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Projections of ambient temperature- and air pollution-related mortality burden under combined climate change and population aging scenarios: A review

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Abstract

Purpose of review Climate change will affect mortality associated with both ambient temperature and air pollution. Because older adults have elevated vulnerability to both non-optimal ambient temperature (heat and cold) and air pollution, population aging can amplify future population vulnerability to these stressors through increasing the number of vulnerable older adults. We aimed to review recent evidence on projections of temperature- or air pollution-related mortality burden (i.e., number of deaths) under combined climate change and population aging scenarios, with a focus on evaluating the role of population aging in assessing these health impacts of climate change. We included studies published between 2014 and 2019 with age-specific population projections.

Recent findings We reviewed 16 temperature projection studies and 15 air pollution projection studies. Nine of the temperature studies and four of the air pollution studies took population aging into account by performing age-stratified analyses that utilized age-specific relationships between temperature or air pollution exposures and mortality (i.e., age-specific exposure-response functions [ERFs]). Population aging amplifies the projected mortality burden of temperature and air pollution under a warming climate. Compared with a constant population scenario, population aging scenarios lead to less reduction or even increases in cold-related mortality burden, resulting in substantial net increases in future overall (heat and cold) temperature-related mortality burden.

Summary There is strong evidence suggesting that to accurately assess the future temperature- and air-pollution-related mortality burden of climate change, investigators need to account for the amplifying effect of population aging. Thus, all future studies should incorporate age-specific population size projections and age-specific ERFs into their analyses. These studies would benefit from refinement of age-specific ERF estimates.

Keywords Climate change; Population aging; Temperature; Air Pollution; Mortality; Projection

Introduction

Climate change has profound implications for public health. Health impacts of climate change may be either direct or indirect. Direct impacts result from rising ambient temperature and more frequent extreme weather events, whereas indirect impacts are mediated through human and natural systems. Indirect impacts include deteriorating ground-level air quality, increased infectious disease incidence, food insecurity, and post-disaster mental disorders [1].

Rising ambient temperature is the most immediate and direct impact of climate change [2], with morbidity and mortality increasing at non-optimum temperatures (both high and low) [3-5]. Heat (cold) exposure in a given location is defined as temperatures higher (lower) than the optimum temperature corresponding to the temperature associated with minimum morbidity or mortality in the local temperature distribution. Often, the exposure of interest is extreme heat or cold (e.g., the >95th or <5th percentile) or prolonged extreme heat (i.e., a heat wave) or extreme cold (i.e., a cold spell). In addition, climate change is expected to worsen air quality through a variety of mechanisms, including an increased frequency of wildfires that emit fine particulate matter ($PM_{2.5}$) and other air pollutants, increased background tropospheric ozone concentrations, and unfavorable meteorological changes (e.g., precipitation and wind speed) in already polluted regions [1, 6].

Globally, ambient air pollution was estimated to contribute to 7.6% of total deaths in 2015 [7] and non-optimum temperatures might account for a similar proportion (7.7%) of mortality [8]. Given the substantial health burdens associated with air pollution and non-optimum temperatures, projecting their future health impacts is critical to understanding and reducing the potential future adverse public health effects of climate change.

While the climate is changing, the world's population is also growing older. In 2018, for the first time in human history, people aged 65 years and older constituted a greater proportion of the world's population than children under five years of age. The proportion of the world's population aged 65 years and older is projected to rise from the current 9% to 16% in 2050 [9]. Due to factors such as a high prevalence of chronic diseases, declining physiological protective mechanisms, and social isolation, older adults are particularly vulnerable to the adverse health effects of both ambient temperature and air pollution [2,5, 10-12], making age a modifier of the effects of these exposures. Thus, the demographic shift toward an older world population may amplify these adverse health impacts of climate change.

Projections of the future mortality burden (i.e., number of deaths) associated with ambient temperature and air pollution under climate change scenarios generally require the following inputs: a) the modelled exposure levels (i.e. temperature, air pollutants) based on a specific future climate scenario; b) the size of the population at risk; c) the baseline mortality rate in the study population; and d) an estimate from prior epidemiological studies of the relationship between the ambient temperature or air pollution exposure of interest and mortality (i.e., the exposure-response function [ERF]), under the assumption that the relationship is causal [13]. For example, under model assumptions these inputs have been used to project heat-related mortality in 2050 by computing the number of excess deaths due to heat on each day of the year, based on modelled daily temperature values, and then summing them over the year [13].

Because age modifies the effects of both ambient temperature and air pollution on mortality, to maximize the validity of projections, age needs to be considered. First, projections of the future size of the population at risk should be age-specific, taking into account changes in the age structure of the population. Second, age-specific ERFs should be applied. Third, to fully assess the future mortality burden on the overall population, analyses should not be restricted to the elderly. Rather, age-stratified analyses using age-specific ERFs should be performed spanning the entire age range. Given the projected aging of the world's population over the remainder of this century, such age-stratified analyses are essential to avoid underestimation of the future mortality burden.

Previous reviews have evaluated studies projecting future heat- or air pollution-related mortality burden under climate change scenarios [13-18]. However, no review to date has systematically examined the impact of population aging on projected temperature- or air pollution-related mortality burden under climate change. Furthermore, although recent epidemiological evidence suggested a much larger mortality burden attributable to cold compared to heat exposure [8, 19-21], no review has addressed future cold-related mortality burden and the net change in temperature (cold and heat)-related mortality burden under both climate and population changes.

We here aim to review original population-based quantitative research articles on projections of temperature- or air pollution-related mortality burden under combined climate change and population aging scenarios. We only include recent studies from the past six years that considered population aging by applying age-specific population projections. We then stratify these studies according to whether or not they conducted age-stratified analyses applying age-specific ERFs.

Methods

We conducted a literature search in November 2019 using the databases MEDLINE/PubMed (National Library of Medicine 2019) and Web of Science (Clarivate Analytics 2019). We limited our search to journal articles published in English from 2014 to 2019 focusing on recent evidence in the past six years. To identify population-based research articles on projecting future temperature-related mortality burden under climate and population changes, we used the following keywords: “climate change,” AND “temperature,” AND (“mortality” or “death”), AND (“projection” or “projecting” or “projected” or “future”), AND “population.” To identify articles on projecting future air pollution-related mortality burden under climate and population changes, we used the following keywords: “climate change,” AND (“air pollution” or “air quality”), AND (“mortality” or “death”), AND (“projection” or “projecting” or “projected” or “future”).

We then screened titles and abstracts to identify studies with quantitative projections of future temperature- or air pollution-related mortality burden under global climate change scenarios. Articles not estimating the mortality burden of ambient temperature or air pollution or not projecting the future mortality burden of global climate change, were excluded, as were reviews, editorials, book chapters, and conference abstracts. Next, we screened the full text of the remaining articles to remove articles that did not consider population aging by applying age-specific population projections, or only considered all ages combined and applied a single ERF without age-stratification, in projecting the future mortality burden.

Results

Characteristics of eligible temperature studies

The literature search yielded 482 unique English research papers for temperature-related mortality impacts. Most of these articles did not estimate temperature-related human health impacts (e.g., only examined temperature exposure or focused on mortality in animals or plants) (n=295), studied current or past mortality impacts (n=84), did not consider future population change (n=15), only considered all ages combined (n=24), or were reviews, editorials, or book chapters (n=48). After the exclusions, 16 papers met our inclusion criteria for investigating the future mortality burden of ambient temperature.

Table 1 summarizes key characteristics of these 16 articles. Half made projections for East Asia (four from China and four from South Korea), and half made projections for the US (n=4), Europe (n=3), or Australia and the UK (n=1). Twelve studies focused only on future heat or heat wave effects, whereas only four studies estimated future effects from both heat and cold. Fourteen studies estimated the future mortality burden of short-term (i.e., daily) temperature exposure and only two studies evaluated the future mortality burden of long-term temperature exposure (i.e., summer average temperature [22] or annual heatwave severity parameters [23]).

Thirteen studies examined the all-cause or non-accidental cause mortality burden. The other three investigated heat disorder deaths, cardiorespiratory deaths, or years of life lost (YLL) due to cardiovascular deaths. With respect to climate scenarios, five studies applied the Special Report on Emissions Scenarios (SRES) that were used in the Intergovernmental Panel on Climate Change (IPCC) Third and Fourth Assessment Reports in 2001 and 2007, respectively. Eleven studies applied the Representative Concentration Pathway (RCP) scenarios that were used in the IPCC Fifth Assessment Report in 2014. Half of the studies used sub-national-specific population scenarios, while the other half used national level projections from the United Nations World Population Prospects (UN WPP) (n=5) or Shared Socioeconomic Pathways (SSP) (n=3). Only three studies considered future changes in baseline mortality rate (BMR).

All reviewed studies considered population size change in one or multiple age groups when projecting future temperature-related mortality burden under climate change. To estimate the future mortality burden, ten studies stratified by age, with nine of these studies spanning the entire age range, and one examining ages ≥20 years. Of the 10 studies that stratified by age, nine applied age-specific ERFs, whereas one included an aging ratio (proportion of elderly in total population) as an independent predictor in a multivariate regression model for deaths by exposure to excessive natural heat as determined from death certificates [23]. Of the nine studies that applied age-specific ERFs, eight estimated age-specific ERFs based on their own daily mortality and meteorological data [24 ••, 25 •, 26 ••, 27-31], whereas one used age-specific ERFs from an earlier epidemiological study in the same location [32]. Six studies estimated the future mortality burden in a single age group without stratifying by age – in five the single age group was at least ≥65 years, whereas in one the single age group was ≥30 years. Thus, these six studies did not consider the entire population and only projected the temperature-related mortality burden for a sub-set of the population (mostly the elderly).

Characteristics of eligible air pollution studies

The literature search identified 236 unique English research papers for air pollution mortality impacts. Most of the articles did not study human health impacts (n=52), did not estimate mortality impacts of ambient air pollution (n=51), did not project future mortality impacts under global climate change (n=30), did not consider future population change (n=13), only considered all ages combined (n=15), or were reviews, editorials, or book chapters (n=60). Excluding these articles, we found 15 papers that met our inclusion criteria for investigating the future mortality burden of air pollution.

Table 2 summarizes key characteristics of these 15 articles. Four had a global focus, whereas six focused on the US, two on Europe, two on China, and one on India. Nine studies examined both $PM_{2.5}$ and O_3 exposure, three studies only examined O_3 exposure, and three studies only examined $PM_{2.5}$ exposure. Most studies (n=13) examined long-term (annual or seasonal) exposure, with two of these studies also examining short-term (daily) O_3 exposure. In addition, two studies only examined short-term exposures.

Most studies (n=11) examined the future mortality burden of at least one specific cause of death, including heart disease, stroke, respiratory disease, and lung cancer, whereas four studies focused on either all-cause or non-accidental mortality. Most studies (n=10) used the RCP climate scenarios, one used SRES, and four focused on specific greenhouse gas (GHG) mitigation policies -- those needed to achieve global warming targets (1.5 °C, 2°C, or 2.5°C) [33-35] or an 80% GHG reduction scenario [36]. Six US studies used sub-national (e.g., gridded or county level) population projections from the Environmental Benefits Mapping and Analysis Program (BenMAP) or the State of California, two European studies used gridded population projections from the European INTARESE and HEIMTSA projects, and seven studies used national level projections from the SSP (n=3), the UN WPP (n=2), or the International Futures (IF) (n=2). Eleven studies considered future changes in BMR.

All reviewed studies considered the change in population size for one or multiple age-specific groups when projecting the future air pollution-related mortality burden under climate change. To estimate the future mortality burden, six studies stratified by age, with one study spanning the entire age range, one study examining ages ≥5 years, one study examining ages ≥30 years, and three studies examining ages ≥25 years. Of the six studies that stratified by age, four applied age-specific ERFs, whereas two did not. Of the four studies that applied age-specific ERFs, three applied integrated age-specific ERFs used in the Global Burden of Disease Study [37] for long-term $PM_{2.5}$ exposure in relation to ischemic heart disease and stroke mortality [38 ••, 39, 40]. The fourth study in China [41 ••] used age-specific ERFs for short-term ozone exposure from a recent nationwide time-series study in 272 Chinese cities [42]. Nine studies examined a single broad age range (mostly ≥30 years) to estimate the future mortality burden, without stratifying by age. Rather, they applied a single ERF to the entire age range. Thus, these nine studies did not consider the entire population and only projected the air-pollution-related mortality burden for a sub-set of the population.

Summary of Findings

Population aging, taken into account using age-specific population size projections and age-specific ERFs, amplifies the projected mortality burden of increases in temperature and air pollution under a warming climate. We discuss the impact of population aging on future temperature- and air-pollution-related mortality separately.

Impact of population aging on future temperature-related mortality

All reviewed temperature studies found an increasing heat-related mortality burden in the future, except for one study which found decreases in the heat-related mortality burden in some areas of the Nordic region [43]. The latter study, which only examined the elderly (≥65 years in Finland and Sweden and ≥67 years in Norway), found that a decline in the elderly population size in some municipalities would outweigh the increasing heat exposure and result in a decreasing heat-related mortality burden in the future [43]. Studies that compared population aging scenarios with a constant population scenario generally found a substantially greater temperature-related mortality burden under population aging scenarios versus a constant population scenario [26 ••, 27, 32, 44]. For example, a study of seven major cities in South Korea considered two population scenarios based on the United Nations world population prospects, each of which involved considerable population aging, but a decrease in the size of the total population. Under each of these population aging scenarios, despite the decrease in total population size, the temperature-related mortality burden was projected to increase four- to six-fold in the 2090s compared to 1992-2010 under any climate scenario, versus a maximum increase of 1.5-fold assuming no population aging [26 ••]. Under the RCP8.5 climate scenario, a study in Houston, Texas projected three times more heat-related deaths in 2061-2080 using SSP3 population projections compared with using a constant population assumption [32], even though the total population was projected to decrease under the SSP3 population scenario.

Each of the four studies that examined both heat and cold exposure conducted age-stratified analyses applying age-specific ERFs, and all of these studies found a net increase in temperature-related mortality [24 ••, 25, 26 ••, 27 •]. In the UK, cold-related mortality was projected to decrease by 2% from the 2000s to the 2050s under population aging versus a 26% reduction in cold-related deaths when population aging is not taken into account [24 ••]. Similarly, from the 2020s to the 2050s in Australia, cold-related mortality was estimated to decrease by 2% and 17% with and without population aging, respectively [25 •].

Impact of population aging on future air-pollution-related mortality

Most of the reviewed studies found that changes in population size and age structure will have notable to dominant implications for future air pollution-related mortality, leading to an increased future mortality burden under high GHG emission scenarios [39, 40, 41 ••, 45-49] or decreased mortality benefits under low GHG emission scenarios [38 ••, 50]. The studies focusing on mortality benefits of GHG mitigation policies did not specifically quantify the impact of population aging [33-36].

Population aging may have a greater effect than future changes in BMR on the future air pollution-related mortality burden. Although BMR will continue to fall along with expected increasing life expectancy, this benefit may be offset by population aging. For example, for the age group ≥30 years, about half of the states in the US under RCP8.5 will have rising $PM_{2.5}$ -related mortality burden in the 2050s compared to the 2000s when considering population growth of this age group, despite decreases in future BMR and future $PM_{2.5}$ concentrations [45]. BMR in China in 2053-2055 is projected to fall by 50% for people aged 65-74 years and 17% for people aged 75 years and older compared to 2013-2015. This BMR improvement by itself would lead to a 53% to 111% reduction in the ozone-related acute mortality burden under different SSP population scenarios [41 ••]. However, taking into account both population aging and age-specific ERFs results in a 110% to 363% increase in the ozone-related mortality burden in China in 2053-2055 versus 2013-2015 under different scenarios of climate and population changes [41 ••]. In India, increasing $PM_{2.5}$ concentrations under RCP8.5 combined with the rapid increase in an aging population under SSP3, will offset the reduction in BMR and thus result in a net increase in $PM_{2.5}$-related mortality burden after 2050 compared with 2001-2005 [40].

Population aging appears to have a stronger effect on future air-pollution-related mortality burden than population size change alone. In Europe, the total population is projected to increase by only 3% from 2000 to 2050, whereas air pollution-related mortality burden in the age group ≥30 years is projected to increase by 13%, mainly due to a > 85% increase in the number of people aged 65 years and older [51]. In China, the total population size in 104 cities in 2050 is projected to decrease by 0.5% to 5.6% compared to 2010, whereas the proportion of older adults between 65 and 74 years and 75 years and older will increase from 5.2% to 11.7%–14.0% and from 3.0% to 12.0%–19.0%, respectively [41 ••]. Compared with population aging, the decrease in total population size will have a neglectable impact on ozone-related excess mortality [41 ••].

Discussion

In this review, we evaluated the recent evidence on the impact of population aging in assessing the future mortality burden from ambient temperature and air pollution under climate change. We identified 16 temperature studies and 15 air pollution studies that considered age-specific population size projections in analyses. Nine of the temperature studies and four of the air pollution studies employed the "gold standard" approach of conducting age-stratified analyses utilizing age-specific ERFs and summing the stratified results over a broad age group. Findings of this review suggest that population aging would result in increased mortality burden attributable to future temperature- and air pollution-level changes associated with climate change by increasing the number of older adults, who have elevated vulnerability to non-optimal ambient temperature and to air pollution.

All reviewed temperature projection studies addressed heat-related mortality burden, but only four studies addressed both heat- and cold-related mortality burden. Due to the warming climate, everything else being equal, one would expect future increases in heat-related mortality burden and decreases in cold-related mortality burden, with an uncertain net change in temperature-related deaths. In fact, previous studies using a constant population assumption reported significant net decreases in future temperature-related mortality burden in temperate areas [52, 53]. These net decreases were explained by a considerably greater reduction in cold-related deaths than increase in heat-related deaths. However, we found that all four reviewed studies that addressed both heat and cold, each of which took both age-specific population size projections and age-specific ERFs into consideration, projected net increases in future temperature-related mortality. Because the elderly are more vulnerable to both heat-related and cold-related mortality, in a warming world a population aging scenario that applies age-specific ERFs results in enhanced increases in heat-related mortality burden and lower reductions in cold-related mortality burden compared with a constant population scenario or with a methodology that does not conduct age-stratified analyses that apply age-specific ERFs. This reversal of direction in the net change of temperature-related deaths in temperate (UK [24 ••, 25 •] and South Korea [26 ••, 27]) and sub-tropical (Australia [25 •]) climates after accounting for population aging indicates that the future temperature-related mortality burden under climate change is underestimated when population aging is not incorporated into the analysis.

Epidemiological evidence shows that elderly people are particularly vulnerable to both short- and long-term exposure to $PM_{2.5}$ [12, 37, 54] and short-term exposure to ozone [12, 55], although further work is needed to refine age-stratified ERF estimates. However, there is limited evidence of effect modification by age of the relationship between long-term ozone exposure and mortality. Results from two American Cancer Society CPS-II cohort studies have been widely used in estimating long-term ozone-related mortality under both the current and future climates [56, 57]. No significant effect modification by age was found in the American Cancer Society CPS-II cohort study with 448,850 subjects in 96 metropolitan statistical areas in the U.S. [56], whereas in an updated analysis the effect modification was the reverse of what might be expected: a stronger association between long-term ozone exposure and respiratory mortality was observed among those aged <65 years at enrollment compared with those aged ≥65 years at enrollment [57]. A recent study using the NIH-AARP Diet and Health Study cohort did not observe significant effect modification by age, with a caveat that study participants were relatively old within a narrow age window (aged 50-71 years at enrollment) [58]. Given the high level of uncertainty about the modifying effect of age on the relationship between long-term-ozone exposure and mortality, it is not surprising that none of the nine reviewed studies that examined long-term O_3 exposure applied age-specific ERFs.

The ERFs from epidemiologic studies used in projecting the future mortality burden of temperature and air pollution under climate change are assumed to represent causal relationships. However, causal inference methods have not been utilized in the epidemiologic studies that generated the ERFs for temperature-related mortality. Application of such methods could refine ERF estimates and provide increased confidence that such estimates represent causal relationships.

All reviewed studies applied age-specific population size projections. Since 2018, SSP population scenarios have been increasingly applied together with RCP climate scenarios (Tables 1 and 2). However, not all RCP-SSP combinations are plausible. For the high emission scenario RCP8.5, only the fossil-fuel development scenario SSP5 can be used in projecting population change; and for the low emission scenario RCP2.6, the regional rivalry scenario SSP3 cannot be applied in population projections [59]. Thus, among the reviewed temperature studies, projection results using the RCP8.5-SSP1-3 combinations [27], the RCP8.5-SSP3 combination [32], the RCP2.6-SSP3 combination [31], and the RCP8.5-SSP2 combination [60] should be interpreted with caution. Likewise, caution is need in interpreting projected future air pollution-related mortality burden using the RCP8.5-SSP1-4 combinations [40, 41 ••].

Another issue in applying age-specific population size projections is potential mis-match between the spatial scale of currently available population projections and the spatial scale of climate change projections. About half of the studies used sub-national population projections, mainly from national government sources. However, the other half used country-level population projections from SSPs, the UN WPP, or IF in conjunction with climate change projections typically at the city or regional levels. Thus, there is an urgent need to develop high-quality age-specific population projections at regional and local scales. In that regard, a 2019 study projected population age structure at the county level in the U.S. under various SSP scenarios, with similar work planned for other countries [61]. Incorporating high-resolution spatial projections of population size and age structure into studies assessing the role of population aging in future temperature- and air-pollution-related mortality has the potential to enhance the validity of these studies.

In general, all-cause and cause-specific mortality rates are expected to decrease in the future [62]. Although the role of BMR projections in assessing the temperature- and air-pollution-related mortality burden under climate change was not a focus of this review, we noted that three of the 16 temperature studies and 11 of the 15 air pollution studies considered future changes in BMR in their analyses. Everything else being equal, decreasing BMR should be associated with decreasing temperature-related and air-pollution-related mortality burden.

Incorporating population aging into projections of health impacts can provide more valid estimates of the potential health threats of climate change for an aging society. These projections can inform the public and policy-makers about the public health benefits of policies and measures limiting global warming, reducing air pollution, and adapting our aging society to changing climate-related exposures.

Conclusion

All future studies should take population aging into account when projecting future temperature- and air-pollution-related mortality burden under climate change by using age-specific population size projections and age-specific ERFs. When this is done, population aging is found to amplify the future mortality burden attributable to both temperature and air pollution. Age-specific ERF estimates need to be refined, especially for long-term ozone exposure.

Compliance with Ethical Standards

Conflict of Interest. Dr. Dubrow reports a grant from the High Tide Foundation during the conduct of the study. The other authors declare they have no conflict of interest.

Human and Animal Rights and Informed Consent. This article does not contain any studies with human or animal subjects performed by any of the authors.

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Table 1. Characteristics of studies that considered population aging in projecting temperature-related mortality under climate change.

Study	Location	Study period	Exposure	Mortality	Climate scenarios	Population scenarios	BMR projections	Age groups (years)	Age-stratified analyses with age-specific ERFs	Projection results
Studies using age stratification										
Hajat, 2014 [24 ••]	UK	2020s, 2050s, and 2080s vs. 2000s	Short-term heat and cold	All-cause	SRES A1B	Region specific (UK govt)	Country specific	0-64, 65-74, 75-84, ≥85	Yes	By the 2050s, heat-related mortality will rise by 257%, and cold-related mortality will decline by 2%, leading to an increased number of temperature-related deaths.
Vardoulakis, 2014 [25 •]	UK and Australia	2020s, 2050s, and 2080s vs. 1993-2006	Short-term heat and cold	All-cause	SRES A1B, B1, and A1F1	Region specific (UK and Australia govts)	No	0-64, 65-74, 75-84, ≥85	Yes	Between the 2020s and 2050s under A1B, heat-related mortality will increase by 125% in the UK and 104% in Australia, whereas cold-related mortality will decrease by 2% in both the UK and Australia.
Kim, 2016 [23]	South Korea	2013-2060 vs. 1994-2012	Long-term heatwave	Heat disorder	RCP 4.5 and 8.5	Region specific (South Korea govt)	No	<65, ≥65	No	Heat disorder deaths will increase by five times under RCP4.5 and 7.2 times under RCP8.5 compared to the baseline period.
Lee, 2016 [26 ••]	South Korea	2010s to 2090s vs. 1992-2010	Short-term heat and cold	Non-accidental	RCP 2.6, 4.5, 6.0, 8.5	UN WPP	No	<60, 60-69, 70-79, ≥80	Yes	In the 2090s, temperature-related mortality will increase 4-6 fold when considering population aging versus a 50% decrease to a 1.5-fold increase when not considering population aging.
Lee, 2018 [27]	South Korea	2016-2090s vs. 1991-2015	Short-term heat and cold	Non-accidental	RCP 4.5, 8.5 and 1.5 °C, 2 °C	SSP1-3	No	0-59, 60-79, ≥80	Yes	In the 2090s under RCP4.5, temperature-related mortality will increase 2.07- and 3.87-fold for the 1.5°C and 2 °C warmings under both climate and population aging, whereas it will increase by less than 1.13- and 1.26-fold for the 1.5°C and 2 °C warmings, assuming a constant population.
Marsha, 2018 [32]	Houston, Texas, US	2061-2080 vs. 1991-2010	Short-term heat	Non-accidental	RCP 4.5 and 8.5	SSP3 and SSP5	No	<5, 5-65, >65	Yes	Under the RCP4.5-SSP3 scenario, heat-related mortality will increase by 200%, whereas it would increase by only 1% assuming no population change.
Lee, 2019 [29]	South Korea	2000-2090s vs. 1991-2015	Short-term heat	Non-accidental	RCP 4.5 and 8.5	UN WPP	No	0-69, ≥70	Yes	In the 2090s, due to climate and population changes, heat-related mortality will increase by 5.1 times for RCP4.5 and 12.9 times for RCP8.5.
Liu, 2019 [30]	Guangzhou, China	2030s, 2060s, and 2090s vs. 1980s	Short-term heat	Non-accidental	RCP 2.6, 4.5 and 8.5	Region specific (investigators)	No	<65, ≥65	Yes	In the 2030s, each increase of 1% in the percentage of persons aged ≥65 years in the population will increase YLLs by 428 per one million population.
Wang, 2019 [31]	China	Future warming vs. 1986-2005	Short-term heat	Non-accidental	1.5 °C and 2.0 °C	SSP1-5	No	15-64; ≤14 or ≥65	Yes	Under 1.5 °C of global warming and SSP1-5 population projections, heat-related mortality will decrease by 42.9%-60.0% for working ages (15-64

Study	Location	Study period	Exposure	Mortality	Climate scenarios	Population scenarios	BMR projections	Age groups (years)	Age-stratified analyses with age-specific ERFs	Projection results
					under RCP 2.6 and 4.5					years) but increase by 78.1%-156.6% for non-working ages (≤14 or ≥65 years).
Gronlund, 2019 [28]	Michigan, US	2041-2070 vs. 1971-2000	Short-term extreme heat	Non-accidental	SRES A2	U.S. BenMAP	No	20-54, 55-64, ≥65	Yes	Extreme heat-related deaths in the age group ≥65 years will increase from 87% of that in all ages during 1971-2000 to 91% during 2041-2070
Studies using only one age group										
Carter, 2016 [43]	Finland, Norway, Sweden	2020-2049 vs. 1971-2000	Short-term heat	All-cause	SRES B1, A1B, and A2	Municipality specific (Finland, Norway, Sweden govts)	No	≥65 in Finland and Sweden; ≥67 in Norway	No	Heat-related mortality generally increases under climate change, though in some regions it might decrease due to population decline.
Li, 2016 [44]	Beijing, China	2020s, 2050s, and 2080s vs. 1980s	Short-term heat	Non-accidental	RCP 4.5 and 8.5	UN WPP	No	≥65 only	No	Heat-related mortality will be five times higher by the 2080s under RCP 8.5 combined with a high population aging scenario compared with a constant population scenario.
Astrom, 2017 [63]	Europe	2036-2065 vs. 1981-2010	Short-term heat	Non-accidental	RCP 4.5 and 8.5	UN WPP	No	≥65 only	No	In Southern Europe under RCP8.5 for people aged ≥65 years, heat-related mortality would need to be reduced by one fifth to remain at 1981-2010 levels.
Huang, 2018 [64]	Ningbo, China	2046-2065 and 2061-2080 vs. 2008-2015	Short-term heat	Cardio-vascular YLL	RCP 2.6, 4.5, and 8.5	UN WPP	No	≥75 only	No	Heat-related cardiovascular YLL will increase by 3-12 times in the future when considering population aging.
Limaye, 2018 [22]	Eastern US	2069 vs. 2007	Long-term heat	Cardio-respiratory	SRES A2	U.S. BenMAP	Country specific	65-99; total population	No	The increase in the heat-related mortality rate for the elderly population is an order of magnitude higher than the increase for the total population.
Morefield, 2018 [60]	US	2085-2095 vs. 1995-2005	Short-term heat	All-cause	RCP 4.5 and 8.5	U.S. BenMAP	Country specific	≥30 only	No	Choice of population scenario matters for projected heat-related mortality. Using the SSP5 vs the SSP2 population projection results in >1200 more projected deaths annually in the Southwest and Northeast US.

Abbreviations: BenMAP: Environmental Benefits Mapping and Analysis Program; BMR: Baseline Mortality Rates; ERF: Exposure-Response Function; RCP: Representative Concentration Pathway; SRES: Special Report on Emissions Scenarios; SSP: Shared Socioeconomic Pathways; UN WPP: United Nation World Population Prospects; YLL: Years of Life Lost.

Table 2. Characteristics of studies that considered population aging in projecting air pollution-related mortality under climate change.

Study	Location	Study period	Exposure	Mortality	Climate scenarios	Population scenarios	BMR projections	Age groups (years)	Age-stratified analyses with age-specific ERFs	Projection results
Studies using age stratification										
Geels, 2015 [51]	Europe	2050-2059 vs. 2000-2009	Short-term O_3, and long-term $PM_{2.5}$	All-cause	SRES A1B	50 km resolution (INTARESE and HEIMTSA)	No	≤15, ≥16, ≥30, ≥65	No	Population aging has a notable impact (~13% increase when using 2050 population projection instead of the 2000 population) on future air pollution-related mortality in some areas in Europe
Silva, 2016 [38 ••]	Global	2030, 2050, and 2100 vs. 2000	Long-term $PM_{2.5}$	IHD and stroke	RCP 2.6, 4.5, 6.0, and 8.5	IF	IF	5-year intervals for ≥25	Yes	Increases in exposed population and BMR for Resp magnify the future air pollution-related mortality impact, leading to an increased global mortality burden in 2030 and 2050, even where air pollution levels will decrease.
			Long-term $PM_{2.5}$ and O_3	LC, COPD, and Resp				≥25 only	No	
Silva, 2017 [39]	Global	2030 and 2100 vs. 2010	Long-term $PM_{2.5}$	IHD and stroke	RCP8.5	IF	IF	5-year intervals for ≥25	Yes	Incorporating population aging results in an increase in $PM_{2.5}$-related mortality in both 2030 and 2100 versus a constant population scenario.
			Long-term $PM_{2.5}$ and O_3	COPD and LC				≥25 only	No	
Chowdhury, 2018 [40]	India	2011-2020 to 2091-2100 vs. 2001-2005	Long-term $PM_{2.5}$	IHD and stroke	RCP 4.5 and 8.5	SSP1-5	Study-specific	5-year intervals for ≥25	Yes	The rapid increase in the SSP3 population, together with higher $PM_{2.5}$ levels under RCP8.5, will offset the reduction in BMR and thus lead to increased $PM_{2.5}$-related mortality after 2050.
				COPD and LC				≥25 only	No	
Chen, 2018 [41 ••]	China	2053-2055 vs. 2013-2015	Short-term O_3	Non-accidental	RCP 4.5 and 8.5	SSP1-5	UN WPP	5-64, 65-74, ≥75	Yes	Population aging offsets the decrease in BMR, resulting in in a 110% to 363% increase in ozone-related mortality under climate change in 2053-2055 than in the baseline of 2013-2015.
Achakulwisut, 2019 [47]	Southwest US	2030, 2050, 2070, and 2090 vs. 2010	Long-term $PM_{2.5}$	All-cause, CDP, and LC	RCP 4.5 and 8.5	U.S. BenMAP	Country specific	30-74, 75-99	No	$PM_{2.5}$ attributable mortality could increase by 230% by 2090 under RCP8.5, with 42% due to climate change and 58% due to changes in population and BMR.
Studies using only one age group										

Study	Location	Study period	Exposure	Mortality	Climate scenarios	Population scenarios	BMR projections	Age groups (years)	Age-stratified analyses with age-specific ERFs	Projection results
Sun, 2015 [45]	US	2050s vs. 2000s	Short-term $PM_{2.5}$ and O_3	All-cause, IHD, LC, CDP, and Resp	RCP8.5	U.S. BenMAP	Study-specific	≥30 for $PM_{2.5}$; 0-64 for O_3	No	Population growth has a dominant influence on future mortality attributable to $PM_{2.5}$ and O_3.
Achakulwisut, 2018 [46]	Southwest US	2076-2095 vs. 1996-2015	Long-term drought-sensitive $PM_{2.5}$	All-cause, CPD, and LC	RCP 2.6 and 8.5	U.S. BenMAP	Country specific	≥30 only	No	Future annual fine dust-related deaths will increase by 24% under RCP2.6 and 130% under RCP8.5 for adults ≥30 years.
Markandya, 2018 [33]	Global	2020-2050	Long-term $PM_{2.5}$ and O_3	IHD, stroke, LC, COPD, and Resp	NDC, 1.5°C, and 2°C	SSP2	WHO	≥30 only	No	Based on the TM5-FAst Scenario Screening Tool (TM5-FASST), global health co-benefits of mitigation are larger than the mitigation costs during 2020-2050 in all scenarios.
Shindell, 2018 [34]	Global	2020-2100	Long-term O_3	Circulatory and Resp	1.5°C and 2°C based on RCP 2.6	UN WPP	No	≥30 only	No	Aggressive emission reductions lead to substantial public health benefits globally.
Zapata, 2018 [36]	California, US	2050 vs. 2010	Long-term $PM_{2.5}$ and O_3	All-cause and Resp	BAU and GHG-Step	County specific (California govt)	No	≥35 only	No	In the "climate-friendly" GHG-Step scenario, air pollution-related deaths in 2050 will drop by 24-26% in California relative to the BAU scenario.
Orru, 2019 [50]	Europe	2046-2055 vs. 1991-2000	Long-term and short-term O_3	All-cause	RCP4.5	50 km resolution (INTARESE and HEIMTSA)	No	Total and ≥65	No	In 2046-2055 compared to 1991-2000, ozone-related mortality will increase by 3% under population change alone versus 0.4% under climate change alone.
Hong, 2019 [48]	China	2046-2050 vs. 2006-2010	Long-term $PM_{2.5}$	IHD, stroke, COPD, and LC	RCP4.5	UN WPP	UN WPP	≥25	No	Compared with climate change alone, China's aging population will further increase $PM_{2.5}$- and O_3-related mortality in 2046-2050 versus 2006-2010 by factors of 2.2 and 3.9, respectively, also taking into account changes in BMR.
			Long-term O_3	Resp				≥30		
Sarri, 2019 [35]	US	2050 and 2100 vs. 2000	Long-term $PM_{2.5}$ and O_3	All-cause	REF, Policy 4.5, and Policy 3.7	U.S. BenMAP	IF	30-99	No	Climate change in 2100 increases air pollution-related mortality by 20%, whereas climate policies would reduce this increased mortality by 70-88%.
Yang, 2019 [49]	US	2050 vs. 2005	Long-term $PM_{2.5}$ and O_3	All-cause, IHD, LC, CVD, and Resp	RCP 4.5 and 8.5	U.S. BenMAP	Country specific	0-99 or 30-99 or 25-99	No	Compared with 2005 population and BMR, using 2050 population and BMR will double the mortality benefits of reduced O_3 under RCP4.5, and increase the dis-benefits of increased O_3 under RCP8.5.

Abbreviations: BAU: Business As Usual; BenMAP: Environmental Benefits Mapping and Analysis Program; COPD: Chronic Obstructive Pulmonary Disease; CPD: Cardiopulmonary Disease; CVD: Cardiovascular Disease; Health and Environment Integrated Methodology and Toolbox for Scenario Development (HEIMSTA); IF: International Futures; IHD: Ischemic Heart Disease; Integrated Assessment of Health Risks of Environmental Stressors in Europe (INTARESE); GHG-Step: low-carbon energy scenario; LC: Lung Cancer; NDC: National Determined Contribution to the Paris Agreement; REF: Reference scenario without climate policy; Resp: Respiratory Disease; SSP: Shared Socioeconomic Pathways; UN WPP: United Nation World Population Prospects; WHO: World Health Organization.