Demographic Determinants of World Population Aging: 1950–1955 to 2095–2100 *

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April, 2019

ABSTRACT

As the world goes through the demographic transition, the distribution of the world population has changed from larger proportions in the younger age groups, to intermediary higher proportions in the working age groups, to final increasing proportions in the older age groups. However, across the globe, the demographic transition has varied with respect to the onset, pace, and scale of mortality and fertility declines, leading to different processes of population aging. Although earlier studies have looked at population aging in various contexts, the international literature lacks a systematic comparative analysis of the demographic determinants of population aging. We examine the contribution of births, deaths, and migrations to population aging in the world from 1950–1955 to 2095–2100. We decompose the rate of change in the mean age of a population, and propose a categorization of the stages of the demographic transition based on the demographic determinants of population aging.

* Paper presented at the Session *Cross-National Comparisons in Aging* of the Annual Meeting of the Population Association of America, Austin, TX, April 10–13.

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1 INTRODUCTION

As the world goes through the demographic transition, it moves from times of high mortality and fertility, and population growth rates around zero to a contemporary era of low mortality and fertility, and minimum or negative population growth rates. As a consequence, the distribution of the world population has changed significantly from initial larger proportions in the younger age groups, to intermediary higher proportions in the working or producing age groups, to final increasing proportions in the older age groups (Lee, 2003; Dyson, 2010). However, across the globe, the demographic transition has varied with respect to the onset, pace, and scale of mortality and fertility declines (Reher, 2004; Reher, 2011), leading to different processes of population aging. Although earlier studies have looked at population aging in various contexts, the international literature lacks a systematic comparative analysis of the demographic determinants of population aging.

In this article, we examine the contribution of births, deaths, and migrations to population aging in the world from 1950–1955 to 2095–2100. Our analysis covers populations that are in distinct stages of the demographic transition, allowing us to analyze the role of the demographic determinants of population aging in diverse demographic contexts. First, we compare some demographic measures of population aging. Second, we present approaches that demographers use to investigate the demographic determinants of population aging, including two mathematical expressions introduced by Preston, Himes, and Eggers (1989) to decompose the rate of change in the mean age of a population. Third, we detail our data, method and estimation approach. Fourth, we decompose the rate of change in the mean age of a population. Last, we propose a categorization of the stages of the demographic transition based on the demographic determinants of population aging.

2 MEASURES OF POPULATION AGING

We can measure population aging based on summary indicators of the age structure that can be either proportions of age groups, ratios between age groups, or measures of central tendency. The age groups are commonly based on life cycle stages related to physical or economic conditions, including young, working or producing adults, and old or retired. The ratio of the old-age population to the working age population is known as the old age dependency ratio (OADR), and its inverse is known as the support ratio (Goldstein, 2009; Hobbs, 2004). Here, we adopt the age group categorization of the United Nations (2017a, p. 33–35, 87): zero to 19 years of age for the younger ages (0–19 years), 20 to 64 years of age for the working ages (20–64 years), and 65 years of age or over for the older ages (65+ years). Accordingly, the United Nations (2017a) OADR is the ratio of the population 65 years of age or over to the population 20 to 64 years of age.

Common measures of central tendency of the age structure are the mean, median, and mode ages of the population. Preston et al. (1989) used the rate of change in the mean age of the population as an indicator of population aging. On the one hand, the disadvantages of using the mean age are the non-symmetric age structure of populations and the required assumptions about the population distribution within the open-ended age group (Goldstein, 2009; Hobbs, 2004). On the other hand, the mean age is easier to understand (Goldstein, 2009), is the leading measure of central tendency used in the social sciences (Preston et al., 1989; Preston & Stokes, 2012), is influenced by all values in the distribution and to its variations (Hobbs, 2004; Murphy, 2017), and gives more weight to values at the right tail of the age structure (i.e., the oldest ages). Also, it is related to the covariance with age (Preston et al., 1989; Vaupel & Canudas-Romo, 2002), and is highly correlated to the proportion of the total population 65 years of age or over (Preston et al., 1989; Murphy, 2017).

3 DEMOGRAPHIC DETERMINANTS OF POPULATION AGING

Traditionally, demographers use two approaches to investigate the demographic contexts that promote changes in the age structures of populations. The first is founded on the formal dynamics and comparative statics of the stable population model (Coale, 1957; Coale, 1972; Keyfitz, 1968; Keyfitz, 1977; Lee, 1994; Lotka, 1922; Lotka, 1939; Preston, 1974). The second is based on counterfactual population projections (Grigsby & Olshansky, 1989; Hermalin, 1966; Heuveline, 1999; Lee & Zhou, 2017; Moreira, 1997; Yu & Horiuchi, 1987).

Although distinct, both approaches consistently reach the same conclusions that fertility is the main determinant of population aging. For example, at the Population Association of America (PAA) presidential address of 1980, Siegel (1980) reviewed stable population theory and population projections studies from demographers. He defined as an error of interpretation the belief that the decline of mortality is the primary factor of population aging, and associated this error to lay persons, many social scientists, and government officials. According to Siegel (1980), demographers have a responsibility to spread the correct message, namely, fertility is the primary determinant of population aging (Siegel, 1980, p. 346–347). Thirty years later, Dyson (2010, p. 20–21) indirectly endorsed Siegel (1980)'s view, by emphasizing that the causal relationship between fertility decline and population aging is "deterministic — the consequence of basic population dynamics [...]", and that "[m]any people incorrectly ascribe population ageing within the [demographic] transition to mortality decline" (Dyson, 2010, p. 231).

Indeed, this conclusion is "consistent with a stylized demographic transition model" (Murphy, 2017, p. 257), as delineated by Dyson (2010, p. 20–23): pre-transitional populations are young because fertility rates are high; as mortality declines, first at childhood ages, populations become younger; later, mortality declines at all ages with negligible consequences for the age structure;

however, as fertility declines, the proportion of the population in the younger age groups falls, and populations age; ultimately, death and birth rates are low and balanced, and the growth of populations are around zero; post-transitional populations are old because fertility rates are low. Dyson (2010) used comparative statics of the pre-transitional and 2010 age structures of Sweden and Sri Lanka to support his assertions.

However, the stable population model has limited applicability to access the demographic contexts responsible for population aging (Preston et al., 1989; Preston & Stokes, 2012), since very few modern populations meet the condition of stability (Preston & Stokes, 2012). Besides, counterfactual population projections assume unrealistic scenarios (i.e., constant mortality or fertility over very long periods); and are sensitive to the choice of the starting date, which may lead to conflicting conclusions (e.g., changes in fertility made the population older vis-à-vis younger) (Murphy, 2017). Moreover, no population follows a simple demographic transition model, or observes long-term constant mortality and fertility (Murphy, 2017). Therefore, both approaches have limitations to explain what we can observe in practice (Murphy, 2017; Preston et al., 1989; Preston & Stokes, 2012). Also, they do not quantify the influence of mortality and fertility to population aging, and consequently derive weak factual evidence that fertility is the primary determinant of population aging (Murphy, 2017).

Nevertheless, the central point from the stable population model and its extensions to non-stable populations (Bennett & Horiuchi, 1981; Preston & Coale, 1982) stands. The age distribution of any population changes not because of mortality, fertility, or migration levels, but because mortality, fertility, or migration rates are changing or have changed in the recent past (Horiuchi & Preston, 1988; Preston et al., 1989). Usually, there is a confusion between levels of rates with changes in rates because people's minds "perform the wrong experiment" (Preston & Stokes, 2012, p.224) or employ the wrong verb tense. As an illustration, a population with low levels of fertility or old-age mortality is older than it *would be* if it had higher levels of fertility or old-age mortality, not necessarily older than it *was*.

A breakthrough came in 1989. Preston et al. (1989) introduced two related expressions that quantify the demographic contexts responsible for changes in the age structure of any population at a moment in time. Specifically, they developed two mathematical expressions to decompose the rate of change in the mean age of a population into its demographic determinants. The first mathematical expression from Preston et al. (1989) (PHE I) decomposes the rate of change in the mean age of a population into *rejuvenating effects*, products of the relative volumes (i.e., crude rates) and age selectivity (i.e., mean age differences to the mean age of the population) of births, deaths, in-migration, and out-migration. The second mathematical expression from Preston et al. (1989) (PHE II) decomposes the rate of change in the mean age of a population into age-specific population growth rates, age-specific proportions in the total population, and age selectivity (i.e., age-specific differences to the mean age of the population); the age-specific population growth rates are further mapped into the adjacent birth cohorts' rate of change in births, rate of change in the cumulative age-specific mortality rates, and rate of change in the cumulative age-specific net migration rates. Murphy (2017) extended the PHE II, by decomposing the birth cohort component into a fertility rate term and the corresponding population at risk, incorporating both the current direct effect of fertility and the indirect effect of historical fertility, mortality, and migration rates.

4 DATA AND METHODS

4.1 *Data*

We draw data from the 2017 revision of the official United Nations population estimates and projections (2017 UN REVISION) (United Nations, 2017c; United Nations, 2017d). It covers 150 years from 1950 to 2100, divided into two periods: 1950–2015 (estimates) and 2015–2100 (projections), and has nine projection variants. We use the medium fertility projection variant, which combines the medium fertility, normal mortality, and normal international migration assumptions (United Nations, 2017d). The 2017 UN REVISION covers a total of 233 countries and areas. It includes detailed data (e.g., population by five-year age groups) for the 201 countries and areas that had 90,000 or more inhabitants in 2017, and only total populations and growth rates for the remaining 32 (United Nations, 2017d, p. 1). We include these 201 countries and areas, both sexes combined, and the variables: a) populations by five-year age groups; b) deaths by five-year age groups; c) abridged life tables; and d) demographic indicators (e.g., crude birth rate, net migration rate.).

The 2017 UN REVISION (United Nations, 2017b; United Nations, 2017d, p. vii) follows the names and composition of geographic areas of the United Nations' *Standard Country or Area Codes for Statistical Use (M49)* (United Nations, 2018), yet with two differences. First, the 2017 UN REVISION groups its countries and areas into six regions: Africa, Asia, Europe, Latin America and the Caribbean, Northern America, and Oceania; whereas the United Nations (2018) adopts five geographic regions based on continental regions: Africa, Asia, Europe, Americas, and Oceania. Second, while the 2017 UN REVISION combines the Southern Asia and Central Asia subregions into South-Central Asia; the United Nations (2018) classifies Central Asia and Southern Asia as separate subregions since 2005. However, none of the 2017 UN REVISION's geographic classification criteria help us to either summarize or drill down its data. First, Northern America has no subregions, and only two countries with detailed data (i.e., Canada and United States of America); second, we risk loosing information when we combine subregions. Therefore, we fine-tune the 2017 UN REVISION's regional and subregional classification of countries and areas. First, we adopt the United Nations (2018)'s standard, specifically, five geographic regions, and Central Asia and Southern Asia as separate subregions. Second, we remove Latin America and the Caribbean as a subregion, but maintain its subregions under Americas; that is, we categorize Americas' subregions as the Caribbean, Central America, South America, and Northern America.

Our methods incorporate simultaneous use of distinct data by age groups (e.g., populations or deaths multiplied by life table functions). Therefore, we make the following changes to obtain populations and deaths with the same open-ended age groups as life tables (see Table 1): a) populations from 1990 to 2100: decrease open-ended age group to 95+ (add 95–99 and 100+); b) life tables from 1950–1955 to 1985–1990: add open-ended age group 80+; and c) life tables from 1950–1955 to 2095–2100: increase open-ended age group to 95+.

Table 1 – Open-ended age groups of the 2017 UN REVISION by variable, year or period, and before and after adjustments

Variable	Years / Periods (1)	Open-ended age group	
		Before	After
Populations	1950 to 1989	80+	80+
Deaths	1950–1955 to 1985–1990	95+	95+
Abridged life tables	1950–1955 to 1985–1990	85+	80+ and 95+
Populations	1990 to 2100	100+	95+
Deaths	1990–1995 to 2095–2100	95+	95+
Abridged life tables	1990–1995 to 2095–2100	85+	95+

Source: Author's calculations, based on United Nations (2017c).
(1): Annual data refer to 1 July of the year indicated. Data for five-year periods are from 1 July of the first year to 30 June of the final year.

We model old-age age-specific death rates to increase the life tables' open-ended age group to 95+. We follow Thatcher, Kannisto, and Vaupel (1998) to choose the explanatory mathematical mortality models; and Horiuchi, Ouellette, Cheung, and Robine (2013) to use the old-age modal age at death (M) as the parameter for the overall level of mortality. We use the following models: Makeham (Makeham, 1860), and Makeham variants of logistic (Perks, 1932), Kannisto (Kannisto, 1992 as cited in Thatcher et al., 1998, p. 16) and Weibul (Weibull, 1951).[1,2] For each geographic area and 5-year period, we choose as the final best model, the one that has the minimum arithmetic average absolute relative differences calculated over the oldest five age groups that were used to fit the models in that period.[3]

1 In all our Makeham variants mathematical mortality models, the modal age at death is from senescent mortality (M_s), which is practically equal to while somewhat higher than the modal age at death (M), assuming that at old ages the proportional level of premature mortality given by the Makeham term is very low (Horiuchi et al., 2013, p. 54). Horiuchi et al. (2013) did not work with or reformulate the Kannisto model in terms of M or M_s; nevertheless, we derive it as a special case of the logistic model.

2 We employ the R program environment (`R`) (R Core Team, 2018) with the MortalityLaws `R` package (`MortalityLaws`) (Pascariu & Canudas-Romo, 2017; Pascariu, 2018), and use the `MortalityLaws` feature that let us define our own parameterized mortality functions.

3 60–64 to 80–84 age groups from 1950–1955 to 1985–1990, and 70–74 to 90–94 age groups from 1990–1995 to 2095–2100. We estimate additional life table age-specific death rates for the 85–89 and 90–94 age groups from 1990–1995 to 2095–2100 based on the 2017 UN REVISION data for populations and deaths.

4.2 *Methods*

The PHE II is preferable to the PHE I, since it decomposes aging into births (a fertility rate term and the corresponding population at risk (Murphy, 2017)), mortality and migration rates, whereas the PHE I incorporates effects of the age structure when it decomposes aging into the *rejuvenating effects* of births, deaths, in-migration, and out-migration. However, the PHE II demands a minimum of one hundred years of continuous data to calculate the first change of the mean ages, which may limit its applicability to recent periods and short-term comparison intervals, as in Preston et al. (1989) for the United States and Sweden in 1980–1985, and Preston and Stokes (2012) for more developed and less developed countries in 2005–2010 (Murphy, 2017). Since we do not want to limit the period scope of our analysis, we use the PHE I with the 2017 UN REVISION.

The PHE I builds upon one fundamental demographic truth: every person ages one year by each one calendar year. Therefore, any population has the natural tendency to age if there are no births, no deaths, and no migration. Births enter populations at age zero, below the mean age of the population; therefore, they rejuvenate populations. In-migrants also enter populations; if the mean age of in-migrants is below the mean age of the population, they rejuvenate populations. On the contrary, deaths and out-migrants exit populations; for both variables, if the mean age of occurrence is below the mean age of the population, they age populations. Formally, these associations can be expressed in Equation 1 (Preston et al., 1989, p. 695). Let N be population; a, age; t, time; D, deaths; I, in-migrations; O, out-migrations; b, crude birth rate; d, crude death rate; i, crude in-migration rate; o, crude out-migration rate; and $dN_{\overline{a}}(t)/dt$, the derivative of the mean age of the population ($N_{\overline{a}}$) with respect to time:

$$\begin{aligned} \frac{dN_{\overline{a}}(t)}{dt} = 1 & \\ & - b(t) \cdot N_{\overline{a}}(t) \\ & - d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] \\ & - i(t) \cdot [N_{\overline{a}}(t) - I_{\overline{a}}(t)] - o(t) \cdot [O_{\overline{a}}(t) - N_{\overline{a}}(t)] \end{aligned} \tag{1}$$

Since the 2017 UN REVISION does not include migration age schedules, and is limited to net numbers of migrants ($I - O$) and net migration rates ($i - o$), it precludes the estimation of the mean age of migrations. Therefore, we adopt an approach similar to the one used elsewhere (Preston et al., 1989; Preston & Stokes, 2012), that computes the rejuvenating effect of net migration as a residual ($\epsilon_{\overline{a}}$) in Equation 1, specifically,

$$\epsilon_{\overline{a}}(t) = i(t) \cdot [N_{\overline{a}}(t) - I_{\overline{a}}(t)] + o(t) \cdot [O_{\overline{a}}(t) - N_{\overline{a}}(t)] \tag{2}$$

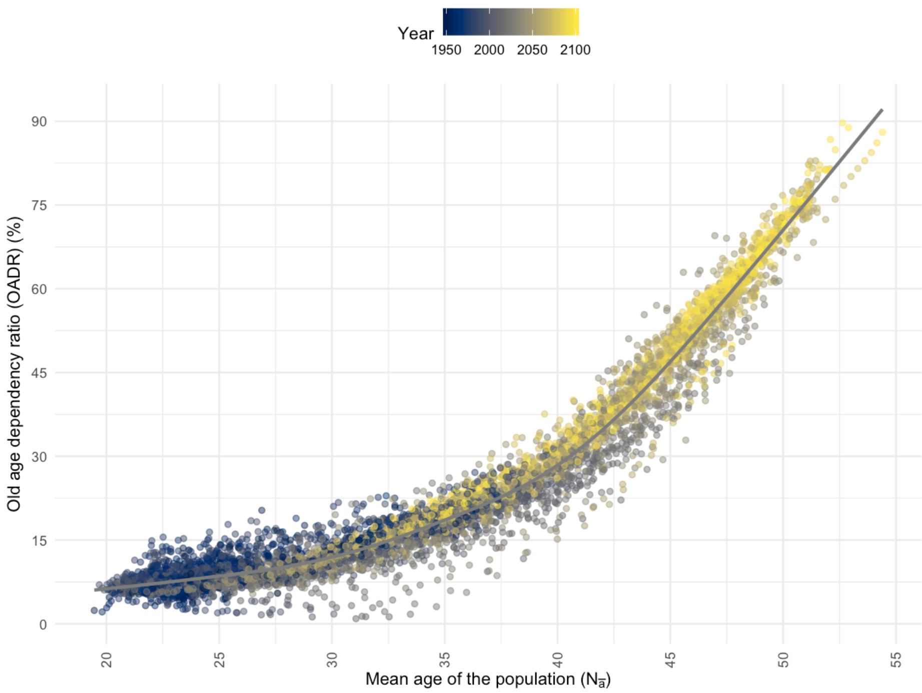
5 RESULTS

We analyze how population aging varies in the world from 1950–1955 to 2095–2100. First, we compare the mean age of the population ($N_{\overline{a}}$) to the old age dependency ratio (OADR), to evaluate whether the mean age is a robust indicator of aging in different scenarios. Second, we apply the first mathematical expression from Preston et al. (1989) (PHE I) to decompose the rate of change in the mean age of the population.

5.1 *Mean age of the population and old age dependency ratio*

Preston et al. (1989) and Murphy (2017) showed that the $N_{\overline{a}}$ is a robust indicator of population aging, since it is highly correlated to the proportion of the total population 65 years of age or over.[4] We observe that the same holds between the $N_{\overline{a}}$ and the OADR. In the 2017 UN REVISION, the $N_{\overline{a}}$ and the OADR are correlated at 0.928 (Pearson), and partially correlated at 0.928 (control for country/area), 0.857 (control for year), and 0.857 (control for year and country/area).[5] Figure 1 and Figure 2 plot the $N_{\overline{a}}$ by the OADR, whole population and subregions, confirming the high correlation between the two measures.

Figure 1 – Mean age of the population ($N_{\overline{a}}$) by old age dependency ratio (OADR)

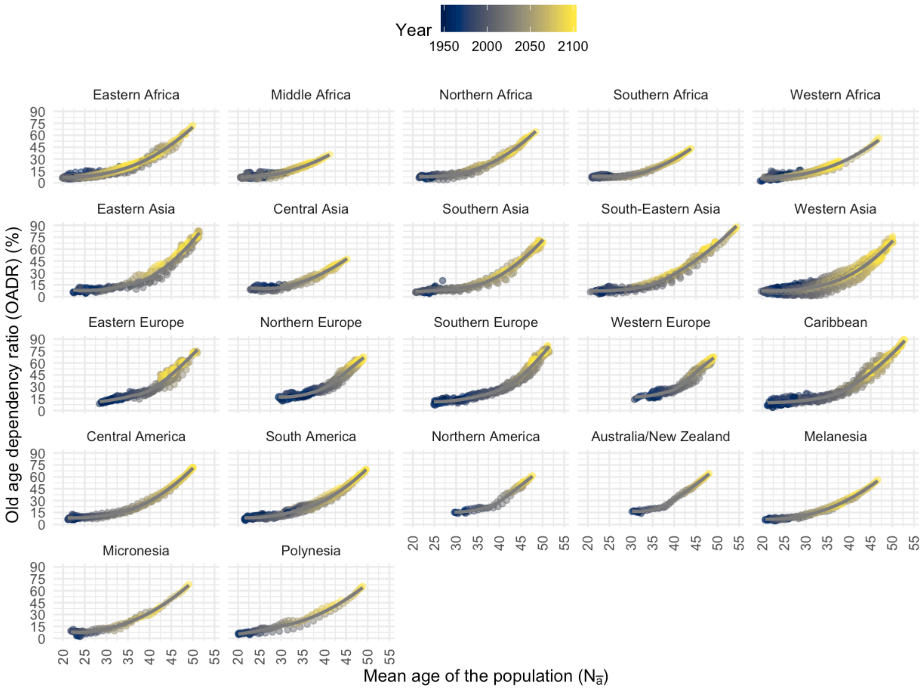


Source: Authors' calculations, based on United Nations (2017c).

4 Preston et al. (1989) for 17 regions of the world in 1970 and 1980, Murphy (2017) for 11 European countries from 1850 to 2012.

5 For 6,030 observations from 201 countries and areas multiplied by 30 five-year periods.

Figure 2 – Mean age of the population ($N_{\bar{a}}$) by old age dependency ratio (OADR) and subregions



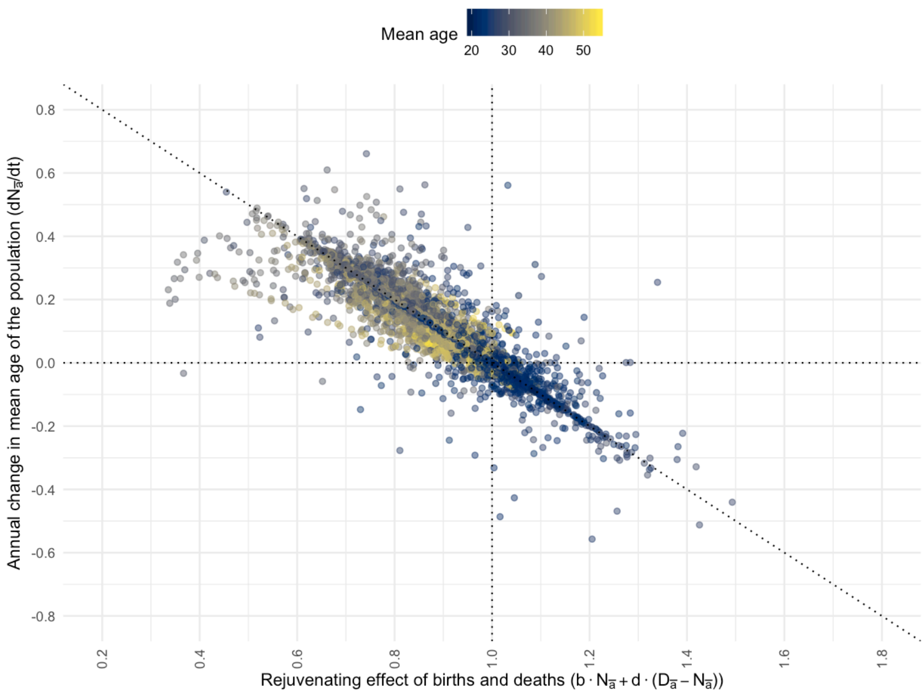
Source: Authors' calculations, based on United Nations (2017c).

5.2 *Demographic determinants of world population aging*

In Figure 3, we present the combined rejuvenating effect of births and deaths ($b \cdot N_{\bar{a}} + d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by the annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$). The results are detailed by subregions in Figure 4. The combined rejuvenating effect of births and deaths varies from around 1.3 to 0.6 years per calendar year, while the change in the mean age of the population varies from rejuvenating 0.3 year per calendar year to aging 0.4 year per calendar year. Northern Europe, Western Europe, and Northern America are mostly limited to combined rejuvenating effects of births and deaths less than or equal to 1, that is, to positive or zero annual changes in the mean age of the population. The observations are displayed around a line that represents Equation 1, when the rejuvenating effect of net migration ($\epsilon_{\bar{a}}$) is equal to zero. Observations that depart from this line indicate the existing rejuvenating effects of net migration ($\epsilon_{\bar{a}}$). They are mostly evident in Western Asia and the Caribbean, and occur to a much lesser degree in other subregions. Figure 5 and Figure 6 show the rejuvenating effect of net migration ($\epsilon_{\bar{a}}$) by the annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$).[6]

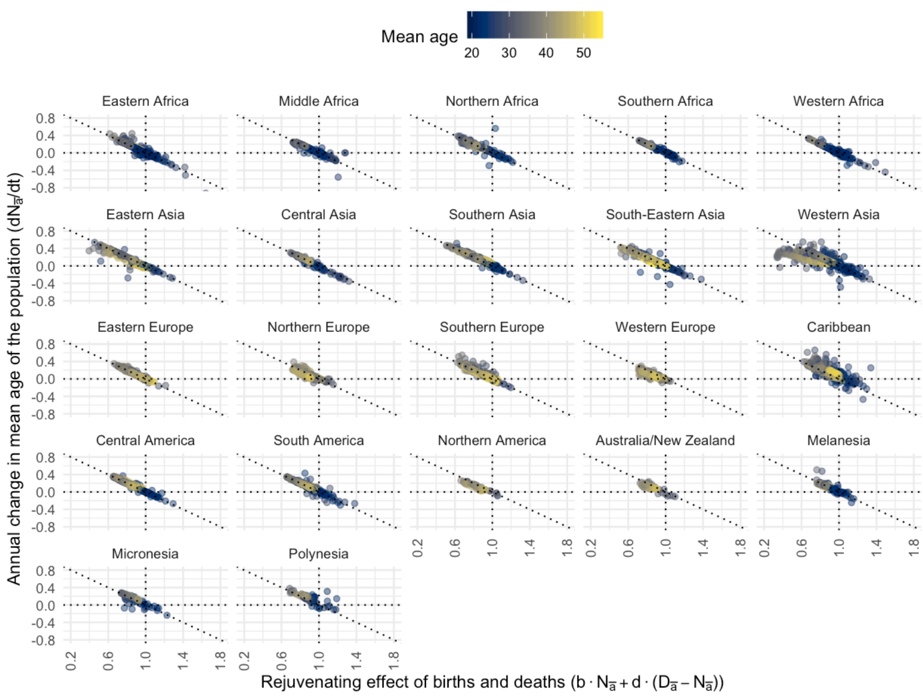
[6] Since $\epsilon_{\bar{a}}$ is computed as a residual, it incorporates any errors that are inherent to our estimates. Depending on the age selectivity between $N_{\bar{a}}$ and the mean age of net migration, $\epsilon_{\bar{a}}$ may be close to zero even if the net migration rates are high. However, independently of the age selectivity between $N_{\bar{a}}$ and the mean age of net migration, $\epsilon_{\bar{a}}$ should always be close to zero if the net migration rates and the inherent errors in our estimates are very low. Our values of $\epsilon_{\bar{a}}$ are consistent with robust estimates, that is, they are close to zero when absolute net migration rates are less than 0.0001 (see Appendix A).

Figure 3 – Combined rejuvenating effect of births and deaths ($b \cdot N_{\bar{a}} + d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$)



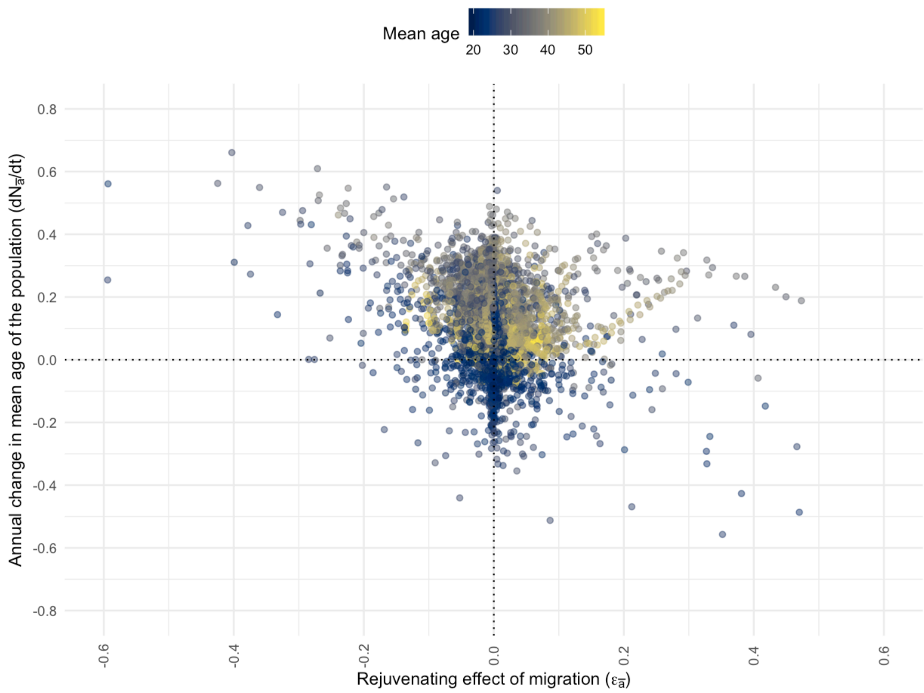
Source: Authors' calculations, based on United Nations (2017c).

Figure 4 – Combined rejuvenating effect of births and deaths ($b \cdot N_{\bar{a}} + d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$) and subregions



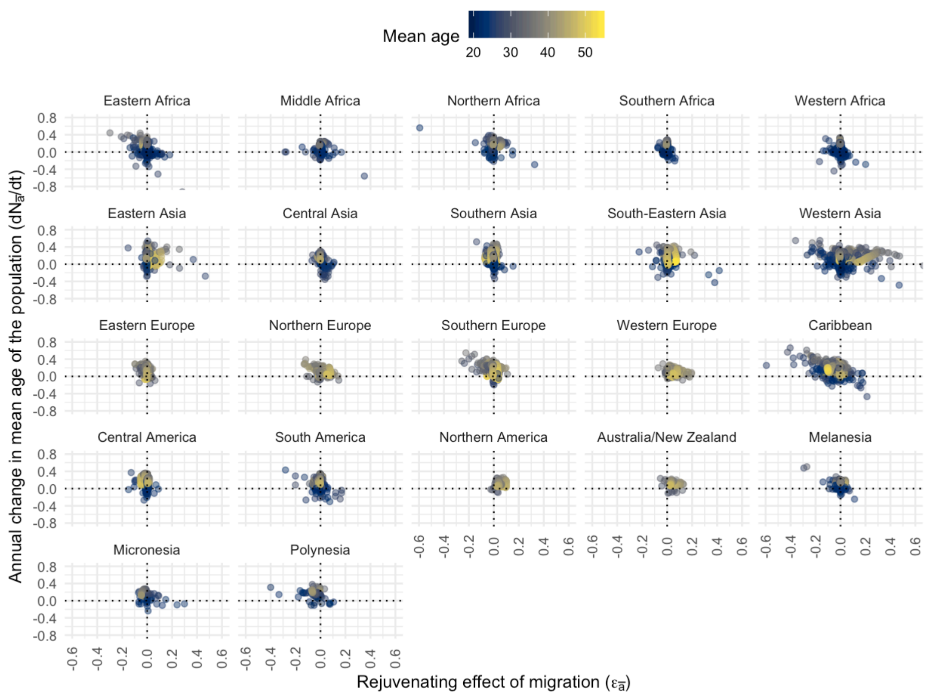
Source: Authors' calculations, based on United Nations (2017c).

Figure 5 – Rejuvenating effect of net migration ($\epsilon_{\bar{a}}$) by annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$)



Source: Authors' calculations, based on United Nations (2017c).

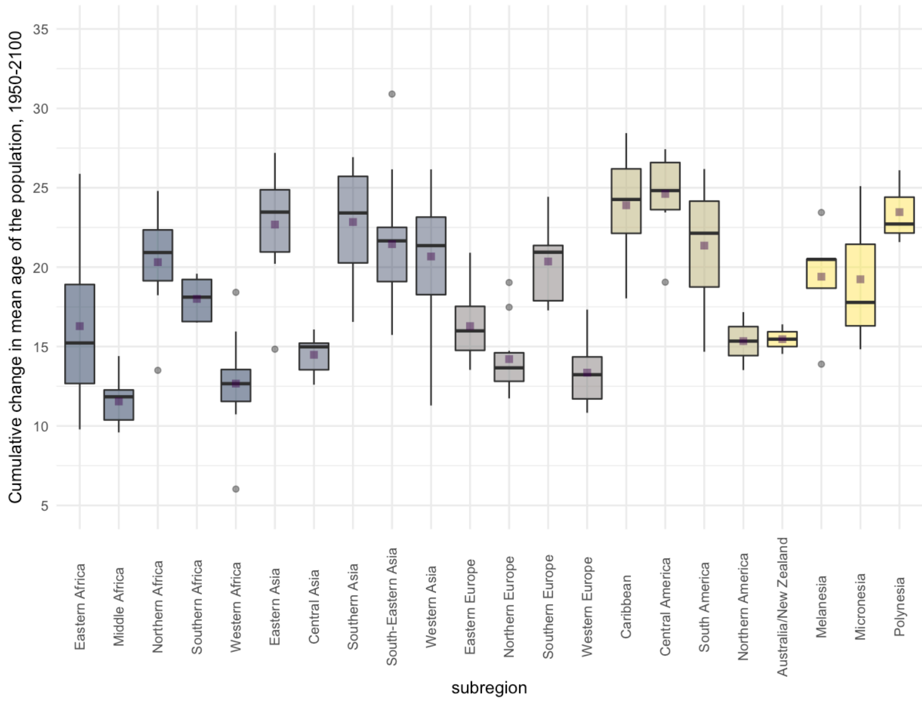
Figure 6 – Rejuvenating effect of net migration ($\epsilon_{\bar{a}}$) by annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$) and subregions



Source: Authors' calculations, based on United Nations (2017c).

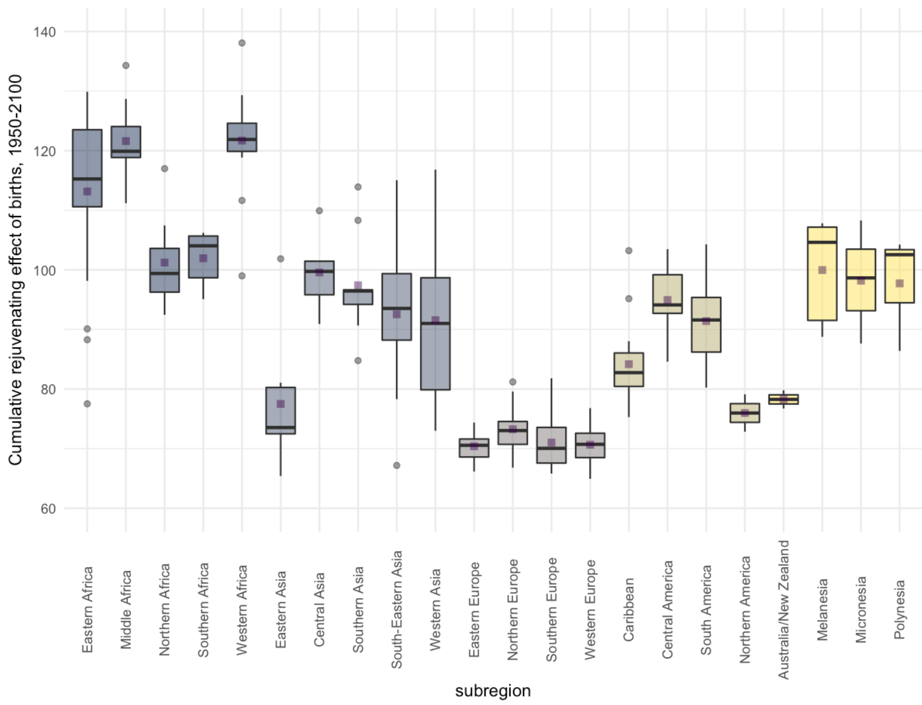
If there were no births, deaths or migration during the 150 years covered by the 2017 UN REVISION, the mean age of all populations would have increased by the same 150 years. However, most populations age between 10 and 25 years (Figure 7), with some aging as little as 6 years (Benin) and some aging as much as 31 years (Singapore). Although some subregions present similar levels of cumulative changes in the mean age of the population (e.g., Western Africa, Central Asia, and Northern Europe), the demographic determinants of aging behind these changes are quite distinct. This is what we observe in Figures 8 and 9 that present the cumulative rejuvenating effect of births and the cumulative rejuvenating effect of deaths from 1950 to 2100 by subregion. The subregions of Europe have the lowest cumulative rejuvenating effect of births (around 70 years), and the highest cumulative rejuvenating effect of deaths (around 60 years). Eastern, Middle, and Western Africa subregions present the highest cumulative rejuvenating effect of births (around 120 years), and the lowest cumulative rejuvenating effect of deaths (around 15 years). The demographic determinants of aging of Central Asia are intermediary to these, presenting cumulative rejuvenating effect of births around 100 years, and cumulative rejuvenating effect of deaths around 35 years. Cumulative rejuvenating effect of births is prominent in Niger (138 years), Angola (134 years), Somalia and Mali (around 130 years), Hungary and Greece (about 66 years), and Japan and Germany (about 65 years). Extreme cumulative rejuvenating effect of deaths are found in Niger (0.79 year), Angola (5.9 years), Mali (7.6 years), Somalia (10 years), Croatia (67 years), Hungary (68 years), and Bulgaria (69 years) and Latvia (69.5 years). The cumulative rejuvenating effect of migration (Figure 10) is small when compared with those from births or deaths. Nevertheless, migration ages the Caribbean and Polynesia, and rejuvenates Western Asia, Northern Europe, Western Europe, Northern America, and Australia/New Zealand. Most notably, migration cumulatively ages the United States Virgin Islands by 18 years, Grenada by 14 years, Jamaica, Martinique, Saint Vincent and the Grenadines, Barbados, and Guadeloupe between 10 and 12 years; and cumulatively rejuvenates Canada, Switzerland, Australia and Kuwait between 10 and 12 years, Luxembourg and Bahrain by 16 years, Macao by 19 years, and Qatar and the United Arab Emirates by 29 years.

Figure 7 – Cumulative change in mean age of the population from 1950 to 2100 by subregions



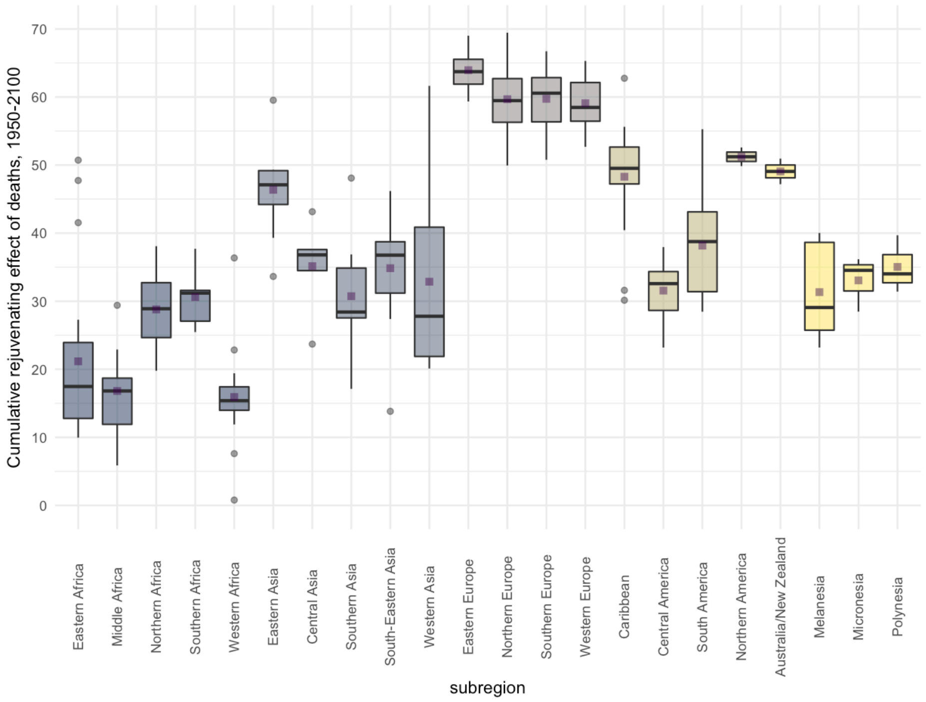
Source: Authors' calculations, based on United Nations (2017c).
Note: Square indicates the mean of the distribution.

Figure 8 – Cumulative rejuvenating effect of births from 1950 to 2100 by subregions



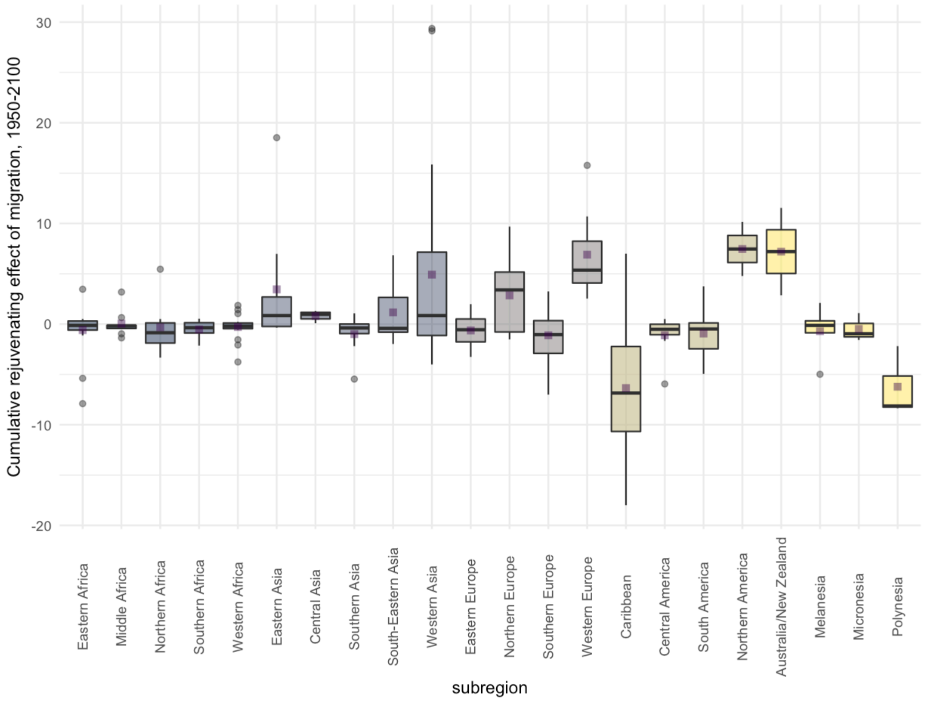
Source: Authors' calculations, based on United Nations (2017c).
Note: Square indicates the mean of the distribution.

Figure 9 – Cumulative rejuvenating effect of deaths from 1950 to 2100 by subregions



Source: Authors' calculations, based on United Nations (2017c).
Note: Square indicates the mean of the distribution.

Figure 10 – Cumulative rejuvenating effect of migration from 1950 to 2100 by subregions



Source: Authors' calculations, based on United Nations (2017c).
Note: Square indicates the mean of the distribution.

6 DEMOGRAPHIC DETERMINANTS OF POPULATION AGING AND THE DEMOGRAPHIC TRANSITION

Based on the comparative statics of stable populations, Preston et al. (1989) demonstrated that there is a pattern between the rejuvenating effect of births and the rejuvenating effect of deaths from scenarios of high mortality and high fertility to scenarios of low mortality and low fertility. The higher are mortality levels and fertility levels, the more of the combined rejuvenating effects of births and deaths originate from births, the less come from deaths. As mortality and then fertility decline, the more of the combined rejuvenating effects of births and deaths come from deaths, the less originate from births. We analyze how this *concerted pattern* unfolds in the diverse demographic scenario of the 2017 UN REVISION. We both examine whether there is a general *concerted pattern* between the rejuvenating effect of births and the rejuvenating effect of deaths along the demographic transition, and propose a categorization of the stages of the demographic transition based on the demographic determinants of population aging.

In Figure 11 and Figure 12, we present the rejuvenating effect of deaths by the rejuvenating effect of births. Let the rejuvenating effect of net migration ($\epsilon_{\overline{a}}$) be equal to zero. Populations that are in the *mean age stability line*[7] have combined rejuvenating effects of births and deaths equal to one, the mean ages of the populations ($N_{\overline{a}}$) are constant, populations are neither aging nor rejuvenating. Populations that are above this line have combined rejuvenating effects of births and deaths greater than one, the $N_{\overline{a}}$ are decreasing, populations are rejuvenating.[8] Populations that are below this line have combined rejuvenating effects of births and deaths less than one, the $N_{\overline{a}}$ are increasing, populations are aging.[9] Figure 11 suggests that there is a general *concerted pattern*, which we propose to categorize into seven stages. We summarize these stages by indicators of the rejuvenating effect of births, the rejuvenating effect of deaths, and the mean age of the population in Table 2.

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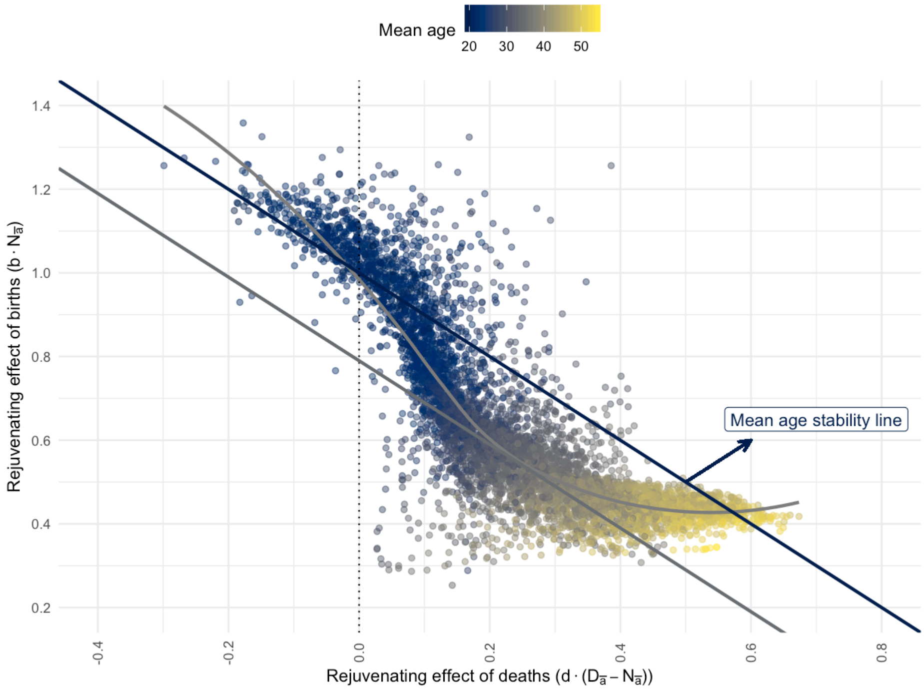
7 Equation 1 for $dN_{\overline{a}}(t)/dt = 0$ and $\epsilon_{\overline{a}}(t) = 0$, that is, $b(t) \cdot N_{\overline{a}}(t) = 1 - d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)]$.

8 $b(t) \cdot N_{\overline{a}}(t) + d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] > 1 \implies dN_{\overline{a}}(t)/dt < 0$.

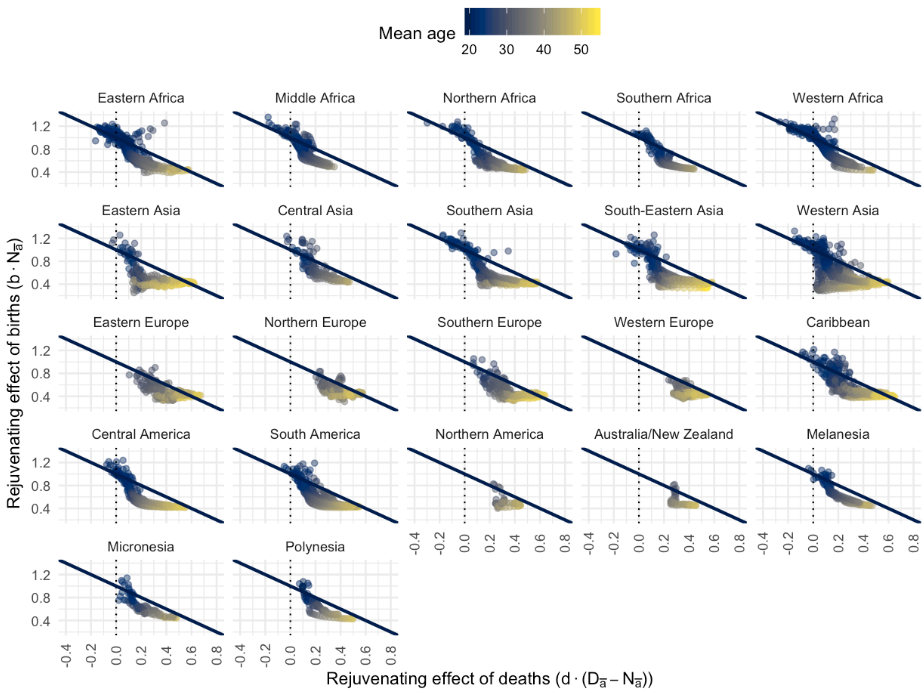
9 $b(t) \cdot N_{\overline{a}}(t) + d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] < 1 \implies dN_{\overline{a}}(t)/dt > 0$.

Figure 11 – Rejuvenating effect of deaths ($d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by rejuvenating effect of births ($b \cdot N_{\bar{a}}$)



Source: Authors' calculations, based on United Nations (2017c).

Figure 12 – Rejuvenating effect of deaths ($d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by rejuvenating effect of births ($b \cdot N_{\bar{a}}$) and subregions



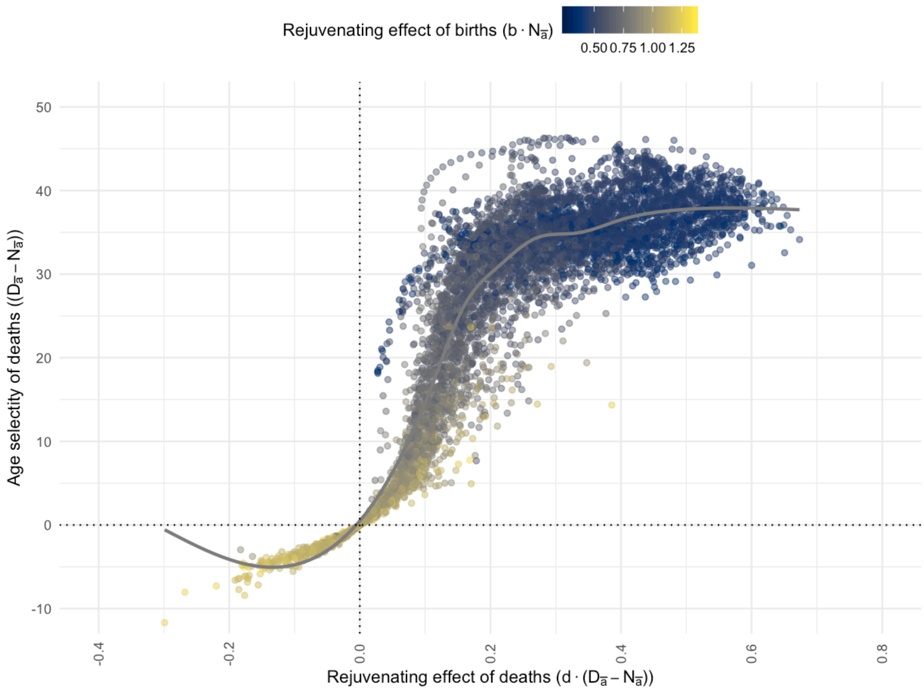
Source: Authors' calculations, based on United Nations (2017c).

Table 2 – Indicators of the rejuvenating effect of births, rejuvenating effect of deaths, and mean age of the population by stage of the demographic transition

Stage	Rejuvenating effect of births	Rejuvenating effect of deaths	Rejuvenating effect of births and rejuvenating effect of deaths		Mean age of the population			Example Countries
			Combined $b(t) \cdot N_{\overline{a}}(t) + d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)]$	$-\frac{d}{dt}b(t) \cdot N_{\overline{a}}(t)$ versus $\frac{d}{dt}d(t) \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)]$	$N_{\overline{a}}(t)$	$\frac{d}{dt}N_{\overline{a}}(t)$	$\frac{d^2}{dt^2}N_{\overline{a}}(t)$	
1	1.0, 1.2	-0.2, 0.0	> 1	>	decrease	negative	positive	Turkey (1950–1955) Afghanistan (1980–1985) Somalia (1990–1995)
1A	1.0	0.0	= 1	>	minimum	zero	positive	Peru (1965–1970) Pakistan (1970–1975) Chad (2005–2010)
2	1.0, 0.6	0.0, 0.2	< 1	>	increase	positive	positive	Bulgaria (1950–1955) China (1955–1960) Angola (2010–2015)
3	0.6	0.2	< 1	=	increase	maximum	zero	Japan (1970–1975) Philippines (2025–2030) Niger (2095–2100)
4	0.6, 0.4	0.2, 0.6	< 1	<	increase	positive	negative	Austria (1950–1955) United States (1965–1970) Brazil (2025–2030)
4A	0.4	0.6	= 1	<	maximum	zero	negative	Portugal (2060–2065) Spain (2060–2065) Jamaica (2080–2085)
5	0.4	> 0.6	> 1	<	decrease	negative	negative	Poland (2070–2075) Albania (2085–2090) Puerto Rico (2090–2095)

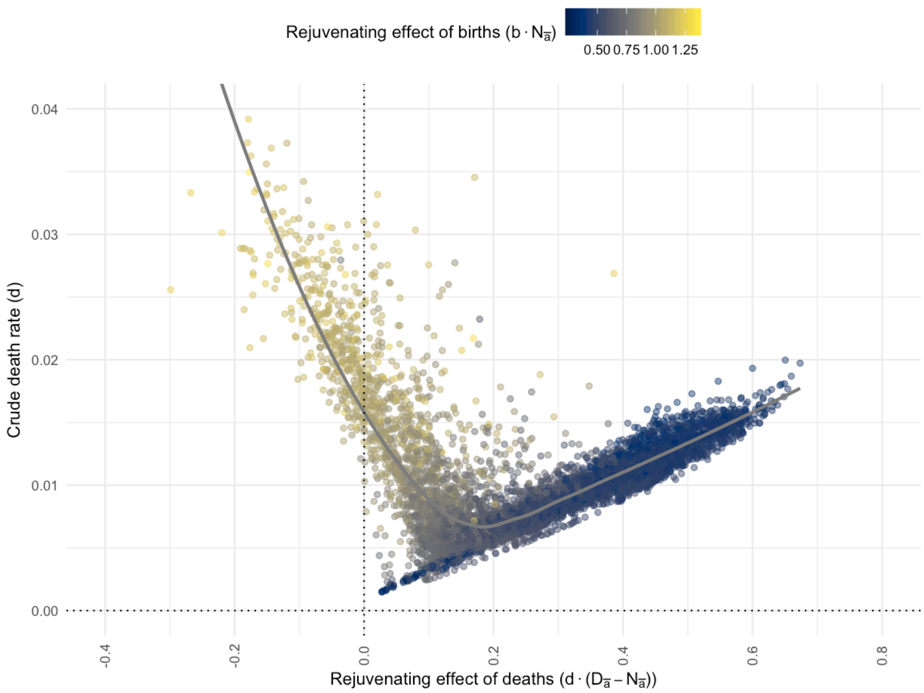
Source: Authors' creation and calculations, based on Preston, Himes, and Eggers (1989) and United Nations (2017c).

Figure 13 – Rejuvenating effect of deaths ($d \cdot [D_{\overline{a}} - N_{\overline{a}}]$) by age selectivity of deaths ($D_{\overline{a}} - N_{\overline{a}}$)



Source: Authors' calculations, based on United Nations (2017c).

Figure 14 – Rejuvenating effect of deaths ($d \cdot [D_{\overline{a}} - N_{\overline{a}}]$) by crude death rate ($d$)



Source: Authors' calculations, based on United Nations (2017c).

Initially, at *Stage 1*, mortality levels and fertility levels are high. Deaths are concentrated at infancy and childhood ages, and thus the age selectivity of deaths are negative (Figure 13). Consequently, populations observe negative rejuvenating effects of deaths between −0.2 and 0, and positive rejuvenating effects of births between 1.0 and 1.2. Despite the negative rejuvenating effects of deaths, the combined rejuvenating effects of births and deaths are greater than one, and thus populations rejuvenate. Then, mortality declines, largely at infancy and childhood ages, and thus the age distribution of deaths shifts to older ages and the age selectivity of deaths gradually increase to zero (Figure 13). The crude death rates (d) solely decline (Figure 14). Consequently, the rejuvenating effects of deaths increase exclusively from the rise of the age selectivity of deaths. Next, fertility declines, and thus the rejuvenating effects of births decrease. The rejuvenating effects of births decrease faster than the rejuvenating effects of deaths increase; consequently, the rates of change in the mean age of the population increase.[10] At the end of *Stage 1*, the combined rejuvenating effects of births and deaths cross the mean age stability line, and the $N_{\overline{a}}$ reach a local minimum. We indicate this moment as *Stage 1A* at Table 2.

At *Stage 2*, populations observe positive rejuvenating effects of deaths between 0 and 0.2, and rejuvenating effects of births between 1.0 and 0.6. The combined rejuvenating effects of births and deaths are less than one, that is, populations age. Mortality and fertility continue to decline. Mortality declines at infancy and childhood ages accelerate, and thus the age selectivity of deaths steeply increase from 0 to 30 (Figure 13). The crude death rates (d) predominantly decline (Figure 14). Consequently, the rejuvenating effects of deaths still increase fundamentally from the rise of the age selectivity of deaths. The rejuvenating effects of births still decrease faster than the rejuvenating effects of deaths increase; consequently, the rates of change in the mean age of the population still increase.

At *Stage 3*, rejuvenating effects of deaths are around 0.2, and rejuvenating effects of births are just below 0.6. The combined rejuvenating effects of births and deaths are still less than one, and thus populations still age. Both rejuvenating effects arrive at an inflection point where the rate of change in the rejuvenating effects of births and the rate of change in the rejuvenating effects of deaths are the same; consequently, the rates of change in the mean age of the population reach a local maximum.[11]

At *Stage 4*, populations observe rejuvenating effects of deaths between 0.2 and 0.6, and rejuvenating effects of births between 0.6 and 0.4. The combined rejuvenating effects of births and deaths are still less than one, that is, populations still age. Mortality continues to decline, now mostly at middle and old ages, and thus the rise of the age selectivity of deaths decelerate (Figure 13). The crude death rates (d) increase (Figure 14). Consequently, the rejuvenating effects of deaths increase from the rise both of the age selectivity of deaths and of the crude death rates (d). Fer-

[10] $-db(t)/dt \cdot N_{\overline{a}}(t) > dd(t)/dt \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] \iff d^2N_{\overline{a}}(t)/dt^2 > 0.$

[11] $-db(t)/dt \cdot N_{\overline{a}}(t) = dd(t)/dt \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] \iff d^2N_{\overline{a}}(t)/dt^2 = 0.$

tility also continue to decline, but now with more gradual reductions. The rejuvenating effects of births decrease slower than the rejuvenating effects of deaths increase; consequently, the rates of change in the mean age of the population decrease.[12] At the end of *Stage 4*, the combined rejuvenating effects of births and deaths cross the mean age stability line again, and the $N_{\overline{a}}$ reach a local maximum. We indicate this moment as *Stage 4A* at Table 2.

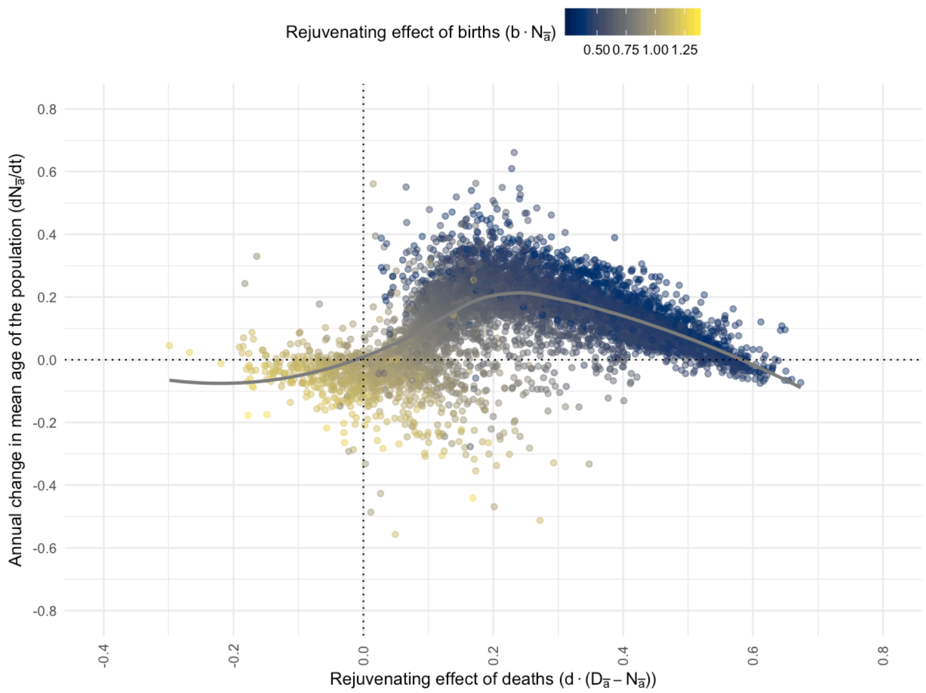
Finally, at *Stage 5*, populations observe rejuvenating effects of births around 0.4, and rejuvenating effects of deaths above 0.6. The combined rejuvenating effects of births and deaths are again greater than one, and thus populations rejuvenate anew. Mortality continues to decline, this time mostly at old ages, and thus the age selectivity of deaths stabilize (Figure 13). The crude death rates (d) still increase (Figure 14). Consequently, the rejuvenating effects of deaths increase entirely from the rise of the crude death rates (d). Fertility stabilizes. The rejuvenating effects of births stabilize, and the rejuvenating effects of deaths still increase; consequently, the rates of change in the mean age of the population still decrease.

7 CONCLUSION

Earlier in this article, we acknowledge that, across the globe, the demographic transition has varied with respect to the onset, pace, and scale of mortality and fertility declines, leading to different processes of population aging. Yet, now we argue that despite these variations, demographic transitions differ alongside a general *concerted pattern* between the rejuvenating effect of births and the rejuvenating effect of deaths. We propose a categorization of the stages of the demographic transition based on levels and indicators of these demographic determinants of population aging (Table 2). Across the globe, population aging vary alongside the same general pattern and the same stages, and we may determine the stages of aging by either only the rejuvenating effect of births, or only the rejuvenating effect of deaths as presented in Figure 15 and Figure 16.

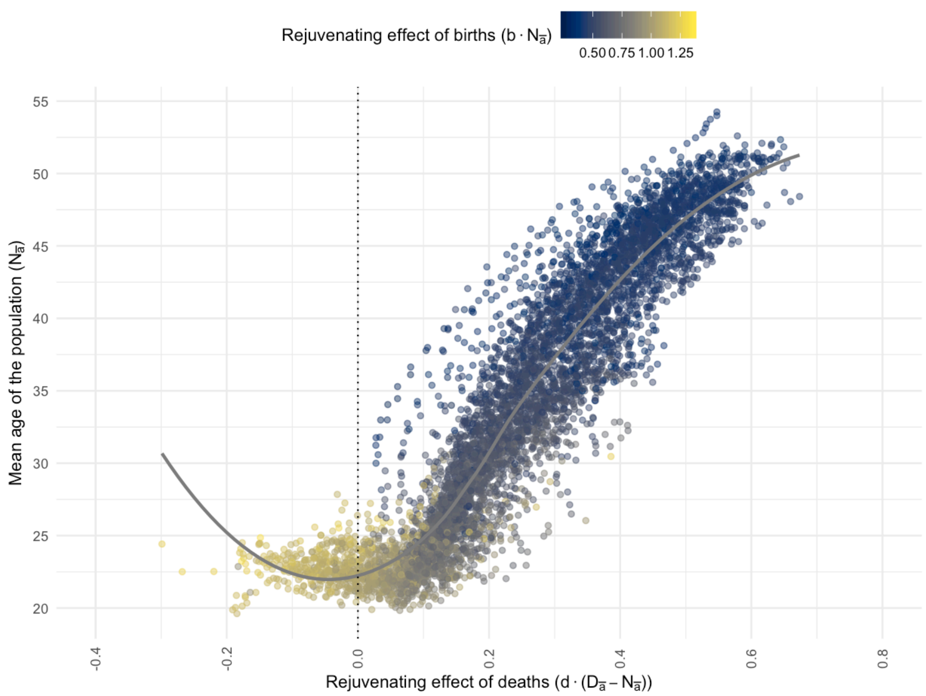
12 $-db(t)/dt \cdot N_{\overline{a}}(t) < dd(t)/dt \cdot [D_{\overline{a}}(t) - N_{\overline{a}}(t)] \iff d^2N_{\overline{a}}(t)/dt^2 < 0.$

Figure 15 – Rejuvenating effect of deaths ($d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by annual rate of change in the mean age of the population ($dN_{\bar{a}}(t)/dt$)



Source: Authors' calculations, based on United Nations (2017c).

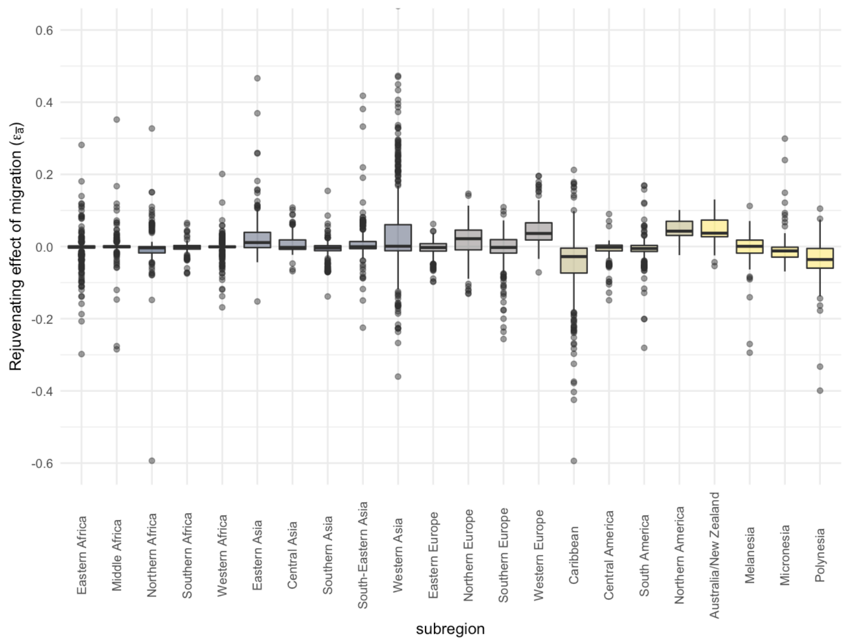
Figure 16 – Rejuvenating effect of deaths ($d \cdot [D_{\bar{a}} - N_{\bar{a}}]$) by mean age of the population ($N_{\bar{a}}$)



Source: Authors' calculations, based on United Nations (2017c).

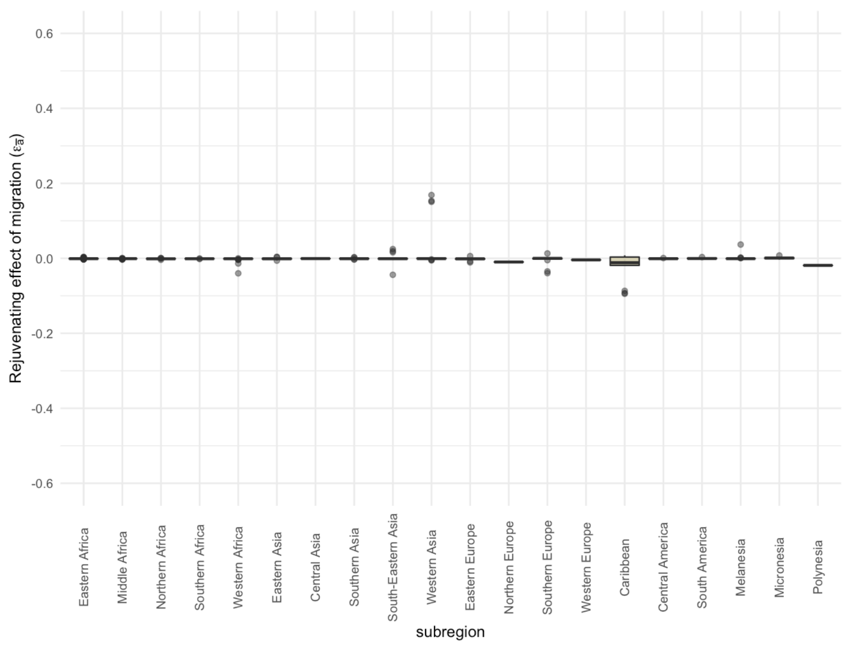
APPENDIX A – REJUVENATING EFFECT OF NET MIGRATION BY SUBREGIONS

Figure 17 – Rejuvenating effect of net migration ($\epsilon_{\overline{a}}$) by subregions, for observations with an absolute net migration rate more than or equal to 0.0001



Source: Authors' calculations, based on United Nations (2017c).

Figure 18 – Rejuvenating effect of net migration ($\epsilon_{\overline{a}}$) by subregions, for observations with an absolute net migration rate less than 0.0001



Source: Authors' calculations, based on United Nations (2017c).

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