximately 21.8%, 23.1% and 21.5% in 2013, 2019, and 2030, respectively, caused by the inequity in medical conditions (i.e., baseline mortality rate) and evolutions in age structure associated with the migration of population between developed and less developed regions. However, the regional inequity in O_3 mortality burden is expected to be mitigated from 21.5% in 2030 to −1.6% in 2030–2050 because of the projected more severe population aging in the developed provinces.

While our analysis predicts a dramatic rise in mortality burden driven by population aging, this is in part attributable to beneficial projected increases in longevity. Nevertheless, control in O_3 concentrations provide an effective pathway to mitigate the O_3-related health impacts; for example, the projected mortality under SSP1-2.6 (strong mitigation scenario) is suggested to be 10.2%–48.0% lower than those in other scenarios because of lower O_3 concentrations. In addition, it may be important to strengthen health services, particularly for older populations in less developed regions, by 2030 because of the enhanced regional inequity in O_3 health impacts due to more severe population aging; however, additional attention is suggested to the long-term O_3 health impacts in developed regions in 2030–2050 driven by the fading of the demographic dividend and more severe population aging issues in developed regions. Stricter controls in O_3 precursor emissions as well as targeted improvement of healthcare services are important to mitigate the O_3 health impacts, which are critical to ensure the sustainability of social development in China in the following decades.

Finally, it should be noted that our study is affected by limitations, such as uncertainties in population, age structure, baseline disease mortality rates as well as the potential downscaling errors due to the coarse resolution of the CMIP O_3 data. In addition, due to factors like different study populations, population characteristics, and causes of deaths considered, exposure-response functions can play a crucial role in health impact assessment. For example, the mean mortality burdens are 882 and 907 thousand yr^{-1} in 2013–2019 by using Chinese population-based CVD and all-causes exposure-response models, compared with 183 thousand yr^{-1} by using the U.S. population-based respiratory exposure-response model. This work thus advises more efforts to investigate the sources of this discrepancy, which is critical for a more accurate estimation of O_3 health impacts and its future projection.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The historical and future O_3 concentrations data can be downloaded from the Tracking Air Pollution in China platform (TAP, 2024) and Coupled Model Intercomparison Project Phase 6 projections (CMIP6, 2024). The analysis is supported by population data (Y. Chen et al., 2020). The historical baseline mortality rates can be downloaded from the GBD database (GBD, 2024), and the future predicted mortality rates can be downloaded from the International Futures model version 7.89 basic scenario prediction (IFs, 2024).

Acknowledgments
This work was supported by the Postdoctoral Fellowship Program of CPSF (GZC20232514) and the National Natural Science Foundation of China (42277082).

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