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Integrating social, climate and environmental changes to confront accelerating global aging

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Abstract

Introduction The global increase in the aging population presents critical challenges for healthcare systems, social security, and economic stability worldwide. Although the studies of the global rate of aging have increased more than four times in the past two decades, few studies have integrated the potential combined effects of socio-economic, climatic, and environmental factors.

Methods We calculated the geographic heterogeneity of aging population growth rates from 218 countries between 1960 and 2022. Public databases were then integrated to assess the impacts of seven global stressors: socio-economic vulnerability, temperature, drought, seasonality, climate extremes, air pollution, and greening vulnerability on growth rates of aging population (a totally 156 countries). Linear regression models were primarily used to test the statistically significant effects of these stressors on the rate of aging, and multiple model inference was then used to test whether the number of stressors exceeding specific thresholds (e.g., > 25, 50, and 75%) was consistently significant in the best models. The importance of stressors and the number of stressors exceeding thresholds was verified using random forest models for countries experiencing different population aging rates.

Results Our analysis identified significant heterogeneity in growth rates of aging population globally, with many African countries exhibiting significantly lower aging rates compared with Europe. High socio-economic vulnerability, increased climate risks (such as high temperature and intensive extreme climate), and decreased environmental quality were found to significantly increase growth rates of the aging population ($P < 0.05$). The positive combined impacts of these stressors were diminished at medium–high levels of stressors (i.e., relative to their maximum levels observed in nature). The number of global stressors exceeding the 25% threshold emerged as an important predictor of global aging rates. Demographic changes in regions with relatively rapid aging (e.g., Africa and Asia) are more sensitive to climate change (e.g., extreme climate and drought) and the number of global stressors, and regions with low to medium rates of aging (e.g., Europe and the Americas) are more sensitive to socio-economic vulnerability and environmental stability (e.g., drought, green fragility and air pollution).

Conclusions Our findings underscore that policy tools or methods must be developed that consider the holistic dimension of the global factor. Further investigations are essential to understand the complex interactions between multiple stressors and their combined effects on global aging.

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Keywords Global aging, Environmental stressors, Economic vulnerability, Climate change, Social care

Introduction

The increase in the aging population globally represents an urgent issue that demands immediate attention [1, 2]. As life expectancy rises and birth rates decline, the proportion of older individuals, defined as those aged 65 years (or 60 years) and above, in the global population continues to grow at an unprecedented rate [3, 4]. This demographic shift seriously challenges healthcare systems, social security, and economic stability worldwide. The consequences of an aging population are profound, including increased healthcare costs, greater burdens on pension systems, and potential declines in economic productivity owing to a shrinking workforce [5, 6]. Developed countries face rapid demographic transitions, leading to substantial financial burdens, and low-income countries could experience a double burden on health systems owing to infectious diseases and rising chronic conditions associated with aging [7, 8]. Moreover, aging is a complex, multifaceted process that involves biological, psychological, and social changes [9]. It is important to recognize that aging does not inherently imply a negative health status; many individuals maintain or even improve their health and well-being as they age, which is often termed "successful aging" or "healthy aging" [10]. This distinction is crucial, as it highlights the potential for individuals to remain active, engaged, and in good health well into older age, depending on the broader socioeconomic and environmental factors they experience [11]. Thus, to effectively address these multifaceted challenges, it is essential to consider the role of the broader environment in shaping health outcomes for older people.

The health and well-being of older people are influenced not only by individual behaviors but also by the broader natural and social environments in which they live [12]. These environments can either support or hinder health-promoting behaviors such as maintaining a balanced diet, engaging in regular physical activity, and avoiding smoking, which are crucial throughout the lifespan to reduce the risk of non-communicable diseases and enhance physical and mental capacity [13]. Supportive environments that include accessible public buildings, safe transportation options, and walkable spaces, are essential to ensure that older people continue engaging in meaningful activities despite potential losses in capacity [14, 15]. Public health strategies must consider the diverse experiences and needs of the older people, addressing not only personal and environmental factors but also emphasizing rehabilitation, adaptation, and psychosocial growth [7]. It is vital to challenge and correct societal attitudes that view older adults as frail or dependent, which can lead to discrimination and limit their opportunities to enjoy healthy aging [16]. Global trends including urbanization, migration, and changing sex norms further complicate the landscape, requiring public health interventions that are responsive to both the current and future challenges faced by a growing aging population [17, 18].

Given the severe global challenges posed by the increasing rate of aging in the world's population, we conducted a bibliographic survey (Web of Science) of peer-reviewed publications for the period from 1947 to 2023 using the term "growth rates of the aging population". Among the 12,064 identified papers (as of 28 December 2023), we found a dramatic increase in the number of publications by more than four times over the past two decades (Fig. 1c). The bibliometric co-occurrence analysis indicated a wide range of topics and multiple-country cooperation covered in research on aging rates (Fig. 1a and b), where the green clusters reflecting research on quality of life and health interventions for older people, the yellow clusters reflecting epidemiological research on aging health, and the purple clusters focusing on end-of-life care and other qualitative research. The most frequently mentioned keywords included quality of life, morbidity, socio-economic development, long-term care, COVID-19 infection, surgery, and medical interventions.

Another notable trend in our bibliometric analysis was that as global changes have accelerated, the paradigm of global aging research has gradually expanded to other fields, such as climate change and environmental change [19, 20]. However, although the literature continues to expand, few studies have explicitly investigated whether the increasing number of global stressors that simultaneously exceed medium-high stress levels (i.e., relative to their highest levels observed in nature) could be related to a significant increase or decrease in the older population. This novel framework has recently been applied in the field of ecology. Previous research has shown that human activities leave a complex footprint on terrestrial ecosystems through multiple environmental stressors (such as drought, soil acidity, or heavy metals [21–23]) that collectively diminish ecosystem functions. Similar research is urgently needed in the context of population aging, given the substantial impacts of climate change and environmental degradation on health outcomes for older people. For instance, a recent study demonstrated that with 1.5 °C, 2 °C, and 3 °C of global warming, heat-related mortality in 800 locations across 50 countries/areas is projected to increase by 0.5%, 1.0%, and 2.5%, respectively, 20 to 25% of heat-related deaths can be attributed to population aging [24]. Additionally, extreme climate and prolonged exposure to environmental

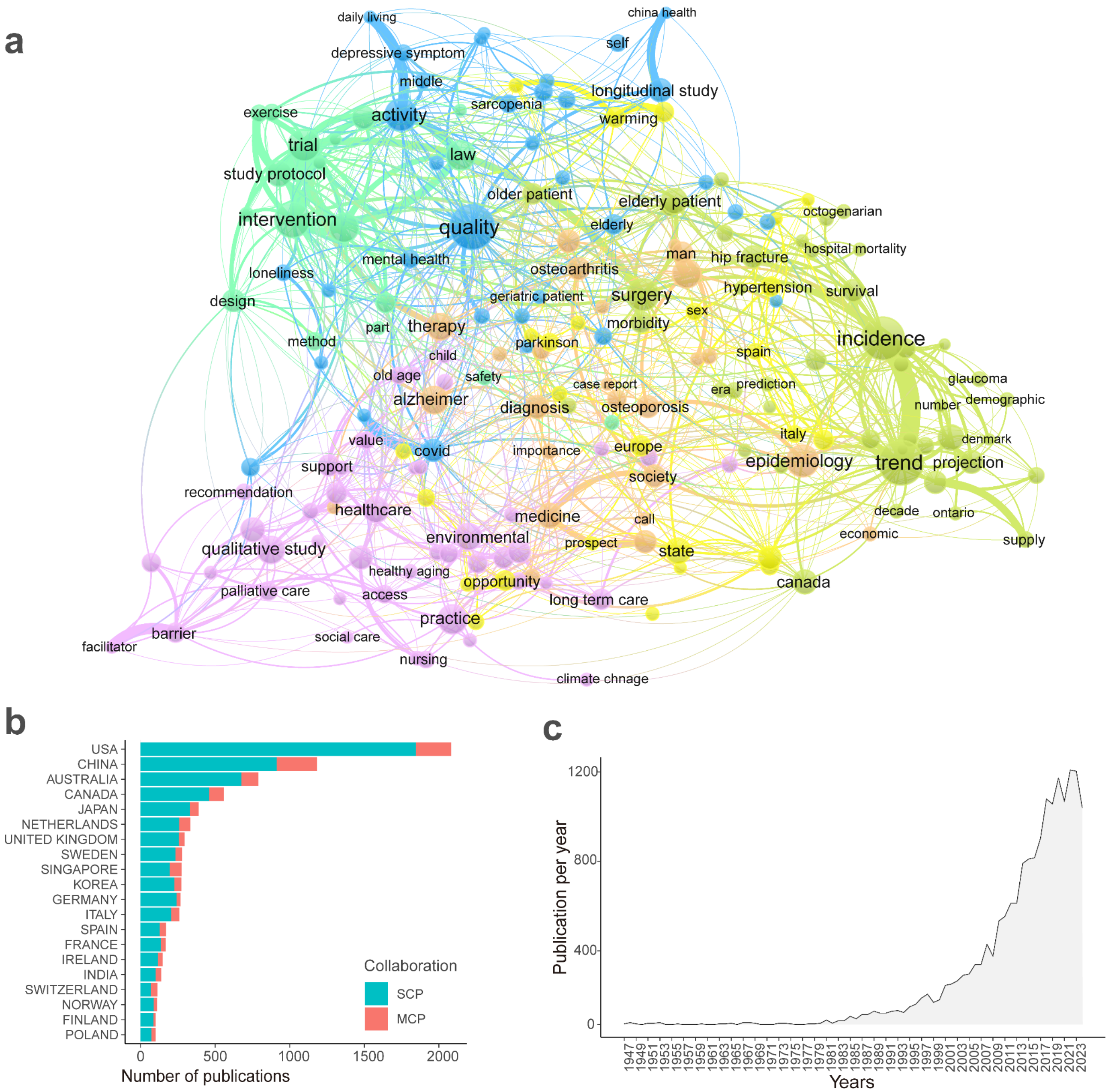

Fig. 1 Bibliometric and keyword co-occurrence analysis of aging rates from mid-20th century to 2023. (**a**) The co-occurrence network for the keyword of "growth rates of the aging population", where nodes indicate high-frequency keywords (links over 50) and edges indicate their co-occurrence relationships in the literature. Different colors represent different topic areas automatically grouped together, with larger nodes indicating higher keyword frequencies and thicker edges indicating stronger co-occurrence relationships. (**b**) Twenty countries with the strongest related publications during 1947–2023. The blue bars indicate single-country publications (SCP), and the red bars indicate multiple-country publications (MCP). (**c**) Annual publications on the topic of "growth rates of aging" from mid-20th century to 2023. Panel **a** was drawn using the "VOSviewer V1.6.18", and panels **b** and **c** were drawn with the R package "bibliometrix V4.1.4"

pollutants can exacerbate health issues in older people [25, 26]. Other factors such as low gross domestic product (GDP) and inadequate social protection systems can hinder the ability of countries to effectively support their aging populations effectively and accelerate the demographic transition (e.g., increased immigration and old retirement age) [27].

Taking inspiration from studies investigating the effects of biodiversity effects on ecosystem function [28], we used an approach that incorporates multiple stressors to draw general conclusions about their combined impact on aging rates and employed a pool of seven global factors, systematically examining gradients of increasing factor numbers. Specifically, we analyzed the effects of seven composite variables from various public databases, including socio-economic vulnerability, temperature changes, drought, seasonality, climate extremes, air pollution, and greening vulnerability. These variables were selected to represent a broad range of stressors that potentially influence aging populations. Our primary objective was to determine which stressors are associated with the rate of population aging and to test the hypothesis that the number of stressors exceeding medium-high critical threshold levels significantly impacts the aging rate. Additionally, we aimed to classify the population according to risk factors and test which factors increase or decrease the likelihood of the population experiencing high, medium, or (relatively) low rates of population aging. Through this approach, we hope to provide new insights that can inform more effective policies and interventions to address the multifaceted challenges posed by global aging.

Methods

Literature synthesis

We conducted a literature search in Web of Science on August 15, 2024 using the following search string: "("older people" OR older OR "Old people") AND ("population increase rate" OR "population growth rates" OR "population statistics" OR "population dynamics")" to extract the data needed for the present study. Research publications from January 1947 (which is the earliest data available) through December 2023 were collected using gross sampling techniques for subsequent bibliometric analyses. Bibliometric variables (e.g., publication title, authors, abstract, keywords, year of publication, publishing journal, publication type, and affiliation) were among the examined variables in the dataset key. Only articles, reviews, and conference papers were included, and the language was limited to English. The downloaded data were pre-processed and merged into a single file. The R package "bibliometrix V4.1.4 [29]" was used for data analysis and data visualization (more detailed information please see: https://github.com/ayo-prog/Biblio/blob/main/analysis/Rscript_pipeline.Rmd).

Global distribution of growth rates of the aging population

First, we accessed the World Bank's publicly available database (https://data.worldbank.org/indicator/SP.POP.65UP.TO.ZS) to obtain the proportion of the population aged 65 years and over (as a percentage of the total population) for each of the 218 countries in the world between 1960 and 2022 [30]. The World Bank database is widely used owing to its comprehensive coverage and reliable estimates, which are based on the United Nations Population Division's World Population Prospects [31]. This makes it an invaluable resource for demographic studies, as this database provides consistent and comparable data across many countries over an extended period, it is an invaluable resource for demographic studies.

Next, we used linear regression models to fit the data and calculated the slopes representing the growth rates of the aging population. Each of these regressions was bootstrapped 10,000 times, and the slopes were obtained to test their significance (significant when 95% confidence intervals (CIs) of the bootstrapped slopes do not include the value of 0). Bootstrapping involves repeatedly sampling data with replacement to create numerous simulated samples. This technique allows for estimating the sampling distribution of the regression coefficients and calculating more accurate CIs [32, 33]. Overall, 90% of the countries showed either a significant increase or decrease in the annual growth rates of the aging population. We then mapped these slopes, with a slope less than zero indicating negative growth rates of the aging population from 1960 to 2022 for that country, and vice versa.

Owing to data limitations (e.g., inconsistent years and only data for 2022), we only conducted the subsequent analyses using 2022 data for growth rates of the aging population. We examined the correlations between the proportion of the older population and the growth rates of the older population in different countries in 2022 to ensure that the subsequent analyses were valid. The analysis showed a strong correlation between the growth rates of global aging and the proportion of the older population in 2022 (R^2 = 0.8, $P<0.001$); the correlation was much weaker for data 1960 (R^2 = 0.17, $P<0.001$). This suggests that the 2022 data more accurately reflects current aging trends.

To further evaluate the adequacy of older care in the context of an aging population [34], we collected the Mercer CFA Institute Global Pension Index 2022 (https://www.mercer.com/insights/investments/), which provides an analysis and ranking of 45 pension systems in countries worldwide, followed by standardization to a 0–1 scale. This project aims to benchmark the quality of pension systems across various countries by examining key indicators, includi system integrity, adequacy, and sustainability. An aging population increases the dependency ratio, with fewer working-age individuals supporting a larger older population [35]. This type of shift can strain public resources and pension systems, leading to potential economic instability if not adequately managed.

Data collection for global stressors

To assess the global stressors impacting the aging population, we considered seven common global factors that could possibly lead to high levels of stress [23]: socio-economic vulnerability (1/GDP, 1/access to reliable water, 1/medical staff, 1/access to sanitation facilities, 1/age dependency ratio, 1/quality of trade and transport infrastructure, 1/political stability and non-violence, 1/control of corruption, 1/rule of law, social inequality, 1/information and communication technology infrastructure penetration rate, 1/higher education enrolment rate, and sex imbalance.), temperature (annual mean temperature), drought (inverse of the drought index), seasonality (seasonality of precipitation, temperature and diurnal temperature range), climate extremes (consecutive dry days, consecutive wet days, daily temperature range, ice days and tropical nights), air pollution (annual mean carbon dioxide equivalent greenhouse gas emissions, annual mean concentration of volatile organic compounds), and greening vulnerability (1/normalized difference vegetation index [NDVI]). The sex imbalance is calculated by calculating the distance between the sex ratio (i.e., ratio of male: female) and 1. All raster data (climate extremes, NDVI, and greenhouse gas emissions) were processed using the R package "raster V 3.6–26 [36]" to scan the latitude and longitude of different countries and compute their mean values. Notably, after aggregating all the data, we only included 157 of the 218 countries for subsequent analysis. Detailed information on the data sources and descriptions is provided in Table S1.

In this study, we examined seven groups of stressors instead of multiple individual factors within each group, for two main reasons. First, individual factors within each group (e.g., climate extremes) are highly correlated with each other, exhibiting multicollinearity. Second, different stressor groups contain varying numbers of individual factors (e.g., ranging from one to five). The seven groups of stressors in this study were chosen based on two criteria: their well-known importance and the availability of data in the databases used [12, 20, 37–42]. Our seven stressor groups did not exhibit statistical multicollinearity among different types of stressors, reflecting largely independent statistical entities. Furthermore, working at the individual factor level would not allow for a fair and weighted assessment regarding the impact of the number of stressors exceeding different thresholds, potentially leading to groups with more individual variables having larger and overrepresented impacts. The selected stressor groups showed relatively low levels of correlation levels (Fig. S5), indicating that they represent different dimensions of global stress.

Statistical analysis

All analyses were carried out with R V4.3 [43]. To understand the relationships between various global stressors and growth rates of the aging population, we conducted a series of analyses structured systematically, as follows:

First, we standardized all individual global stressors within each dataset to values between 0 and 1. This standardization process involved normalizing the data to ensure that each stressor group (e.g., temperature, drought) contributed equally to our multi-stressor index [44]. By averaging all environmental stressors, within each group, the risk of overrepresentation from groups with multiple environmental variables could be mitigated [45].

Following standardization, we conducted an initial exploration using simple linear models to identify the relationships between the magnitude of different stressor combinations and the growth rates of the global aging population. This preliminary analysis helped us identify potential correlations and interactions among the stressors and their impact on aging demographics. We next performed principal component analysis (PCA) to reduce the dimensionality of the data and uncover the principal components that explain the most variance in the global stressor data. PCA facilitated the identification of patterns and relationships among the stressors, which provided a clearer understanding of how these stressors collectively influence the growth rates of the aging population [46].

Next, we determined the number of stressors exceeding each threshold at each location, ranging from 5 to 95% in increments of 1% [47]. This approach allowed us to assess whether the growth rates of the aging population responded to critical levels of stressors [48]. For example, if a relationship became significant at the 20% threshold, this indicated that the variance in the number of stressors at this level could significantly impact growth rates of the aging populations. This stress level was associated with the combined effect of multiple stressors rather than a single stressor [49].

We then conducted a series of analyses to evaluate the significance of the multi-stressor index compared with isolated stressors. We performed multiple linear regressions using both individual stressors and the multi-stressor index for the 25%, 50%, and 75% thresholds [50, 51]. Variance inflation factor ($VIF<5$) analysis revealed a lack of multicollinearity between predictors, confirming the reliability of our model [52]. Additionally, we used multi-model inference to assess the relative importance of each predictor. Using the R package "MuMIN V1.47.5 [53]", we extracted the Bayesian Information Criterion (BIC) for each combination to rank models according to the principle of maximum parsimony. Models with the lowest BIC were considered the best models, and those with BIC differences up to 4 were considered to have similar performance [54]. We focused on the conservative criterion of all models with $\Delta BIC<4$ from the best model, which allowed us to focus on the most parsimonious models, ensuring robustness in our findings [55]. Models were then ranked according to the principle of maximum parsimony, with the best model (lowest BIC) ranked first and the rest ordered based on their BIC deviation. The results for the Akaike Information Criterion and R^2 were also included in our model comparison as alternatives to reveal the model fitting effect. Next, we determined the relative importance of variables included within the selected best models, focusing on the unique variance contributions of each predictor using the R package "relaimpo V2.2-7 [56]".

We further conducted a random forest analysis to assess the impact of different global stressors on the global rate of aging, considering all stressors and the number of stressors above various thresholds (i.e., >25, >50, and >75%). Because of the well-known importance of demographic momentum for the projection of the aging population [40, 57], we included two additional predictors in the model, the net migration rate (migration rate per 1000 people) and mortality rate among people aged under 60 years. Data for these two variables were obtained from the Word Bank public database. However, these two demographic momentum factors themselves may be affected by other global stressors [39, 58, 59], which lead to bias in the estimates of interest because they absorb part of the effect on aging (i.e., as mediating factors [60]). In this case, the random forest may attribute more variable importance to the mediating factors than to the original predictors. We therefore took advantage of this so-called poor control problem by assessing whether the estimated effect sizes of the stressors and the number of stressors differed depending on whether the potential mediating factors were included in the original specification or not [61]. We first conducted a linear mixed model including all stressors and the number of stressors (random factor: Continents). We then added the two mediating factors one at a time to observe the standardized coefficients of the other control factors (all predictors were standardized). If a particular factor was indeed an intermediate pathway, then controlling for it should reduce the influence of other factors on the global rate of aging (i.e., the standardized coefficients of other factors are decreased) compared with a model that does not include the intermediate factor [62]. If the intermediate factor does have a significant influence, then the random forest model analysis of global demographic changes in aging should only capture the direct influence and discount the indirect influence through the intermediate factor.

For the random forest models, in each resampling iteration, the model was cross-validated 20 times using random forest, with 75% of the dataset used for training and 25% for validation [63, 64]. The model was trained using 1,000 trees and 2 to 6 predictors per node were sampled to select the one that minimized the root mean square error (a variance measure, RMSE). After 1,000 simulations, we determined the mean of the RMSE and the importance of all models.

We also conducted a sensitivity analysis, in which countries were divided into three categories according to the current observed aging rate, i.e., countries with low, medium, and high aging pressure. Random forest prediction and the importance ranking of the predictors were performed separately.

Results and discussion

Global distribution of growth rates of the aging populations

Our analysis revealed significant heterogeneity in growth rates of the aging population across different countries (Fig. 1a). Using linear regression for the proportion of individuals aged 65 years and above from 1960 to 2022 for 218 countries, we determined that the global average aging growth rate is 0.065%/year (95% CI: 0.057%/year to 0.073%/year, $P<0.001$). Among these 218 countries, 93.6% exhibited a significant change in the proportion of the aging population over time ($P<0.05$), with 19.5% showing a significantly decreasing trend and 80.5% showing a significantly increasing trend (Fig. S2b). This variation in growth rates was largely influenced by baseline values from earlier periods (1960) and their correlation with the average growth rate ($R^2 = 0.17$, $P<0.001$), leading to the current distribution pattern of the aging population (such as improved correlation with the aging population in 2022, $R^2=0.80$, $P<0.001$; Fig. S1).

Among the 218 countries included in our analysis, the top three countries with the highest growth rates of the aging populations were Japan (0.415%/year, $P<0.001$), Serbia (0.257%/year, $P<0.001$), and Italy (0.240%/year, $P<0.001$). Conversely, the top three countries with the highest rates of decline were Gabon (-0.076%/year, $P<0.001$), Benin (-0.047%/year, $P<0.001$), and the Central African Republic (-0.044%/year, $P<0.001$). When analyzed by continent, the average aging rate change from highest to lowest was as follows: Europe (0.151%/year, 95% CI: 0.133 to 0.168), North America (0.089%/year, 95% CI: 0.073 to 0.102), South America (0.083%/year, 95% CI: 0.067 to 0.097), Oceania (0.051%/year, 95% CI: 0.038 to 0.065), Asia (0.056%/year, 95% CI: 0.044 to 0.069), and Africa (0.002%/year, 95% CI: -0.003 to 0.008). Notably, only one country from Antarctica was included in this study (South Sandwich, aging growth rate of 0.003%/year, $P<0.001$). We also note that around 2000, Africa uniquely experienced a shift from a declining to an increasing trend in the average aging population (Fig. S3), which is likely owing to improvements in healthcare, policy changes, demographic adjustments, and accelerated urbanization [65, 66].

Developed countries, particularly in Europe and Japan, exhibited higher aging rates owing to historically lower birth rates and higher life expectancies [67]. In contrast, many African countries have lower or even negative aging rates, influenced by higher birth rates and different socioeconomic dynamics [2]. Furthermore, this spatial heterogeneity at the national level also exhibited a significant distance-decay pattern (Fig. S4). With increased geographic distance, the differences in growth rates of the aging population between countries become more pronounced. This implies that neighboring countries tend to have more similar aging population dynamics than countries that are further apart, which could be influenced by regional economic, social, and cultural factors [68, 69].

We also collected the global ranking of pension systems for 45 countries in 2022 to evaluate their effectiveness in addressing the challenges posed by an aging population (Fig. 2b). Pension system rankings provide a comprehensive assessment of the quality, coverage, and sustainability of each country's pension system. We found substantial disparities in pension system rankings across different countries (Fig. 2b and Fig. S2b), reflecting large differences in their capacity to manage aging populations. The three countries with the highest pension system rankings in 2022 were the Netherlands, Iceland, and Denmark. In contrast, countries with the lowest rankings were India, the Philippines, and Argentina. When ranked by continent, Europe had the highest average pension system rankings, followed by South America, North America, Asia, and Africa. However, no significant correlation was found between the proportion of the aging population and pension system rankings globally (Fig. S5). This suggests that although pension systems play a critical role in supporting aging populations, they do not determine a country's capacity to manage demographic aging. Other factors, such as healthcare infrastructure, social welfare policies, and overall economic development, also considerably influence the quality of life among older people [70, 71].

Global factors that correlated with aging population growth

To understand global factors influencing the growth rates of the aging population, we conducted a comprehensive

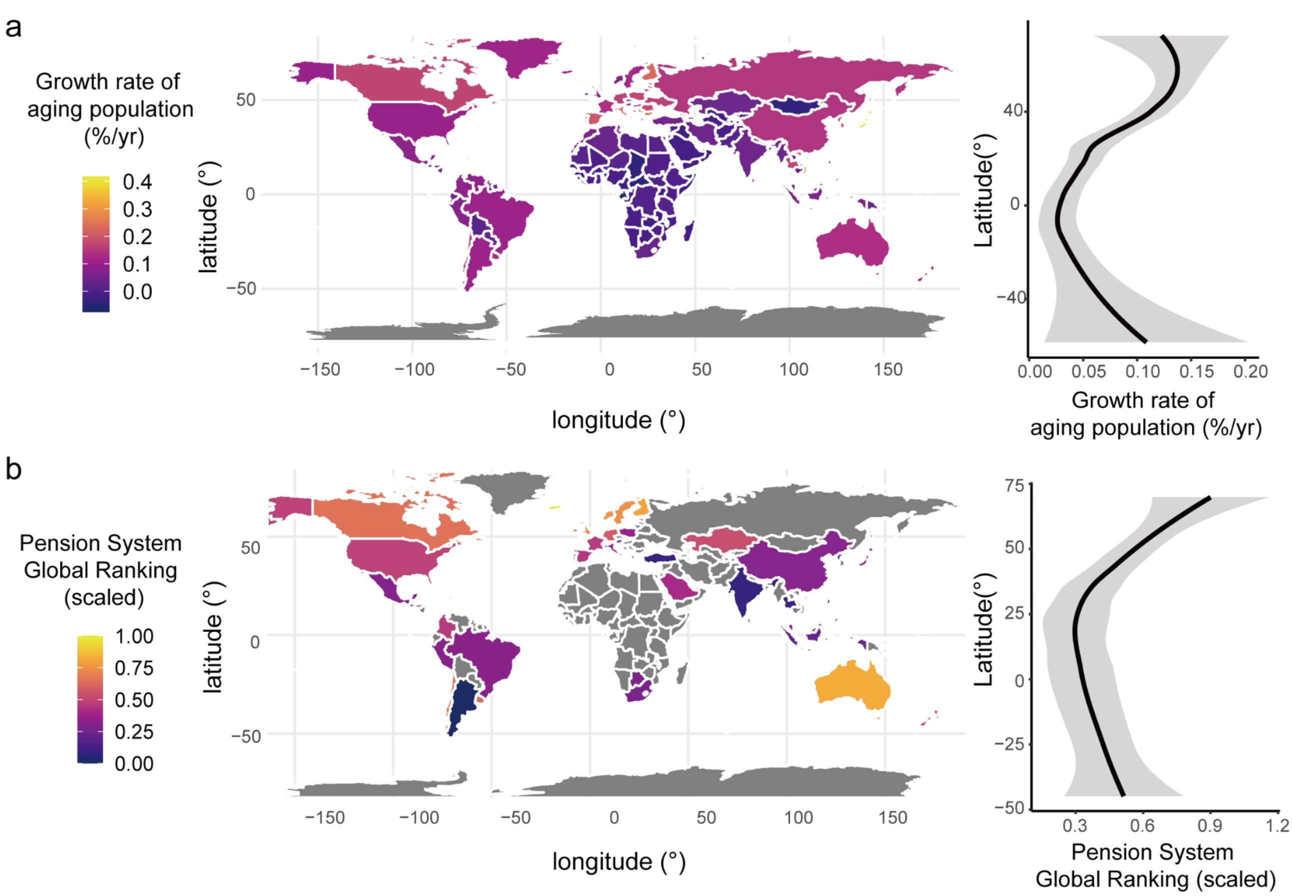

Fig. 2 Global distribution of growth rates of the aging population. (**a**) the growth rate of the aging population was extracted as the slopes of linear regression for the individual proportion of the annual aged population above age 65 years (%) versus year for 218 countries from the World Bank publicly available data from 1960 to 2022 (https://data.worldbank.org/indicator/SP.POP.65UP.TO.ZS), bootstrapped 10,000 times of bootstraps to avoid non-normality of the data. (**b**) Pension system global ranking for 45 countries in 2022. (https://www.mercer.com/insights/investments/). The 95% CIs are shaded in the plots on the right of panels **a** and **b**

analysis of economic, climatic, and environmental indicators sourced from various public databases (a total of 26 indicators, detailed information about these indicators is listed in Table S1). These indicators were selected owing to their established impact on demographic trends, health outcomes, and environmental conditions, which collectively shape the dynamics of aging populations [72–75].

We first performed correlation analyses between these indicators and growth rate of the aging population (Table S2). Generally, among all 26 country-level indicators, 21 were significantly correlated with the global rate of change in the older population (10 we positively correlated and 11 negatively correlated), where the factors that represent social and economic vulnerability have the highest average correlation with the rate of growth of the aging population. Specifically, the top three indicators that were positively related to global aging rates were low education level (R^2=0.32, slope=0.41), high corruption (R^2=0.31, slope=0.43) and political instability (R^2=0.22, slope=0.34), while the top three indicators that are negatively correlated with aging rates are annual temperatures (R^2=0.26, slope = -0.44), poor sanitation facilities (R^2=0.25, slope = -0.28) and economic vulnerability (R^2=0.23, slope = -0.52). Additionally, regional variations (here characterized as the variations among continents) had significant independent effects on changing global aging, but their interactive effects with these global factors were relatively less significant (Table S3). For instance, educational deprivation (F=144.77, P<0.001) and different continents (F=7.21, P<0.001) both significantly affected the rate of aging, but their interaction was not significant (F=0.71, P=0.645).

We grouped the 14 global factors into seven stressor groups and calculated their correlations with growth rates of the aging population to further categorize the impact of these factors (157 countries, Fig. 3, Table S2). This grouping allowed us to observe how combinations of factors influence growth rates of the aging population. For instance, the stressor group related to extreme climate (including indicators such as consecutive dry days and tropical nights), showed a stronger correlation (R^2=0.08) with growth rates of the aging population compared with averaged individual factors (averaged R^2=0.036). Unexpectedly, in addition to the stressor groups of socio-economic vulnerability, high temperatures and extreme climate that demonstrated significant positive correlations with aging rates, other factors showed significantly negative relationships.

The results of PCA provided further insights into the primary factors influencing growth rates of the aging population. The PC_1 values characterized changes mainly from economic vulnerability and climatic stressors, and PC_2 values characterized changes mainly from environmental stressors. We found that the values of PC_1 showed a significantly positive relationship with growth rates of the aging population (R^2 = 0.14, P<0.001), but PC_2 did not show a significant impact on growth rates of the

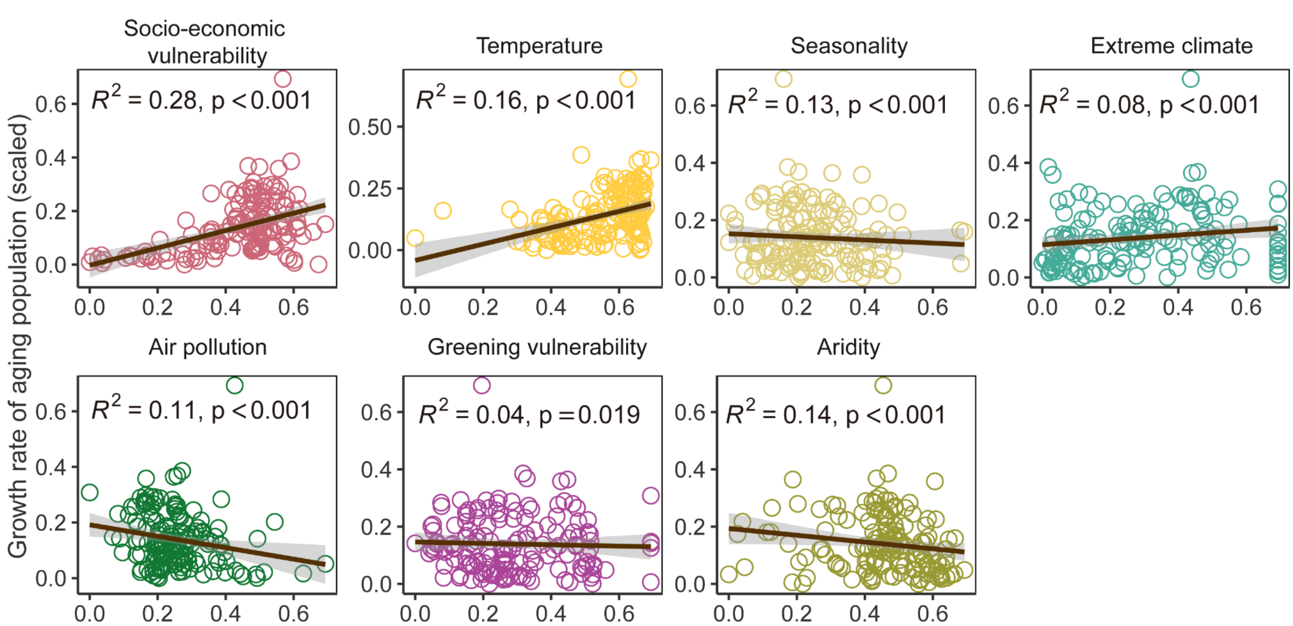

Fig. 3 Relationships between economic, climate and environmental stressors and the growth rates of the aging population. We included seven composite variables of economic, climatic, and environmental stressors: socio-economic vulnerability, temperature, drought, seasonality, climate extremes, air pollution, and greening vulnerability. An explanation of the indices included in each composite variable is given in Table S1. We found a linear relationship between different stressors and the growth rate of the aging population (normalized to between 0 and 1) for 157 countries. Adjusted R2, *P* values, and 95% CIs are shown

aging population (R^2 = 0.004, P=0.41; Fig. 4). This further supports our conclusion that increased stress related to socio-economic and climate factors is more likely to accelerate the global rate of aging.

The number of stressors operating simultaneously over medium levels decreased the global aging rates

Given the potential coexistence of various global stressors in different regions, we systematically assessed the relationship between the number of stressors exceeding all possible threshold values (5–95%) and the growth rates of the aging population (Fig. 5a and Table S4). By iteratively calculating the effect of the number of stressors exceeding selected thresholds on growth rates of the aging population, we determined that these thresholds represent an assumed minimum level of stressor required to detrimentally affect growth of the aging population [76].

Our analysis showed that the global aging rate exhibited a change from positive to negative with an increase in the number of high-level stressors (Fig. 5a and b, and Table S4). Interestingly, a threshold of >50% of stressors may serve as an important inflection point for the collective impact of stressors. For example, at lower thresholds (e.g., < 50%), the increase in the number of stressors is largely constant and has a positive effect. In contrast, at a threshold of >50%, this effect weakened or even became negative (i.e., a negative correlation between the number of stressors and the global aging rate, as shown for the threshold of >75%). This suggests that the cumulative effect of multiple stressors has a stronger inhibitory effect on the growth of the aging population at higher thresholds than at moderate thresholds.

To more thoroughly evaluate the significance of multiple stressors at different critical thresholds (we selected >25%, > 50%, and >75% as representative), we used multimodel inference to test whether the number of stressors consistently appears in the best models (see Methods section). The analysis results showed that besides temperature (included in all the best models), the degree of aridity and the number of stressors exceeding the >25% threshold are consistently selected as factors in most of the best models predicting global growth rates of the aging population (Table S5, appearing in 16 out of 26 of the best models). This indicates that, after controlling for individual stressors, the number of multiple stressors under high-threshold conditions significantly impacts the prediction of growth rates of the aging population. The full models, which include all dependent variables in a generalized linear additive model, also highlight this point, showing the importance of the number of stressors (Fig S5c).

Next, we examined the interactions among three sets of composite variables— socio-economic, climatic, or environmental factors—and multiple stressor indices at the >25% threshold or >75% threshold (Fig. 5d and Table S6). The results showed that the effects of individual stressors on the global aging population rates generally increased under the high-level stress threshold (>75%) compared to the low threshold (>25%; Fig. 5d and Table

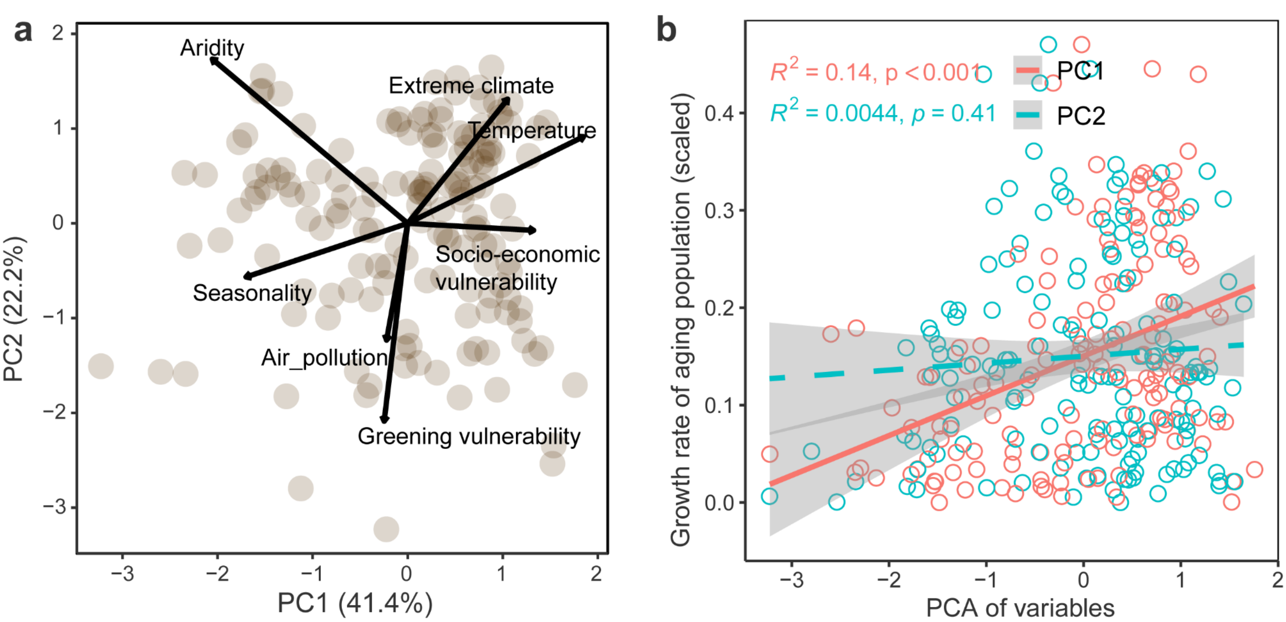

Fig. 4 Principal component analysis (PCA) of seven global stressors. (**a**) The seven stressors were downscaled us PCA, where PC1 values characterize changes mainly from climatic and economic stressors, and PC2 values characterize changes mainly from environmental stressors. (**b**) We tested the relationships between the different principal components and the scaled growth rates of the aging population. The adjusted R^2, P values, and 95% CIs are shown

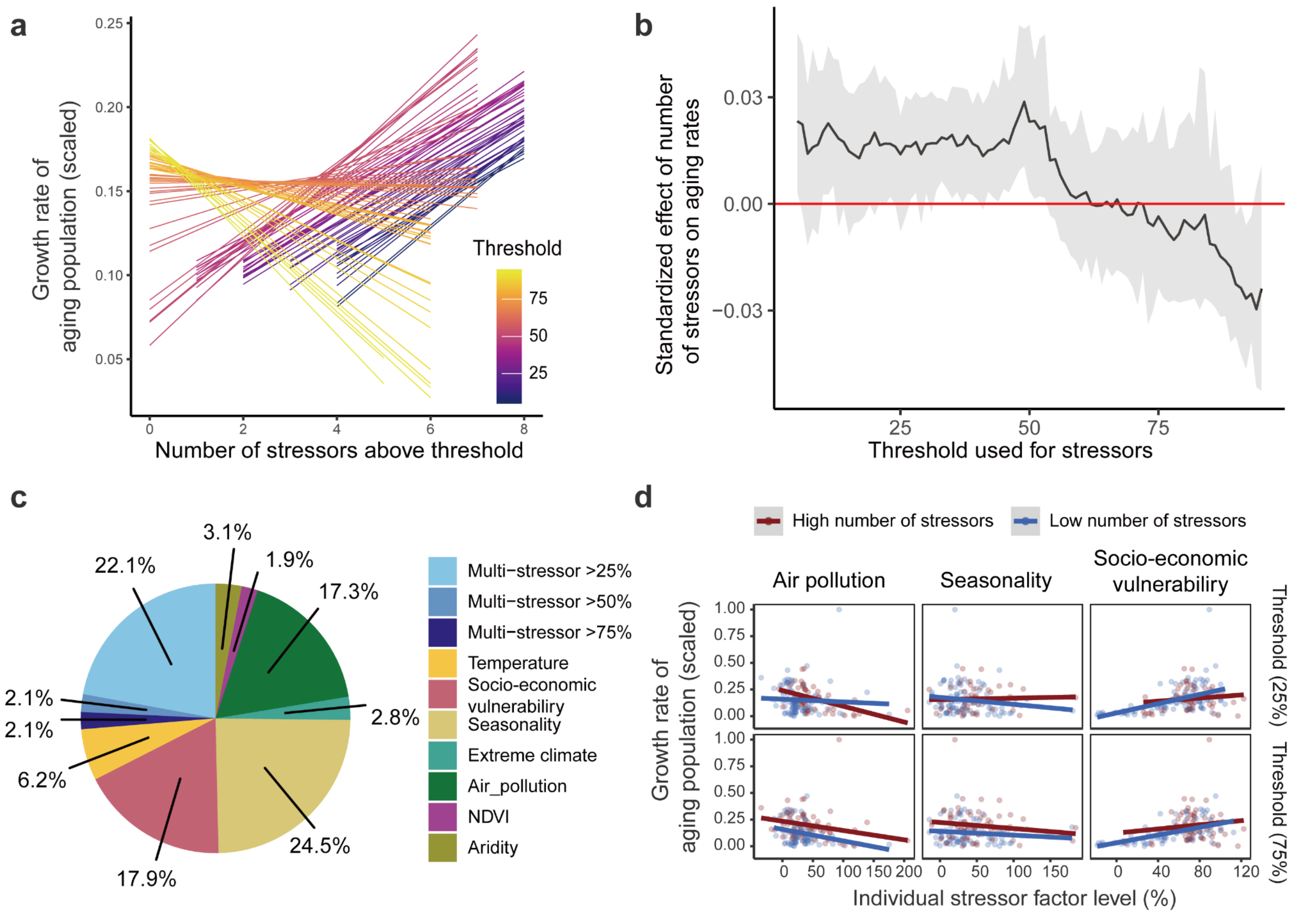

Fig. 5 Stressors operating above high levels reduced the positive effects on the global growth rates of the aging population. (**a**) Demonstration of linear regressions of the number of stressors exceeding each threshold (measured as % maximum value of each stressor) and the growth rates of the aging population ($n=157$). (**b**) Changes in standardized effect values with increasing thresholds shown in panel a, the shaded areas correspond to the 95% CIs of the average standardized coefficients. (**c**) Quantitative assessment of the significance of each predictor of the saturated generalized additive model ($R^2=0.436$) using the variance partitioning scheme, with the percentage showing explained variance (R^2) associated with each factor. (**d**) The number of stressors operating at high-stress levels reduces the negative impact of individual stressors. Interaction effects between individual stressors (standardized values of air pollution, seasonality, socio-economic vulnerability and the number of stressors over (red) or below (blue) different threshold (25 and 75%) stress levels are shown. More information correlated to panel **d** is shown in Table S3

S6). Specifically, the models under high threshold conditions generally had higher explanatory (e.g., the average R^2 for >25% threshold was 0.12 and the average R^2 for >75% threshold was 0.16, $P<0.001$).

Our results deepen current understanding regarding the role of multiple stressors in driving the dynamics of population aging by explicitly considering the number and intensity of stressors in the real world. Previous studies on aging populations have often been constrained by limitations in data analysis approaches that typically focus on a limited set of factors at fixed levels [77], making it challenging to capture the complexity of multiple interacting stressors. In contrast, our approach fundamentally reflects the natural variation in these factors, translating them into quantifiable variables via a threshold-based approach [22, 23]. This allowed us to examine the cumulative effects of multiple stressors in different environmental and socio-economic contexts. Our results showed that global aging rates are highly sensitive to the accumulation of stressors, with a critical inflection point occurring when more than 50% of stressors exceed their respective thresholds. At this level, the collective impact of stressors can not only weaken but can even reverse the pace of aging, indicating that high-stress levels have a significant dampening effect on the aging of the population. This highlights the importance of considering the combined impact of multiple stressors rather than focusing on individual factors in isolation.

Because the changes in the aging population may be regulated by other related demographic factors, we additionally analyzed two demographic factors, including the net migration rate (NMR; migration rate per 1000 people) and mortality rate of people aged under 60 years (MR60). The correlation results showed that the aging rate is significantly negatively correlated with the MR60. Furthermore, we showed that MR60 is also closely related to high-level stressors and showed very different results from global aging. The global mortality rate of people under 60 showed a negative to positive change with increasing levels of high stressors, and the number of stressors above the 75% threshold was an important predictor. This suggests that other demographic factors that correlate with the rate of change in the aging population are also significantly affected by the number of global stressors that act simultaneously.

We especially explored the roles of the NMR and MR60 as two potential mechanisms explaining the effects of different stressors and the number of stressors on the rate of aging. If these do represent mechanisms, then controlling for them when predicting the rate of aging would lead to a reduction in the magnitude of the effects of stressors. In fact, found that these investigations eliminated the potential mediating effects of the NMR and MR60 on global aging. On average, models containing the NMR and MR60 resulted in a corresponding stressor effect of 0.012 and 0.020 standard deviations, respectively. This suggests that both NMR and MR60 may represent potential mechanisms explaining the effects of various stressors on the rate of population aging. This may be because of the influence of economic and socio-political factors on the relationship between climate change and the rate of population aging, which occurs in diverse ways [78]. Moreover, climate change and environmental depletion can potentially disrupt people's livelihoods and, in certain instances, give rise to and facilitate the emergence and spread of conflict [38]. This is particularly evident in regions characterized by weak governance, which often results in increased mortality, forced displacement, and migration [79]. In summary, by using indirect estimation methods, we provide additional support for the role of other demographic factors in explaining the relationship between stressors and the global rate of population aging.

Finally, we divided the 156 countries into three categories (i.e., those facing low, medium, and high aging population pressures) based on the current observed aging rates and we performed random forest modeling and importance ranking of predictors for each category (Fig. 6). Overall, socio-economic vulnerability, temperature, greening vulnerability and the number of stressors exceeding the 75% threshold were the most important predictors of global aging rates (Fig. 6a). Notably, we found that the importance of these predictors varied under different aging pressures (Fig. 6b, c and d). Specifically, countries with relatively fast aging rates (primarily countries in Africa and Asia) are more vulnerable to climate change (such as extreme climate and drought) and the number of global stressors exceeding the medium threshold (>50%; Fig. 6d). Other countries experiencing medium and low aging rates (mainly for countries in Asia, Europe, and North or South America) are more sensitive to socio-economic vulnerability and environmental stability-related factors (such as drought, green vulnerability, and air pollution intensity; Fig. 6b and c). Therefore, in countries with a faster rate of aging, policies should focus more on developing climate adaptation strategies that specifically consider the needs of elderly people to mitigate the broader impacts of climate change [12, 19]. Countries with relatively low aging pressures should improve the overall resilience of elderly groups by increasing their socio-economic adaptive capacity (which may include strengthening healthcare infrastructure) and focusing on environmental sustainability (especially by reducing pollution and protecting natural resources) [37, 80].

Embracing more holistic policies in response to the accelerating global aging trend

Figure 7 shows the three key fields highlighted herein to confront the accelerating global rate of aging, which influence each other and may also be affected by demographic changes as follows. 1) Social care and economic development: As aging populations grow, the demands for health care services, pensions, and social support increase; strong economic development is needed to sustain these services [27]. Developed economies typically have more robust pension systems and healthcare coverage, which enables older people to maintain their quality of life after retirement [19]. However, less economically developed countries may lack adequate social security, and the elderly population often must continue working, which may lead to increased health problems and shorter life expectancy, which in turn affects the aging process [42]. 2. Climate change: Elderly people are particularly vulnerable to extreme weather events, rising temperatures and other climate-related stresses [81]. Such vulnerability is caused by several factors, including age-related health conditions, reduced mobility, and generally greater sensitivity to heat and pollution [25, 82]. As climate change exacerbates these risks, countries with a rapidly aging demographic must incorporate climate adaptation strategies that specifically address the needs of older people [19, 83]. This may include improving the healthcare infrastructure to address climate-related health issues and ensuring that older people have access to resources during extreme climate events [84]. 3. Environmental protection: This area emphasizes the need for environmental sustainability, which is essential to protect the aging population from the effects of environmental degradation, such as air and water pollution [85]. Ensuring clean air and water and maintaining green spaces are essential for the health and well-being of older people [41]. Additionally, sustainable environmental practices

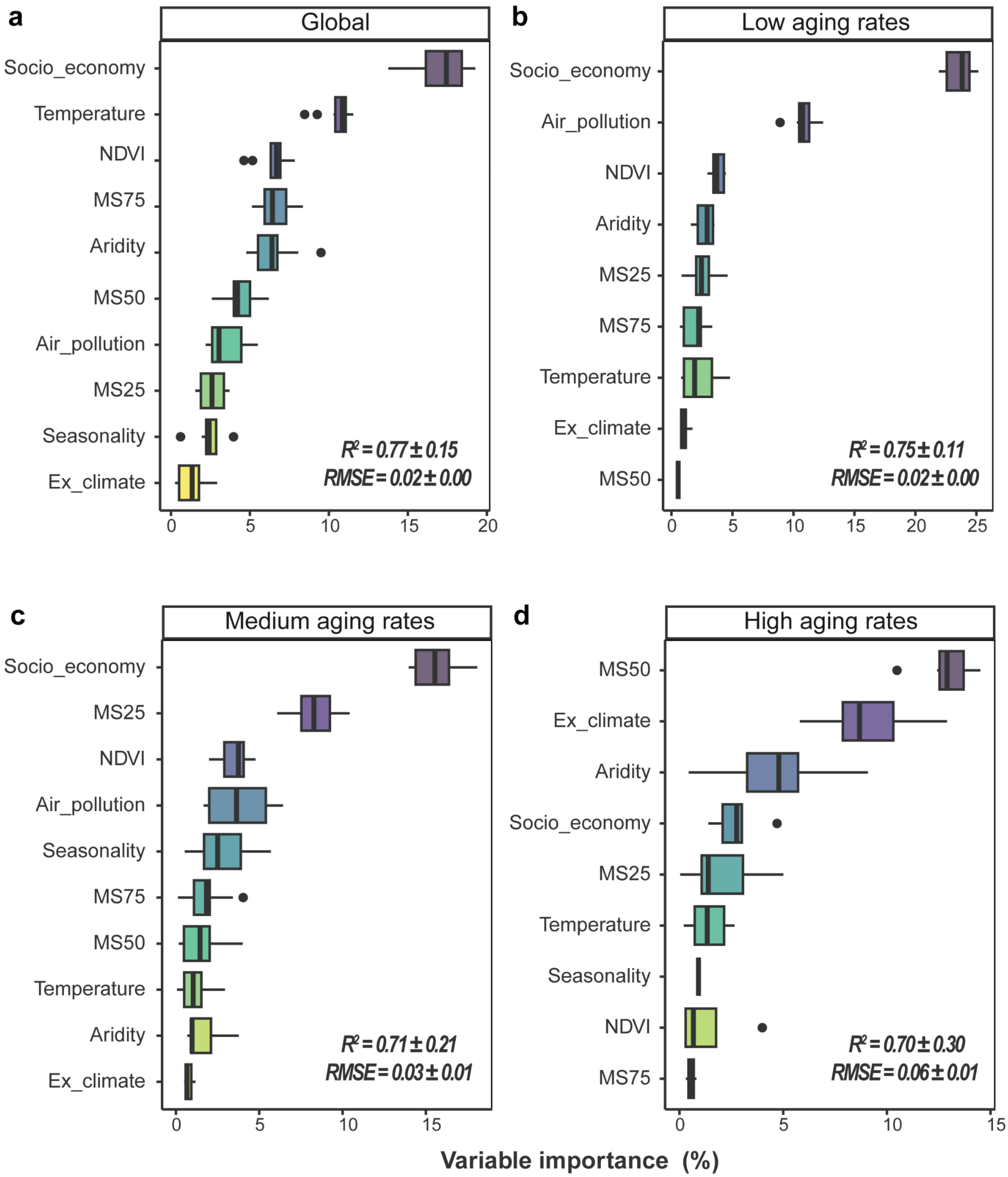

Fig. 6 Importance of global stressors and different thresholds in predicting the rate of global aging in regions with different aging pressures. Using random forest modeling to assess the impact of different global stressors on the global rate of aging, we considered all stressors and the number of stressors above specific thresholds (i.e., > 25, > 50, and >75%). Panels **a**, **b**, **c**, and **d** represent total global prediction and prediction of countries with relatively low, medium, and high rates of aging, respectively (i.e., the data were divided into three equal groups according to the rate of aging). For random forest modeling, we used box plots to assess the importance of each environmental variable 1000 times and calculated the average root mean square between the model prediction and observed values

Fig. 7 Integrating multiple factors in response to accelerating global aging. The concept map illustrates the multifaceted nature of the response to challenges posed by accelerating global aging, highlighting the need to shift in the direction of policy support for elderly populations in relation to climate change and environmental protection, based on social care as well as economic development

help mitigate the widespread effects of climate change, which in turn supports the overall goal of healthy aging [86].

Policymakers must integrate economic, social, and environmental policies in a coordinated and strategic manner to effectively address the multifaceted challenges of global aging. Such integration can help build resilient communities in which aging populations can be supported under various global stressors and can help to capture the complex interactions between demographic change and environmental risks, such as the increased vulnerability of older people to extreme weather events and pollution [83, 87]. Moving toward a more comprehensive policy framework can not only help develop targeted strategies but will also allow for reflection on ways to enhance social resilience, thereby ensuring that aging populations are adequately protected and supported in a social environment that is increasingly affected by global changes.

Conclusion

Although this study provides valuable insight into the complex dynamics of global aging, it is important to acknowledge certain limitations. The integration of demographic and non-demographic factors, such as environmental and climate variables, may not fully capture nuanced interactions that influence aging populations [88]. Additionally, potential oversimplification of these stressors, data quality issues, and reliance on modeling assumptions could affect the accuracy of predictions. This study could also benefit from a more robust scenario analysis to explore a wider range of potential outcomes and consideration of regional specificities to avoid overgeneralization across diverse contexts (e.g., various RCP situations [89]). Moreover, we did not incorporate longitudinal data or control for all potential confounders, which resulted in our conclusions being limited to observed associations rather than direct causal effects. Incorporating long-term time series data and conducting counterfactual analyses, such as observing changes with alteration of specific variables, is also important [90].

Despite the limitations, our study emphasizes that to address accelerating population aging, the cumulative effects of multiple global stressors of change must be considered rather than the effects of a single stressor. This highlights that policy tools or methods must be developed that take into account the holistic dimension of the global factor [23]. Future research should shift the focus to comprehensive environmental, climatic, and policy frameworks that address the complex interactions of multiple stressors, which are essential for predicting and mitigating the effects of global change on population aging. Research on multiple stressors affecting the life expectancy of the elderly population is also important, as more stressors may lead to reductions in life expectancy and influence the overall aging dynamics. Additionally, as other demographic factors (e.g., migration and mortality) continue to change, policymakers should adopt comprehensive and adaptive policies (e.g., considering geographic heterogeneity) to address the indirect or direct impacts of the multifaceted nature of these challenges [91]. In summary, by considering the combined effects of multiple stressors and implementing targeted interventions, more effective strategies can be developed to address the acceleration in global population aging.

Supplementary Information

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Supplementary Material 1

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Author contributions

KH, YP and HY conceived the framework of the paper and prepared a first draft of the article. KH and YP contributed equally to this paper and are joint first authors. All authors performed the in-depth and final analyses of data and synthesised results through discussions. All authors provided oversight and strategic guidance for the implementation of the study as a member of the steering committee of the study. All authors critically reviewed the draft, contributed to the finalisation and approved the final manuscript.

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Data availability

Data are available upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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