An Aging Giant At The Center of Global Warming: Population Dynamics and Its Effect on CO_2 Emissions in China

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Abstract

Managing the aging crisis and mitigating CO_2 emissions are currently two great challenges faced by China. Revealing the complex correlation between aging and CO_2, and projecting their future dynamics are fundamentally necessary to inform effective strategies and policies toward a low-carbon and sustainable development in China. In this paper, we quantitatively investigated the impacts of population aging, economy, and energy intensity on CO_2 emissions through a STIRPAT model based on balanced provincial panel data from 1995-2019, and employed a cohort model and scenario analysis to project the demographic change and CO_2 emissions till 2050. It is found that CO_2 emissions in China has witnessed a significant growth during 1995-2019, and will exhibit an inverted U-shaped growth till 2050 with its peak appears between 2030-2040. Every 1% increase of aging will exert a 0.69% emission of CO_2 in China. However, a big regional difference was also detected as aging contributed to CO_2 reduction in the eastern region, but stimulated CO_2 emissions in the central and western regions. Policy implications for achieving a low-carbon and aging-oriented sustainable development include the integration of aging into the decision-making of industrial structure upgrading and CO_2 emission reduction in both national and region levels, the promotion of the further transition to low-carbon consumption and green products in the eastern region, and strengthening the deep fusion of aging-oriented industries with local resource and environmental endowment in the central and western regions such as the development of eco-agriculture and green pension industries.

1. Introduction

Rapid growth and aging of population have been observed all over the world[1]. It has been recognized that such substantial changes in both the size and composition of population have posed significant impacts on global warming [2,3]. However, the question whether the population aging (hereafter aging) will stimulate or reduce energy consumption and CO_2 emissions has not gained a widely accepted answer[4–8]. The controversy could be largely caused by different methods and variables used for interpretation. Moreover, the overlook of the differences across regions and over different development stages could be another important reason. Many studies have verified that the impacts of human activities on environment vary in different development stages with their changing trajectories exhibit diverse forms, such as U-shaped and inverted U-shaped [5,9–11]. However, it remains underexplored regarding the relationship between aging and climate change. More empirical case studies with in-depth examination are needed to fill our knowledge gap.

China, a double world champion in CO_2 emissions and population, faces more serious challenges in carbon mitigation and population development than any other country does. Since the fast urbanization began in the early 1980s[12,13], China's energy-based CO_2 emission has been soaring unprecedentedly[14]. It jumped by more than 6 times and reached 9.8 billion tons in 2019, accounting for 28.8% of global carbon emissions[15]. As one of the most important driving factors behind, population of China has undergone an astonishing increase with its number swelled from 987 million to 1400 million despite the implementation of “one-child policy”, which aims to limit excessive population growth[16]. Meanwhile, China is becoming older due to extended life expectancy, baby boomer in the 1940s-1950s, and strict population control since the 1980s. As a result, the age structure has been rapidly changing, especially the ratio of elderly people is increasing faster than any other age group with its share doubled from 5% in 1982 to 12.6% in 2019. In 2030, China will likely become the most aged country, and its elder will even be expected to touch 330 million until 2050, or 1/4 of its total population[17]. In sum, as an aging giant at the center of global warming, how China copes with its problems of population and climate change will to a large extent determine the changing paths of world’s demography and CO_2 emissions.

Against this background, it is fundamentally necessary to systematically investigate the interaction between population (including both the size and age composition) and CO_2 emissions in China. Through the empirical analysis of panel data of 29 provinces during the last decades from 1995 to 2019, and scenario analysis of future CO_2 emissions accompanying demographic change till 2050, it will deepen our understanding of how population dynamics affect CO_2 emissions across different regions and development stages, and eventually provide policy implications for addressing the challenges of aging and climate change.

The remaining parts of this paper after the introduction are arranged as follows. The second part is literature review of the impact of population aging on CO_2 emissions. The third part introduces the empirical analysis models and related data. The fourth section provides the model results and policy discussions at both national and regional level. The fifth part draws conclusions.

2. Literature Review

The existing literature concerning the relationship between aging and CO_2 emissions has mainly focused on two questions. One is whether the impact of aging on CO_2 emissions is significant. The other is the mechanism behind the relationship between aging and CO_2 emissions. Table 1 summarizes the recent studies on aging-emission correlation in the last decade with respect to their case study area, research time span, methods, aging-emission correlation, and driving factors of CO_2 emissions. Generally, though some certain studies showed that CO_2 emissions are not significantly correlated to the aging or the age composition[18], most scholars agreed that aging should be taken into consideration when analyzing the drivers of CO_2 emissions[19,20]. However, when it comes to relationship between aging and emission, the results are complex and diversified, such as positively correlated, negatively correlated, U-shaped, and inverted U-shaped relationship. Moreover, due to the data limitation for population structure, CO_2 emissions, and socio-economic driving factors, it is found that most of the case studies are carried out on country or cross-country scales rather than on region or even city scale.

Table 1

Recent studies on aging-CO_2 correlation

Effect	Literature	Region	Methods	Determinant
aging⇨CO_2↑	Liddle& Lung (2010)[21]	17 developed countries	STIRPAT model	aging
transport/residence aging⇨CO_2↓/↑	Liddle (2011)[20]	22 OECD countries	STIRPAT model	aging
aging⇨CO_2↑	Menz& Welsch (2012)[22]	26 OECD countries	KAYA identity and its extended forms	aging
aging⇨CO_2↓ consumption⇨CO2↑	Zhu & Peng (2012)[4]	China	IPAT model	aging, consumption level
aging⇨CO_2 (U-shaped)	Wang & Zhou (2012)[23]	9 countries	KAYA identity	aging, GDP/cap, urbanization rate
nation/region: aging⇨ CO_2↑/↕	Zhang & Tan (2016)[5]	29 provinces in China covering	STIRPAT model	aging
aging⇨CO_2 (inverted U-shaped)	Li et al. (2018)[6]	30 provinces in China	expanded STIRPAT model	aging
aging⇨CO_2↑	Yu et al. (2018)[7]	China	extended STIRPAT model	aging, industrial structure
aging⇨CO_2 (inverted U-shaped)	Wang et al. (2019)[24]	China	dynamic panel method	ageing, urbanization
aging⇨CO_2↓	Yang & Wang (2020)[8]	10 provinces in China	panel threshold model	aging
aging⇨CO_2↓	Kim et al. (2020)[25]	16 provinces in Korean	fully modified ordinary least square	aging

Note: ↑, ↓ means significantly positive or negative correlation; ↕ denotes significant or negative correlation

Effect	Literature	Region	Methods	Determinant
aging⇨CO_2 (nonlinear)	Wang & Li (2021)[26]	154 countries	panel threshold regression	aging, life expectancy
Note: ↑, ↓ means significantly positive or negative correlation; ↕ denotes significant or negative correlation				

Internationally, some studies have reported that aging would increase energy use and generate more CO_2 emissions due to the rise of residential electricity consumption[20,21]. While others held an opposite opinion as they thought aging would slow down the economic growth thus lower the energy consumption and related CO_2 emissions. For example, based on the cross-nation data, Cole et al.[18] and Wang[23] got different results. The former indirectly indicated that the aging would impede emissions since there was a positive correlation between the increased share of age group between 15 and 64 years and CO_2 emissions. The latter suggested that there was an inverted U-curve relationship between CO_2 emissions and aging, since the low energy consumption pattern of aged people reduced CO_2 emissions initially, but the increasing share of elders would increase the expenditure on health care thus stimulated CO_2 emissions. Fan et al.[9] proved that aging and CO_2 emissions had a positive correlation at high income level, but had a negative correlation at other income levels. Based on the data of developed countries, Liddle and Lung[20] concluded that the aged group (65-79 years) prompted CO_2 emissions from residential electricity and other energy consumption, since these elders stay at home longer hence consume more energy. Moreover, Carlsson-Kanayama and Lindén[27] found an inverted-U relationship existed between transport CO_2 emissions and aging because the preference to own and use a car and the distance traveled by car firstly increase and then decrease when the age increases. Liddle[20] explored the impact of the age structure change on CO_2 emissions in OECD countries and found that people over 70 years old emitted less transport CO_2 emissions, but more residential emissions. Similarly Menz and Welsch[22] indicated that people over 60 years in OECD countries inhibited CO_2 emissions though the coefficient was insignificant.

Regarding China's case, the findings varied as well. A number of studies directly or indirectly proved that aging inhibited CO_2 emissions because aging means the decline in labor supply, which hinders the economic development and thus slowed down CO_2 emissions[19,28–30]. This viewpoint was opposite to that of Li et al.[31] and Huang[32], who claimed that aging facilitates residential CO_2 emissions at national level. In addition to linear relationship, some found an inverted U-curve correlation existed between CO_2 emissions and aging at national level[33,34]. The reasons may include the followings. Firstly, at the preliminary stage, aging is mainly caused by the decrease of birth rate and the increase of life expectancy. But the supply of labors continues to increase. However, with the share of elders increase, aging is largely caused by life extension. Consequently, the demographic dividend fades, and the negative effect of aging on emissions begin to appear. Secondly, the willingness to pay for better environmental quality[35] and the favor of stricter environmental regulations[36] decreases significantly with aging, since aged people cost a lot but benefit less from the higher environmental quality. However, as to regional level, the impact of aging on CO_2 emissions exhibits big differences depending on the different levels of aging in each region[5]. For example, by analyzing the data of Hunan province in China from 1985 to 2007, Yin[37] stated that aging drive CO_2 emissions growth if the population pressure was large. Because large population pressure indirectly brings about poverty. Thus, residents in Hunan tend to raise children to guarantee living standard when they get old, which is inhibited by “one-child policy”. People have no choice but to rely on “extensive way” of economic growth. Therefore, in a region with large population pressure, aging facilitated CO_2 emissions. Based on the aforementioned studies, we acknowledged that the correlation between aging and emissions may depend on the development stage of a country or region.

As for the driving mechanism analysis, a number of methods have been developed to explore the effects of both the socioeconomic and biophysical factors on carbon emissions, among which Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model is one of the most commonly used ones. Differing from the IPAT equation, which is the earliest attempt to describe the multiplicative contribution of population (P), affluence (A) and technology (T) to environmental impact (I), STIRPAT model is more flexible and allows additional factors to be taken into account as long as they are conceptually appropriate for the multiplicative specification [5,20,21,38,39]. The recent applications of STIRPAT model in investigating the driving forces of CO_2 emissions include the followings, such as Balezentis (2020)[40], Liddle (2011)[20], Liddle & Lung (2010)[21], Mehmood et al. (2021)[41], Wang et al. (2019)[24], Wang & Wang(2021)[42], Wang et al. (2017)[43], Wang & Liu (2015)[44], Yu et al. (2018)[7], Zhang & Tan (2016)[5].

Yet, despite recent advancements in research aimed to understand the effect of aging on carbon emissions, there remain great challenges in the following two aspects that could be further improved. i) A great number of studies have been carried out based on the cross-country or country level data, while the heterogeneity of the impact of aging on CO_2 emissions across the different stages of regional development has not been examined adequately. ii) Most of the studies have focused on the research question whether the population aging stimulates or constrains CO_2 emissions using historical data for analysis. The dynamic path of CO_2 emissions, its association with population structure change in the future, and more importantly the policy implications for coping with aging and climate change are still lack of thorough investigation and discussion.

3. Data And Methods

3.1 Data description

This paper used panel data of 29 Chinese provinces from 1995 to 2019 for empirical analysis. Hong Kong, Macao, Taiwan and Tibet are excluded due to the unavailability of data. Chongqing is still considered as a part of Sichuan Province as it is officially designated as a municipality in 1997. All the variable-related statistics were collected from China's Statistical Yearbook, China's Population and Employment Statistics Yearbook, and provincial Statistical Yearbooks. CO_2 emissions were calculated based on the energy balance table of each province, which is obtained from China Energy Statistical Yearbook. Table 2 describes the definition and unit of each variable used in this study.

Table 2
Description of data

Variable	Definition	Unit	Data source
PC	CO_2 emissions per capita	tons / person	China's Energy Statistical Yearbook, China's Statistical Yearbook
AGE	Share of population over 65 years old	%	China's Population and Employment Statistical Yearbook, and Statistical Yearbook of each province
PA	GDP per capita	Yuan RMB	China's Statistical Yearbook
EI	Energy intensity	tons / thousand yuan	China Energy Statistical Yearbook
IND	Share of secondary industry	%	China's Statistical Yearbook
THR	Share of tertiary industry	%	China's Statistical Yearbook

As shown in Fig. 1, China is divided into three regions in accordance with the State Statistics Bureau for better identification of the aging-CO_2 correlation in consideration of its level and speed of socioeconomic development. GDP in the eastern, central, and western regions accounts for 56.37%, 26.25%, and 17.39% of the country's total respectively in 2019. In the meantime, the share of aged people reached 13.03%, 12.35%, and 12.17% in the eastern, central, and western regions, respectively. It can be found that eastern region was more developed in economy and facing severer challenge in population aging than the central and western regions did.

3.2 Energy-based CO_2 emissions accounting

According to the IPCC Guidelines for National Greenhouse Gas Inventories[7], the energy-based CO_2 emissions are calculated as follows.

$$C = \sum_i FCi * LCi * EFi * CR_i$$

1

where C represents the total CO_2 emissions; FC is the amount of fuel consumption; LC is the low calorific value of fuel; EF is the effective CO_2 emission factor; CR denotes the CO_2 oxidation ratio; and the subscript i represents the fuel type.

3.3 SPIRTAT model for CO_2-aging correlation analysis

Ehrlich and Holdren[45] proposed a IPAT model as a framework to quantify the impacts of socioeconomic factors on environment, in which the impact (I) could be determined by population (P), affluence (A) and technology (T). Afterwards, IPAT has evolved into ImPACT model, where *T* was disaggregated into consumption per GDP (*C*) and impact per unit of consumption (*T*)[46]. However, these two models can merely be employed to estimate the constant proportional or partial impacts of the independent variables on the dependent variable. Specifically, the IPAT and ImPACT model fail to adequately reflect the complicated interaction between environmental quality and the influencing factors. Additionally, both IPAT and ImPACT models do not permit hypothesis testing, and do not readily allow for non-monotonic or non-proportional effects from the drivers [46,47].

To overcome the limitations of the IPAT model, Dietz and Rosa (1994) put forward a STIRPAT model[48]. This conceptual model is not an accounting equation, but a stochastic model that can be used to empirically test hypotheses[47]. In this paper, we employ the STIPRAT model to quantitatively measure the effects of aging on the CO_2 emissions in China.

$$I = aP_i^b A_i^c T_i^d e_i$$

2

where *I, P* and *A* have the same meanings as in the IPAT model; *T* represents all factors that influence per unit of production other than population and affluence; i =1, 2, 3, ..., N represents the cross-sectional dimension; the constant a scale the model; *b, c* and *d* are coefficients of *P*, A and *T*, respectively; *e* denotes the error term. After taking natural logarithms, we get the panel data regression model for investigating the driving factors of CO_2 emissions as follows:

$$LnPCit = a + \beta 1 LnAGEit + \beta 2 (LnAGEit)^2 + \beta_3 LnPAit + \beta_4 LnEIit + \beta_5 LnINDit + \beta_6 LnTHRit + eit$$

3

where CO_2 emissions per capita (*PC*) to represent *I*, GDP per capita (*PA*) to represent A, and energy intensity (*EI*), the share of the secondary industry (*IND*) and the share of tertiary industry (*THR*) to represent *T*. The share of people over 65 years old (*AGE*) is included in the equation. i = 1,2,3,...,N represents provinces observed over the period t = 1,2,3,...,T.

3.4 Cohort model and scenario settings

In order to know the future trend of CO_2 emissions especially its interaction with aging, a cohort model with scenario analysis are performed based on the correlations identified in the aforementioned regressions. Here, population and its composition are the most important factors in future projection. Instead of extrapolating the historical change of population into the next decades as whole, cohort model is employed as it considers the natural birth and death, migrations of different age groups of people, and performs a cross-section at intervals through time[49].

$$P_i^{t+n} = P_i^t + B_i^{t+\mathrm{n}} - D_i^{t+n} + I_i^{t+n} - E_i^{t+n}$$

4

where P_i^{t+n} represents the total population of age group i at time $t+n$; P_i^t is the population of age group i at time t; B_i^{t+n} and D_i^{t+n} are number of births and deaths happening between t and $t+n$ interval, respectively. I_i^{t+n} and E_i^{t+n} indicates the number of immigrants and of emigrants during the period t to $t+n$.

The first step of cohort model for population projection is to calculate the amount of surviving people in each age group at the current projection interval. Then, the immigrants to each age cohort are added and the emigrants are subtracted from each age cohort. The births occur during current projection interval are accounted and divided by sexuality. Afterward, the number of births of each sexuality that will remain alive at the end of the projection interval, together with the net migration into the youngest age group are calculated. Finally, the above-mentioned calculations for the next projection interval are repeated until the end year [50].

The possibilities and options of fertility policy transition in China have been discussed in the previous literature over the last few decades[51–54]. Based on the discussions by Chinese scholars and government officials [55–57], we designed three demographic scenarios as follows. 1) Business as usual (BAU) scenario. It assumes that the composition and changing patterns of all variables will follow the historical trend. According to Chen and Duan[54], China's total fertility rate has remained stable between 1.41 and 1.78 in the recent decade (2006-2017). Therefore, the total fertility rate in the BAU scenario was set as the median value 1.65. 2) Rapidly aging scenario. It assumes the rigorous birth control policy remained unchanged, which will result in a low population in total number. Such assumption is based on the expectation that declining effects of policy control on people’s fertility behavior during the recent institutional reform in China may be compensated by the further socioeconomic development. Here, the fertility rate was set as 1.41. 3) Slowly aging scenario. In October, 2015, China's one-child policy was replaced by a two-child policy. The new fertility control policy allows all Chinese residence to have their preferred number of children maximum to two. Thus, this scenario will stimulate the population growth in total number. The fertility rate was set as 2.44 by following the previous studies[53–55].

According to historical data, the long-term historical trend from 1990 to 2010 and short-term trend from 2000 to 2010 of net immigrants are different, so that we used short-term historical data to project net population immigrants. By using exponential smoothing method, the trends of net population immigrants in both BAU and rapidly aging scenarios are projected. Under the slowly aging scenario, we adopted moving average method to forecast net immigrants.

The sex ratio at birth, an important parameter assessing sex structure, is the ratio of new born male infants to female infants (whose number is setting as 100). According to the findings of United Nations, without anthropogenic interference, the sex ratio at birth should be stable between 103 to 107, though it slightly varies from country to country. If it seriously deviates from this range, a series of social problems would emerge. Currently, the sex ratio at birth in China was abnormally high with the value in 2010 climbed up to 118.06 based on the 6th nationwide census. It remarkably outnumbered the normal range suggested by the United Nations, and has grabbed the experts and government's attention. Wang (2012)[58] claimed that the peak of sex ratio at birth has appeared, and it would decline with further administration. Accordingly, we assumed that the sex ratio at birth in China would drop to normal level after 15 years from the current 118 to 107 between 2025 and 2050.

Besides of population growth and aging, the change of economy and energy intensity were also projected in the three scenarios. The detailed parameter settings are illustrated in Table 3. The growth rate of GDP and per-capita GDP in different scenarios refer to the estimates by scholars for the period 2021-2050[59,60] and China's 14th Five-Year Plan for the period 2021-2025. Regarding the annual decline rate of energy intensity, the rate in 2015 (3.93%/yr) was set for the BAU scenario as a reference. It is set as 2.93% and 4.93% for the slowly aging and rapidly aging scenarios respectively.

Table 3
Parameter settings in three scenarios

Scenarios	Population fertility rate	Growth rate of GDP	Reduction rate of energy intensity
Business as usual	1.65	6.8%/yr	3.93%/yr
Slowly aging	2.44	5.5%/yr	2.93%/yr
Rapidly aging	1.41	4.2%/yr	4.93%/yr

4. Results And Discussions

4.1 Changing patterns of CO_2 emissions and aging

Figure 2 presents the time-series change in CO_2 emissions per capita and aged people in China during 1995-2019. Generally, CO_2 emissions per capita has witnessed a significant growth in the last three decades, with its level nearly tripled at both national and regional scale especially during 2000-2010. At regional level, the eastern region had the relatively higher level of CO_2 emissions, with its PC soared from 3.2 tons in 1999 to 11.4 tons in 2019, followed by the central and western region whose PC in 2019 was

8.2 and 8.5 tons. When it refers to aging, the share of people over 65 years old had been up-rocketing and approached 13% in 2019 for the whole country. The share aging people reached 13.03%, 12.35%, and 12.17% in the eastern, central, and western regions, respectively.

Figure 3 demonstrated the spatial distributions of CO_2 emissions per capita in each province between 1995 and 2019. It is found that the CO_2 emissions per capita increased rapidly in most of China's provinces from 1995 to 2019, especially in the central and western regions. The top provinces with highest CO_2 emissions per capita were mainly located in the central and western regions China, most of which are coal-mining provinces. The leading provinces with fastest growth rates are mostly in eastern and western regions China, such as Liaoning, Ningxia, Hainan. Ningxia province registered the fastest increase in PC from 3.56 to 29.22 tons/person, followed by Inner Mongolia (23.08 tons in 2019) and Xinjiang (20.05 tons in 2019). Beijing, Jilin and Hunan exhibited the slowest growth, with their increment below 3 tons/person in 2019.

4.2 Correlation between CO_2 emissions and aging

First, in order to ensure the effectiveness and stability of the panel data, three unit root tests, namely Levin-Lin-Chu (LLC) test[61], Fisher-ADF test, and Fisher-PP test[62] were performed before the panel data regression. Table 4 shows the results of the panel unit root tests. Only AGE and THR are found stationary at their levels in the LLC test, rejecting the null hypothesis of non-stationarity at 1% significance level. When the first difference is considered, all variables are found stationary at the 1% significance except PA was at the 5% significance, which suggests all variables are stationary at the first difference. Therefore, the relationship between CO_2 emissions and the other variables can be further identified by the cointegration test.

Table 4
Result of unit root tests

	Levin, Lin & Chu		**ADF - Fisher Chi-square**		**PP - Fisher Chi-square**	
Variables	Levels	1st difference	Levels	1st difference	level	1st difference
lnEI	-0.55	-10.70***	71.81	162.90***	59.03	188.45***
lnPA	4.57	-4.27***	20.18	82.31**	14.89	77.58**
lnAGE3	-5.00***	-21.72***	53.71	396.89***	51.27	761.96***
lnIND	-0.64	-13.26***	32.55	229.99***	22.30	228.48***
lnTHR	-3.92***	-11.36***	53.70	151.09***	51.56	175.78***
Note: **, *** denotes the rejection of the null of non-stationarity at 5% and 1% level of significance						

Second, the Pedroni cointegration test[63–65] was conducted to detect the long-run equilibrium relationship between variables with a null hypothesis that the cointegrating relationship does not exist. The results consist of two sets of statistics. i) A panel test based on the within dimension approach, which calculate four statistics, namely Panel v-, rho-, PP-, and ADF-Statistic; ii) A group test based on the between dimension approach, which calculate three statistics, namely Group rho-, PP-, and ADF-Statistic. As shown in Table 5, the results of Pedroni cointegration tests indicate all the statistics of variables reject the null hypothesis except panel rho-statistic and group rho-statistic. However, Panel ADF-statistic, Group ADF-statistic reject the null hypothesis at less than 1% significance. According to the study results of Ã-Rsal[66] and Liddle[20], the Panel ADF-statistic and group ADF perform better than the other statistics. Therefore, the long-term relationship among the variables do exist.

Table 5
Result of Pedroni cointegration tests

Within dimension test statistics		**Between dimension test statistics**	
Panel v-Statistic	16.41***	Group rho-Statistic	6.86
Panel rho-Statistic	4.78	Group PP-Statistic	-7.14***
Panel PP-Statistic	-1.44*	Group ADF-Statistic	-3.44***
Panel ADF-Statistic	-2.98***	—	—
Note: *,**,*** means significant at 10%, 5%, and 1% confidence level.			

Third, using Eq. (3) as a basis, the panel data regression model was applied at China's national level. As illustrated in Table 6, the Hausman test indicates the fixed effect model should be selected. Generally, it is found the economic scale and energy intensity played a dominant role in mitigating CO_2 emissions. Besides, the effect of population aging was significant and nonnegligible as it has a positive impact on CO_2 emissions in the country level during 1995-2019, whose elasticity suggested every 1% increase of population aging would cause 0.69% emission of CO_2. Moreover, the existence of an inverted U-shaped relationship between aging and CO_2 emissions has also been detected since the coefficient of lnAGE is positive, whereas that of $(\ln AGE)^2$ is negative, which is consistent with previous studies [48,50,68,69]. Though some studies argued that due to the less active behaviors of the elders, the increase of aging degree of the society should constrain CO_2 emissions[4,8,25], we thought the increasing use of elder products and services such as indoor heating and cooling, electric appliances, health-care products stimulated the energy consumption and CO_2 emissions in current China. However, we also believed that with the further improvement of dispensable income, technological advancement, and transition toward a low-carbon lifestyle, the growth of aging is supposed to reduce CO_2 emissions.

When looking at the CO_2-aging correlation cross three China regions, Table 6 indicated the effect of aging on CO_2 exhibited a big regional difference. The eastern region has entered a more developed stage, in which aging has posed a significant contribution to CO_2 reduction. Nevertheless, the central and western regions were both facing severe challenges in coping with climate change since the aging process had a significant and negative effect on CO_2 reduction. The pressure of Western region in CO_2 reduction was larger than that of central area as the elasticity of age to CO_2 was 1.61 and 1.15 respectively. The economic scale and energy intensity played an important role in mitigating CO_2 emissions, which suggested that in the context of population aging, the enhancement of energy efficiency and the development of a low-carbon economy should be paid great importance in the future long run. Besides of economic scale, the industrial structure also matters in CO_2 reduction. A correlation between the secondary industry and CO_2 emissions was found significant and positive in the eastern and western regions, but statistical insignificant in the central area. The tertiary industry would constrain emissions as its elasticity was significant at -0.55 and -0.23 in the eastern and central regions, but insignificant in the western area.

Table 6
Results of panel data regressions at national and regional scales

	Nation	**Eastern region**	**Central region**	**Western region**
C	-9.390***	-10.349**	-8.194***	-10.607***
lnEI	0.870***	0.932***	0.788***	0.773***
lnPA	1.020***	1.015***	0.939***	1.013***
lnAGE	0.620***	-0.689*	1.146***	1.612***
$(\ln AGE)^2$	-0.016***	0.0153*	-0.025***	-0.045***
lnIND	0.150***	0.283***	0.115	0.346***
lnTHR	0.050	-0.550***	-0.228**	-0.135
Adjusted R^2	0.990	0.992	0.997	0.995
F-statistic	2063.167	1588.005	3557.857	2245.793
H test	0.000	0.000	0.000	0.000
Note: *,**,*** means significant at 10%, 5%, and 1% confidence level.				

4.3 Future trend of aging and CO_2 emissions

Based on the cohort model, the projection of the total and aged population (65+) are shown as Fig. 4a). Generally, under both the BAU and the rapidly aging scenarios, the total population exhibits an inverted U-shaped curve, whereas it will turn to stable after 2030 under the slowly aging scenario. Specifically, under BAU scenario, the population peak will appear between 2030 and 2035, and reach slightly over 1.39 billion people in 2050, which is lower than the current total population. Under the slowly aging scenario, the peak will appear later between 2035 and 2040, and reach approximately 1.51 billion in 2050. When focusing on the percentage of aged people, it is found that proportion of aged people in the total will increase at least until 2050 under all the scenarios. Additionally, 2035 marks as a tipping point, after which the slope of every curve becomes smooth. Under the slowly aging scenario, the share of aged people will become stable after 2035, reaching 19.3% in 2035 and steadily increasing to 20.2% in 2050. Under BAU scenario and rapidly aging scenario, the share of aged people will rise to 23.4% and 25.8% in 2050 respectively.

On the basis of population change, both the CO_2 emissions and its per capita value between 2015 and 2050 are projected. As is shown in Fig. 4b), under slowly aging scenario, there exists a significant inverted U-shaped curve. The peak of CO_2 emissions and per capita value will saturate at 230. 2 billion tons and 15.1 tons/cap in 2040, respectively. Under BAU scenario and rapidly aging scenarios, an inverted U-shaped curve can also be detected. The emission peak will appear between 2030 and 2035 in these two scenarios. Specifically, under the BAU scenario, the peak of CO_2 emissions and per capita value will be 190.7 billion tons and 13.3 tons/cap in 2035, respectively. And under the rapidly aging scenario, the peak will be 156.2 billion tons and 11.4 tons/cap for CO_2 emissions and its per capita value respectively.

Our findings of an inverted U-shaped correlation between aging and CO_2 emissions pc in China was also consistent with the previous studies such as Balsalobre-Lorente et al. (2021)[67], Li et al. (2018)[6], Wang et al. (2019)[24], Zhang & Tan (2016)[5], whose research were conducted in some cross-country cases. It indicates aging will stimulate CO_2 emissions at the initial stage, but constrain CO_2 emissions in the later stage. In addition, as discussed widely in the literature, the relationship between economic structure and CO_2 emissions exits obvious regional difference, and the level of economic development has an impact on the aging-CO_2 correlation [5,8,9].

4.4 Policy implications

Based on the aforementioned theoretical foundations and empirical regression analysis, the interactions between aging, economy, and CO_2 emissions and its policy implications are probed as follows.

(1) Integrating aging into the decision-making of industrial structure upgrading and CO_2 emission reduction.

Demographic dividend plays a vital role in economic development and industrial structure transformation[68]. In the initial stage of aging, because the growth rate of working age (14-64 years old) population was larger than that of aged people, the development of economy can rely on the labor-intensive industries, such as construction, manufacturing, and heavy chemical industrial sectors[69]. Usually the secondary industry was the largest contributor to China's energy consumption and CO_2 emissions[70–72], the rise of labor supply contributed substantially to the increase of CO_2 emissions associated with economic miracle in developing countries. However, the demographic dividend does not last long. After the aging reached a certain degree, the demographic dividend of the society gradually disappears. The aging, caused by the extension of life expectancy and low birth rate, would cause the reduction of the working age population, so that the economic development cannot depend on the labor-intensive industries any more. In China's case, it has been reported the demographic dividend disappeared since the 2010s[43,73]. As suggested by Zhang and Tan (2016)[5], population aging was positively correlated with China's CO_2 emissions at the national level in 1997-2012. This suggested 2012 a turning point, after which the industrial structure will turn to a low CO_2-intensive but a technology-intensive one, and the CO_2 emissions are expected to decline accordingly. Thus, due to the important role of ageing in CO_2 reduction especially in the future China, aging should be integrated as an important factor in the decision-making and planning process of industrial structure upgrading, so as to achieve a low-carbon development in the long run. On one hand, the aging speed could be slowed down through the active mitigation countermeasures such as the relief of fertility control policies including the recently introduced two-children policy in 2016, and three-children policy in 2021. It could help directly to alleviate the social pressure and curb CO_2 emissions. On the other hand, aging-oriented industries such as smart transportation, health-care industries, elderly product manufacturing and service industries should be given high priorities and developed as an adaptation countermeasure against the inevitable aging trend and low-carbon growth needs in the future.

(2) Developing differentiated regional policies against the different development stage and socioeconomic condition.

As suggested by the regression results, the effect of aging on CO_2 emissions were different cross three regions. Due to the different socioeconomic condition, and geographical and natural endowment, differentiated policies for coping with aging and climate change should be developed.

In the eastern region, it was the largest area in China to attract the labor force migration during the last decades. Though this region had a relatively higher aging degree (13.03% in 2019), the continuous inflow of working age population makes the economic condition, infrastructure ownership, social welfare system developed to a relatively higher level than the rest of China. Moreover, the educational level and environmental awareness of the people in the eastern region are also high. For example, citizens in those eastern cities like Beijing, Shanghai, and Shenzhen had strong willingness to practice energy-saving and low-carbon activities in their daily life, such as using bus and metro as the first choice of mobility, classifying and recycling the household solid waste, and inclining to use energy-saving appliances. In the future, the transition to low-carbon consumption and green products should be further promoted. Since the inter-regional industrial transfer will further reduce the proportion of traditional industries in the eastern region, the high-level manufacturing, technology-intensive and service industries will become the leading ones, the development of the aging-oriented industries and products and at the same time making them low-carbon could achieve a win-win effect. Taking the booming development of new-energy car industry as an example, provinces in the eastern region have attached great importance and given policies preference in developing new-energy vehicle manufacturing industries. Those biggest new-energy vehicle companies such as Tesla, BYD, NIO has built the production base in Shanghai, Guangdong, and Anhui provinces respectively. It not only meets the mobility demand of aging society but also copes with the increasing needs for a better environment.

In the central and western regions, aging has exhibited an inverted U-shape correlation with CO_2 emissions. Thus, what the policy instruments should do is to accelerate the approaching to and across over the turning point of the inverted U-curve so as to facilitate the reduction effect of aging on CO_2 emissions. Differing from the situation in the eastern region, the central and western area of China have encountered the aging challenges before their economy get rich enough and social welfare system get well built. Due to the continuous and massive outflow of working age population to the eastern region, it accelerated the aging process and increased the economic burden of the society of the central and western regions. That is why the elasticity of aging on CO_2 emissions was larger than that of economy, energy intensity, and industrial structure in these two regions. As pointed out by many studies that the cultural accomplishment of the elders in the central and western regions were relatively lower than eastern region[74,75], which results in a lower environmental awareness, less environmentally friendly consumptions, and increasing CO_2 emissions in these regions. However, these inland regions also have abundant natural resources and important ecosystems in China, which provides essential services to the local and whole China. Against this background, policies should be developed to strengthen the deep fusion of aging-oriented industries with local resource and environmental endowment.

Specifically, 1) Promoting the development of eco-agriculture industry to meet the needs of aging-care market. Usually aged people cared more about their health, their needs for healthy and green food and medicine have been increasingly boomed especially when their dispensable income improved. The central and western regions have the advantages in natural environment and resources. For examples, there are 8 out of 11 key biodiversity areas located in the central and western China[76]. Moreover, these two regions contributed to over 60% planting area of the genuine traditional Chinese medicine within country’s seven major planting bases [77]. Differing from the traditional agriculture, the development of eco-agriculture could stimulate technology innovation, provide high added-value and healthy products, and more importantly exert low impact on environment. Thus, the promotion of eco-agriculture industry could be an important direction for coping with aging and CO_2 reduction challenges.

2) Accelerating the construction of green pension industry. Due to the relatively low urbanization rate, the environmental quality is better in most central and western regions than that in the densely populated eastern region. Taking the forest coverage as an example, among the top 10 provinces, 6 are located in the central and western regions[78]. The over 50% forest coverage in these areas provide high-quality ecosystem services including fresh air, recreation, mental health care, and etc. The construction of green-

based pension industry could not only provide services to the local elders but also those from the eastern region, which may attract more labor forces flow back to the inland areas, and at the same time reduce CO_2 emissions.

5. Conclusions

To reveal the correlation between population aging and CO_2 emissions and their dynamics in China, we firstly examined the effect of aging on CO_2 by employing a STIRPAT model based on the panel data covering 29 provinces from 1995 to 2019, and then projected the long-term changes of demography and CO_2 emissions till 2050 through a cohort model and scenario analysis. The major findings and policy implications for achieving a low-carbon and aging-oriented sustainable development are summarized as follows.

First, China has witnessed a significant growth of CO_2 emissions during 1995-2019, with its per capita value nearly tripled especially in the eastern and western provinces. In the future, due to the further progress of aging, CO_2 emissions will follow an inverted U-shaped growth till 2050, and will reach the peak around 2030-2040, with its per capita value ranged from 11 to 15 tons/cap.

Second, besides of the dominant role of the economic scale and energy intensity in mitigating CO_2 emissions, population aging has also exerted a nonnegligible and positive impact on CO_2 emissions on the country level, whose elasticity suggested every 1% increase of aging would cause 0.69% emission of CO_2. However, a big regional difference was also detected as aging has posed a significant contribution to CO_2 reduction in the eastern region, but stimulated CO_2 emissions in the central and western regions.

Third, results from the national and regional analysis revealed the importance of further investigation of the interplay between economy, population, technology, and CO_2 emissions so that proper policies could be developed. In this study, integrating aging into the decision-making of industrial structure upgrading and CO_2 emission reduction in both national and region levels, promoting the further transition to low-carbon consumption and green products in the eastern region, strengthening the deep fusion of aging-oriented industries with local resource and environmental endowment in the central and western regions such as the development of eco-agriculture industry, and the construction of green pension industry, could be effective policy implications for coping with aging and climate change challenges in China.

Declarations

Author contributions:

Guo, H.W., Conceptualization, Methodology, Writing – original draft preparation. Jiang, J., Data curation, Investigation. Li, Y.Y., Methodology. Liu, M.Q., Software, Investigation. Han, J., Writing-Reviewing and Editing, Supervision.

Competing Interests Statement:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

Three regions in China

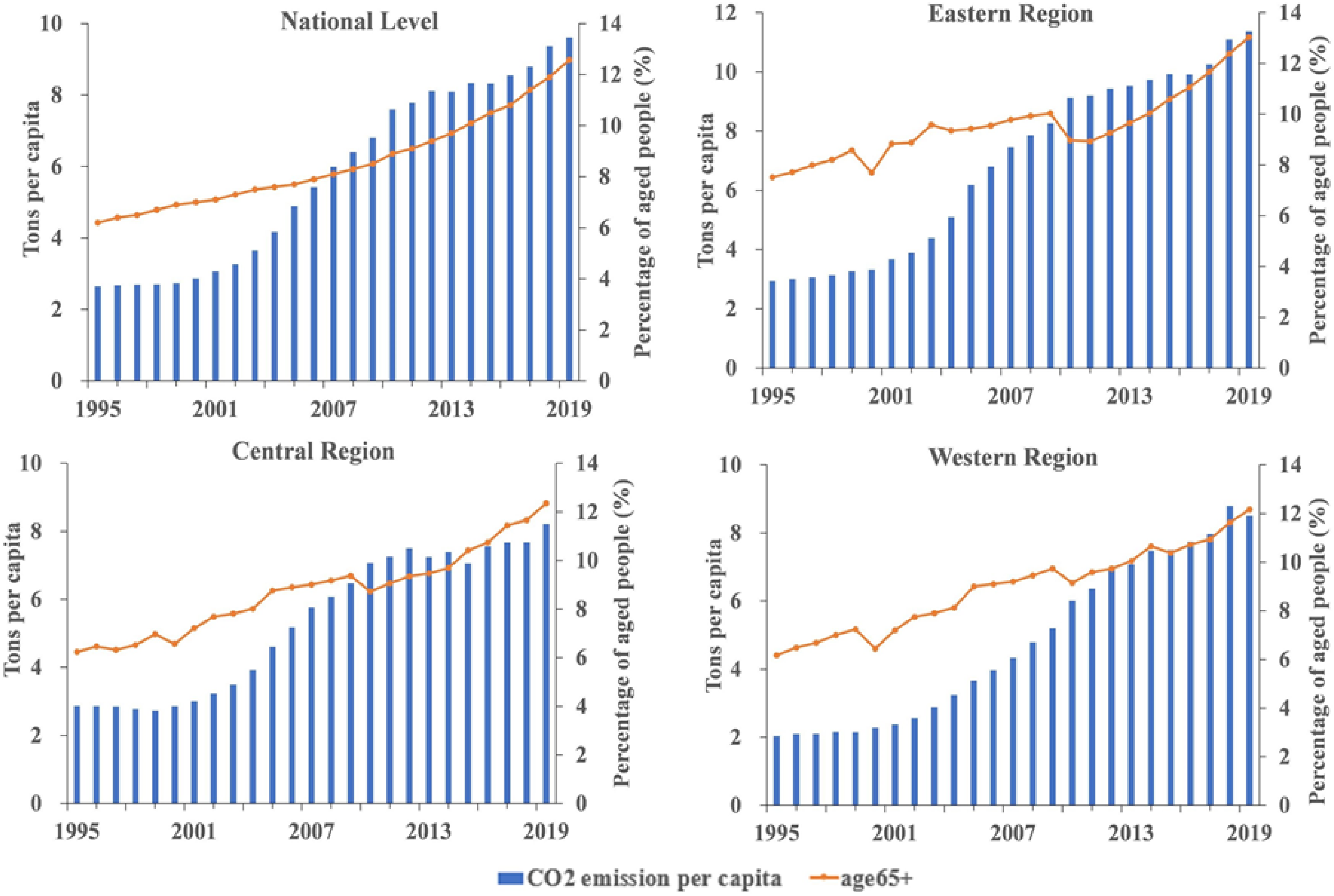

Figure 2

Changes in CO_2 emissions per capita and percentage of aged people in China.

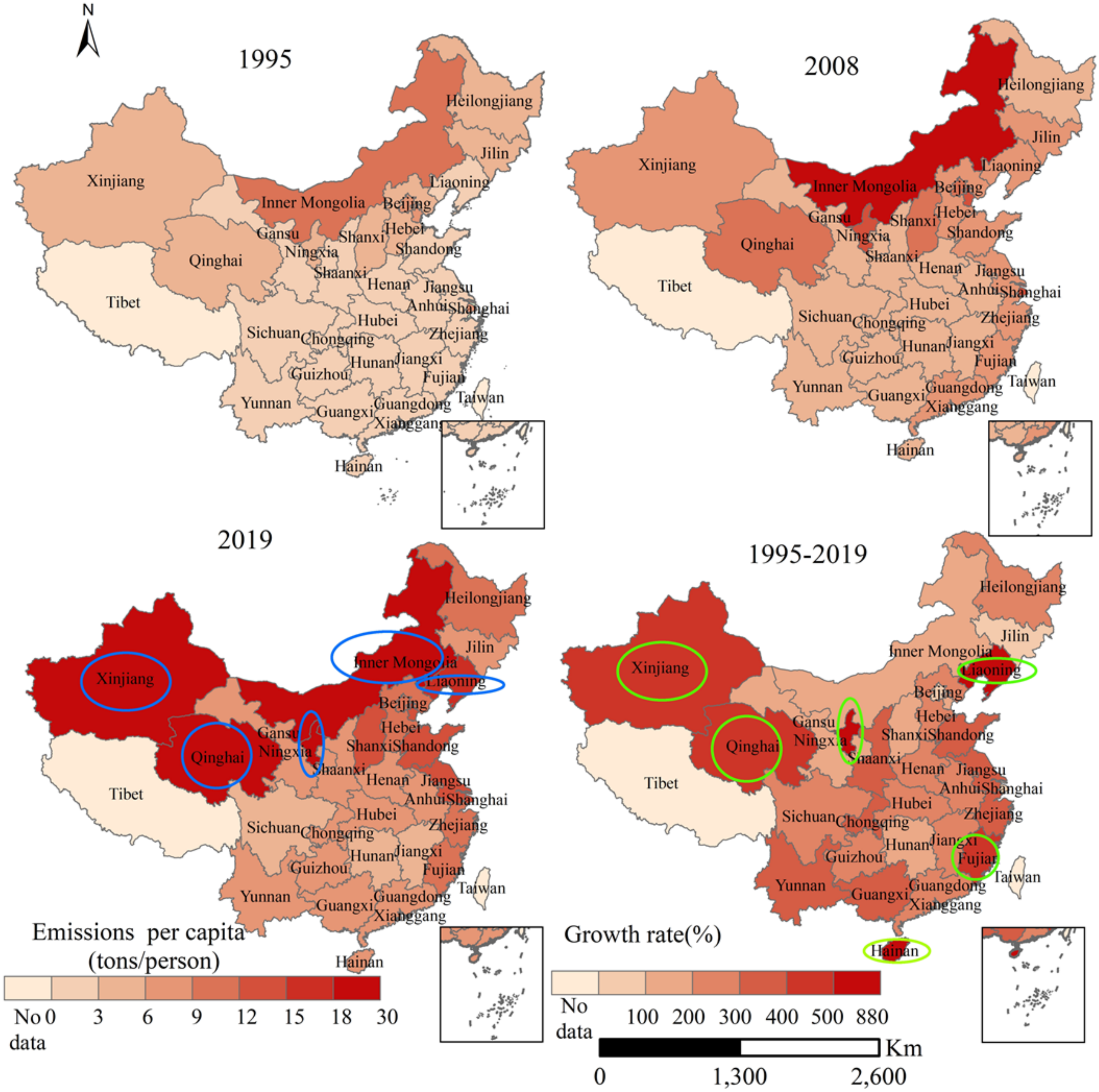

Figure 3

Provincial CO_2 emissions per capita 1995-2019

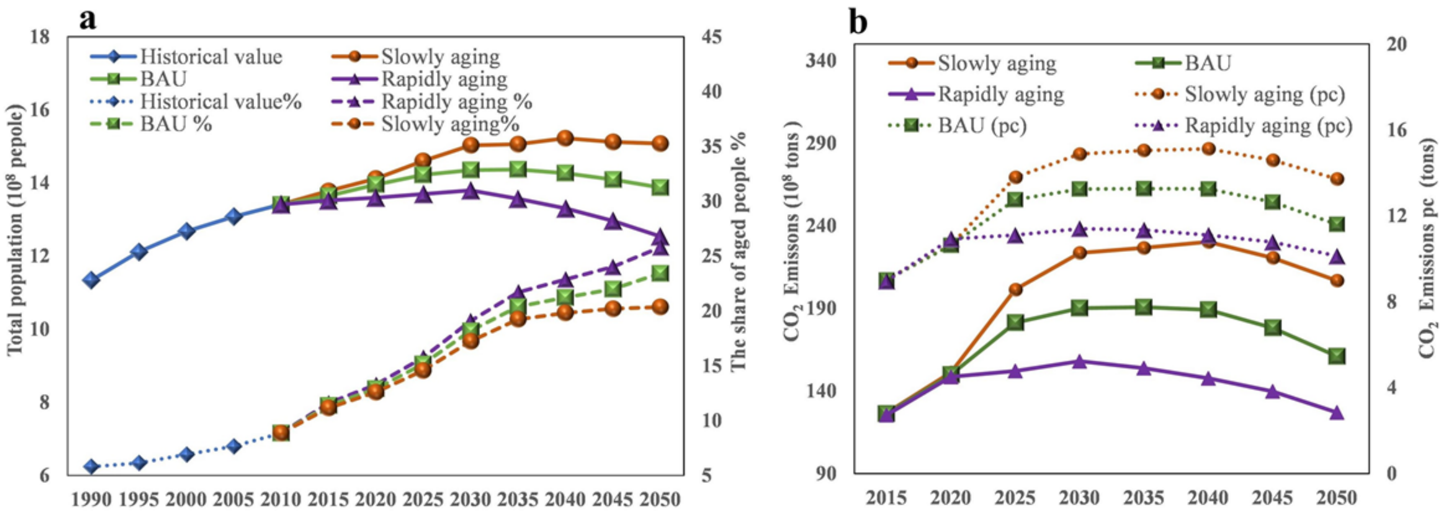

Figure 4

Projection of population (a) and CO_2 emissions (b) till 2050