Subnational contribution to national life expectancy

Vladimir Canudas-Romo and Dmitri Jdanov

During the 20th century, major declines in mortality took place globally, resulting in the unprecedented rise of life expectancy. This process initiated cycles of convergences and divergences in longevity between countries. Yet life expectancy at the national level hides subnational existing longevity variability. Furthermore, little research has been conducted on the existent mortality differentials within populations and the contribution of subnational mortality to changes in national life expectancy. Using data on mortality at the subnational level for Australia (state/territories), Canada (provinces), Japan (prefectures), and the USA (states) the contribution of subnational mortality on the overall national life expectancy of these nations is studied. The decomposition method used highlights the relevance of the structure of the population at the subnational level, to determine the overall mortality changes in the nation. All subnational areas in Australia, Canada, and Japan, have contributed to the increase in the national longevity of these nations. However, for the USA disproportional changes, some positive other negative, make the country's longevity increase at the lowest pace.

Introduction

During the 20th century, major declines in mortality took place globally, resulting in the unprecedented rise of life expectancy. Despite the general progress in mortality in almost all countries and linear progress in record life expectancy, the expected absolute convergence towards the highest life expectancy has failed to materialise (Bobak and Marmot, 1996; Leon, 2011; Shkolnikov et al. 2013; Mackenbach, 2013; Meslé and Vallin, 2017). This has led to incorporation of cycles of divergence/convergence in the theory of the health transition. Despite this, geographical disparity at the subnational level has received little attention. Moreover, it is expected that in high income developed countries where (theoretically) the same health benefits are available to all citizens, convergence across regions should be observed. However, recent publications shows that this is not the case. Furthermore, mortality differences exist both between and within populations, and life expectancy at the national level hides existing subnational longevity variability (van Raalte et al. 2018). The inequality in mortality and health within a country might be even higher than the disparity between countries. Unfortunately, availability of data on subnational mortality of acceptable quality and comparable across time, space, between and within countries is limited. Consistent monitoring outcomes on regional mortality changes within countries are critical for evaluation of sustainability and inequalities in many dimensions of national development.

Our study is focused on analysis of contribution of subnational mortality to the overall national life expectancy. Using decomposition methods, we analyse two components of this contribution: level of mortality in particular regions and differences in population structure.

Data

The Human Mortality Database (HMD, www.mortality.org) is the leading source of mortality and population data at the national level and contains detailed data for over 41 populations. Additionally, there exist four country-specific databases devoted to subnational mortality:

-Australia (AHMD, demography.cass.anu.edu.au/research/australian-human-mortality-database)

- Canada (CHMD, www.bdlc.umontreal.ca/CHMD/)
- Japan (JHMD, www.ipss.go.jp/p-toukei/JMD/index-en.asp)
- United States (USAHMD, usa.mortality.org)

These database use the standard methodological approach based on the HMD Methods protocol (Wilmoth et al. 2017) and provide continuous mortality data series comparable across time, and within and between countries. All four HMD type databases were used in this study. From the subnational databases the death counts and person-years by country, as well as the life expectancy from the HMD were extracted, analysed and compared. An exception to this is for the USA where only death rates are available and not population counts, as such only partial analysis could be done for the country.

Methods

Subnational contribution to national life expectancy

From each subnational population (*i*), age-specific rates by age (*x*) and time (*t*) were calculated for mortality and population growth, denoted as $\mu_i(x,t)$ and $r_i(x,t)$ respectively. The latter growth rate, is calculated as the relative derivative of the subnational age-specific population size $N_i(x,t)$, or in mathematical notation as $r_i(x,t) = \frac{\dot{N}_i(x,t)}{N_i(x,t)}$, with a dot on top of the variable denoting the derivative with respect to time (Vaupel and Canudas-Romo 2003). Additionally, the proportion of the population at each subnational population respect to the entire population by age was also calculated as $c_i(x,t) = \frac{N_i(x,t)}{N(x,t)}$, based on the population counts for the total $N(x,t)$ and the subnational populations.

The national age-specific death rate is the ratio of deaths over persons-years in the overall population. It can be also calculated as the weighted mean of the subnational age-specific rates, with the subnational age-specific population proportion as the weighting function, or $\mu(x,t) = \sum_i \mu_i(x,t)c_i(x,t)$, and national life expectancy is then

$$e_0(t) = \int_0^\omega \ell(x,t)dx = \int_0^\omega e^{-\sum_i \int_0^x \mu_i(a,t)c_i(a,t)da}dx, \qquad (1)$$

where $\ell(x,t)$ is the national survival function. The change over time in national life expectancy is then calculated as

$$\dot{e}_0(t) = \int_0^\omega \ell(x,t) \sum_i \left[-\int_0^x \dot{\mu}_i(a,t)c_i(a,t) + \mu_i(a,t)c_i(a,t)[r_i(a,t) - r(a,t)]\, da\right] dx, \qquad (2)$$

where the first term on the right of equation (2) corresponds to the change in mortality in each of the subnational populations, denoted as $\dot{\mu}_i(x,t)$, and the second term is determined by the relation between the growth in the subnational population respect to the growth in the entire nation, or $[r_i(x,t) - r(x,t)]$. Details of the calculations are found in the online supplementary material.

Assessing subnational life table methods

The existent subnational HMD databases are currently based on the methods protocol developed for national populations in the HMD (Wilmoth et al. 2017). However, no specific methods exists to construct subnational life tables coherent with life tables at the national level. The main problem of applying those methods to subnational data is related to old age mortality. In the HMD, to avoid random fluctuation and increase reliability of result, the mortality at old ages is smoothed using the Kannisto logistic model. The following rule is applied in the HMD methods: smoothed death rates replace observed death rates for all ages at or above Y, where Y is defined as the lowest age where there are fewer than 100 deaths, but is constrained to $80 \leq Y \leq 95$. The same rule and same method are used to adjust death rates at old ages for national data series and, independently, for subnational data. In other words, at ages above 80 there are two additional sets of age-specific deaths rates, namely $\tilde{\mu}(x,t)$ and $\tilde{\mu}_i(x,t)$, corresponding to the national and subnational smoothed death rates (for ages below 80 smoothed and unsmoothed rates are equivalent). Because of non-linearity of the Kannisto model, the national age-specific death rates as a weighting function of subnational mortality should be changed to $\tilde{\mu}(x,t) \cong \sum_i \tilde{\mu}_i(x,t) c_i(x,t)$, $x \geq 80$. Nevertheless, for the latter relation there is no direct mathematical representation for the weighting variable $c_i(x,t)$. Thus, as a checking procedure the national life expectancies calculated as a weighted average of subnational mortality (smooth and unsmooth) were cross-checked against the standard HMD data series.

Preliminary Results

The heterogeneity in subnational life expectancies existing in all studied countries are found in the three panels of Figure 1. The extreme subnational values for longevity are depicted here by the names of the highest and lowest subnational life expectancies: Australian Capital Territory (High) and Northern Territory (Low) for Australia, British Columbia (H) and Norwest Territory (L) for Canada, Nagano (H) and Aomori (L) for Japan, and Hawaii (H) and Washington DC and Mississippi (L) for the USA.

The subnational life expectancies for Japan progressively move towards higher levels in a narrow range of values between the highest and lowest life expectancies (maximum difference of 4.1 years and minimum 2.2 years). An exception is the year of 2011 when the earthquake, tsunami and nuclear disaster affected the longevity of some prefectures, however, Japan held the highest life expectancy in the world also this year. Opposing this, wider bands of values for subnational life expectancies are seen in all remaining three countries between 1970 and 2016: maximum minus minimum subnational life expectancies ranges for Australia (5.1-14.4 years), Canada (3.9-10.3 years) and the USA (6 -11.6 years).

[Figure 1 about here]

The assess the use of the HMD methods protocol to subnational HMD databases our main equation (1) can be used as an alternative way for calculating national life expectancy from the available subnational databases, and as such compare the feasibility of using the HMD methods also for subnational populations. Figure 2 presents the gap in national life expectancy as obtained from the HMD and contrasted with that calculated from subnational life tables for Australia, Canada and Japan from available years between 1970 and 2017. The nearly perfect matching of the national life expectancy from the two databases for Canada and Japan are remarkable (less than 0.05 in absolute values except for the last year in Canada). Opposing this are the high fluctuations existing for the Australian results. The later likely arising from mismatch in the input databases, or given the high migration at older ages within the country which are not accounted for in the methods.

[Figure 2 about here]

The change over time in life expectancy is analysed in two ways: i) An scenario where all subnational populations have exactly the same population proportion, so that only changes in mortality can be obtained from this scenario; and ii) the actual contribution of each of the subpopulations is also presented. Figure 3 presents the panels for all four countries, although for the USA only scenario (i) can be shown.

Different changes in national life expectancies are seen for the four countries: Australia (annual change of 0.14 years between 2006 and 2016), Canada (0.20 years for 2001-2011), Japan (0.16 years for 2006-2016) and the USA (0.09 years for 2006-2016). While for Australia, Canada and Japan all subnational populations contribute to the increase in the nation's life expectancy, in the USA some states oppose this development.

[Figure 3 about here]

Further steps

It is foreseen that much will be learned from the decomposition of the contribution of the subnational life expectancies to the national value into the mortality and the population growth effects. Additionally information for the USA will be investigated to allow comparable analysis to that carried for the other three nations.

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Methodological appendix

From each subnational population (i), age-specific rates by age (x) and time (t) were calculated for mortality and population growth, denoted as $\mu_i(x,t)$ and $r_i(x,t)$ respectively. The latter growth rate, is calculated as the relative derivative of the subnational population size $N_i(x,t)$, or in mathematical notation as $r_i(x,t) = \frac{\dot{N}_i(x,t)}{N_i(x,t)}$, with a dot on top of the variable denoting the derivative with respect to time (Vaupel and Canudas-Romo 2003). Additionally, the proportion of the population at each subnational population respect to the entire population by age was also calculated as $c_i(x,t) = \frac{N_i(x,t)}{N(x,t)}$, based on the population counts for the total $N(x,t)$ and the subnational populations.

The national age-specific death rate is the ratio of deaths over persons-years in the overall population. Additionally, it can be also calculated as the weighted mean of the subnational age-specific rates, with the subnational population proportion as the weighting function, or $\mu(x,t) = \sum_i \mu_i(x,t)c_i(x,t)$, and national life expectancy is then

$$e_0(t) = \int_0^\omega \ell(x,t)dx = \int_0^\omega e^{-\sum_i \int_0^x \mu_i(a,t)c_i(a,t)da} dx, \qquad (1)$$

where $\ell(x,t)$ is the national survival function, and the subnational specific information in this survival function is denoted as $\mathbb{l}_i(x,t) = e^{-\int_0^x \mu_i(a,t)c_i(a,t)da}$. Although, this is not the survival function of the subnational populations, its use simplifies the description of the life expectancy as a function of the subnational information as

$$e_0(t) = \int_0^\omega \ell(x,t)dx = \int_0^\omega \prod_i \mathbb{l}_i(x,t)\, dx, \qquad \text{(A1)}$$

and its change over time as

$$\dot{e}_0(t) = \frac{\partial}{\partial t}\int_0^\omega \prod_i \mathbb{l}_i(x,t)\, dx = \int_0^\omega \sum_i \dot{\mathbb{l}}_i(x,t) \frac{\ell(x,t)}{\mathbb{l}_i(x,t)} dx, \qquad \text{(A2)}$$

each of the subnational specific information can then be simplified as

$$\frac{\dot{\mathbb{l}}_i(x,t)}{\mathbb{l}_i(x,t)} = -\frac{\partial}{\partial t}\int_0^\omega \mu_i(a,t)c_i(a,t)da = -\int_0^\omega [\dot{\mu}_i(a,t)c_i(a,t) + \mu_i(a,t)\dot{c}_i(a,t)]da. \qquad \text{(A3)}$$

Since the second term on the right for the derivative of the proportion can be re-written as

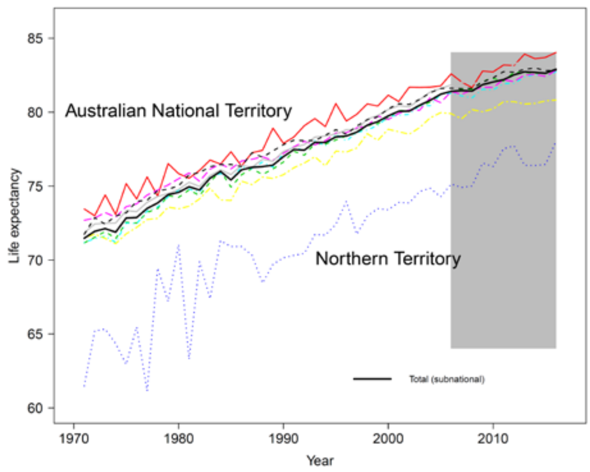
$$\dot{c}_i(t) = \frac{\partial}{\partial t}\left[\frac{N_i(t)}{N(t)}\right] = \frac{N_i(t)}{N(t)}\left[\frac{\dot{N}_i(t)}{N_i(t)} - \frac{\dot{N}(t)}{N(t)}\right] = c_i(t)[r_i(t) - r(t)] \qquad \text{(A4)}$$

and substituting equations (A4) in (A3) and the latter in (A2) gives us the desire equation (2) in the main text for the change over time in national life expectancy as

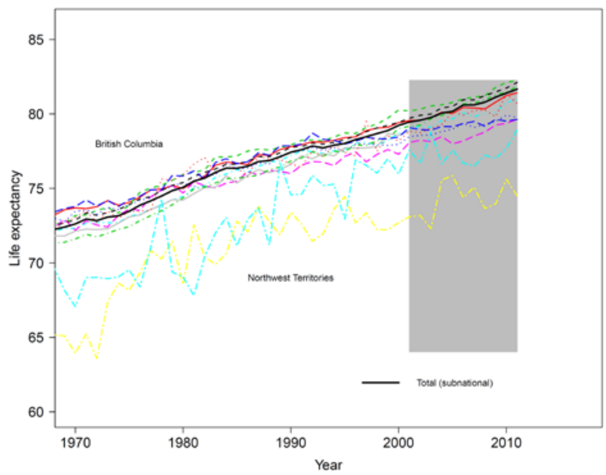
$$\dot{e}_0(t) = \int_0^{\omega} \ell(x,t) \sum_i \left[- \int_0^{x} \dot{\mu}_i(a,t)c_i(a,t) + \mu_i(a,t)c_i(x,t)[r_i(a,t) - r(a,t)]\, da\right] dx. \qquad (2)$$

Figure 1. Subnational life expectancy trends, females and males combined, for Australia (A), Canada (B), Japan (C) and the USA (D), from 1970 to 2017.

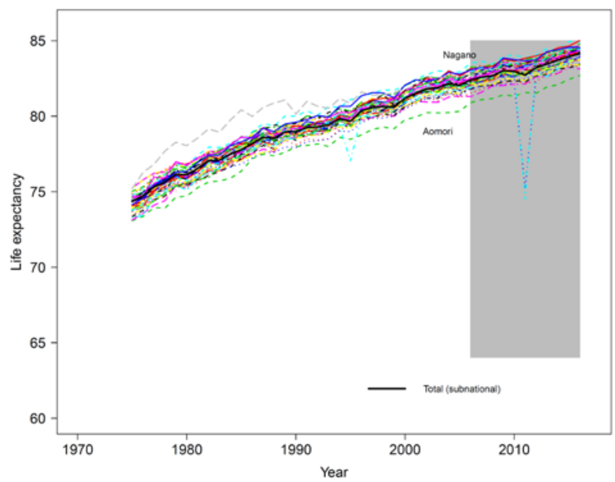
A



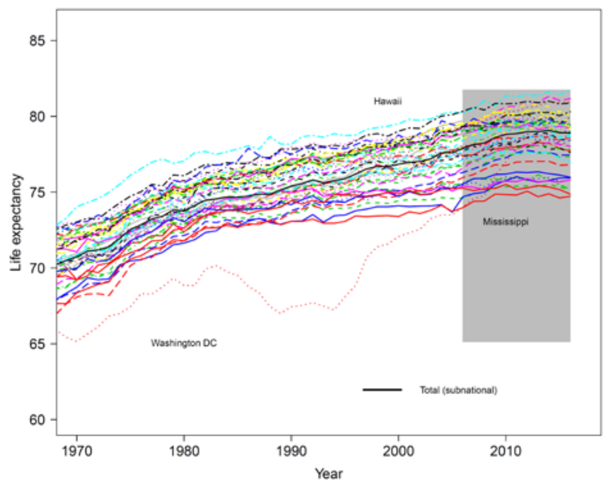
B



C



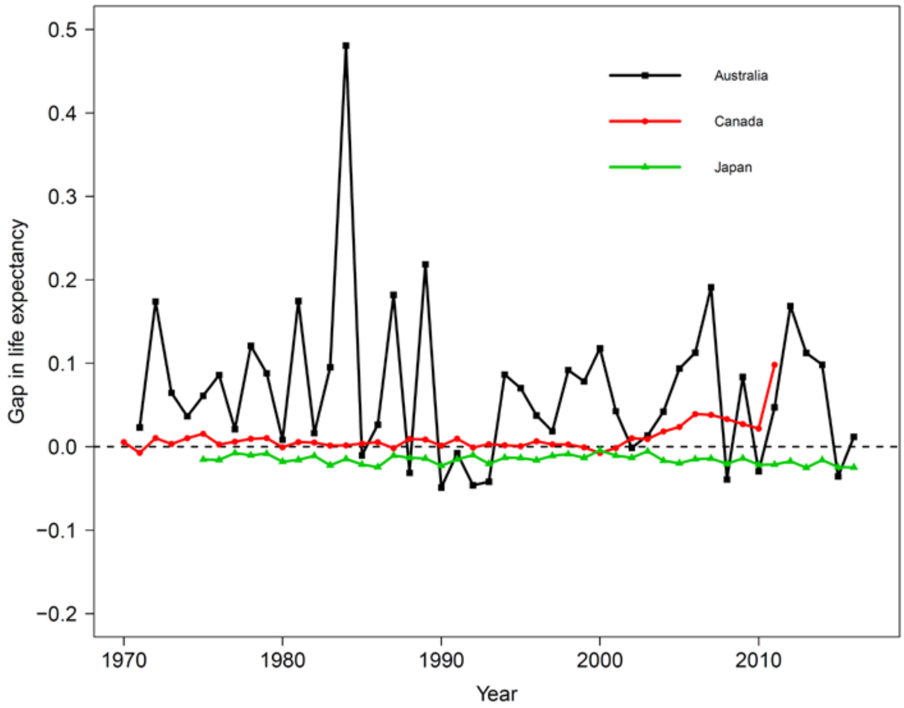
D



Note. The highest and lowest subnational life expectancy populations are highlighted in text, the national life expectancy resulting from the average of the subnational values is in black, and the last decade which is further analysed here is highlighted.

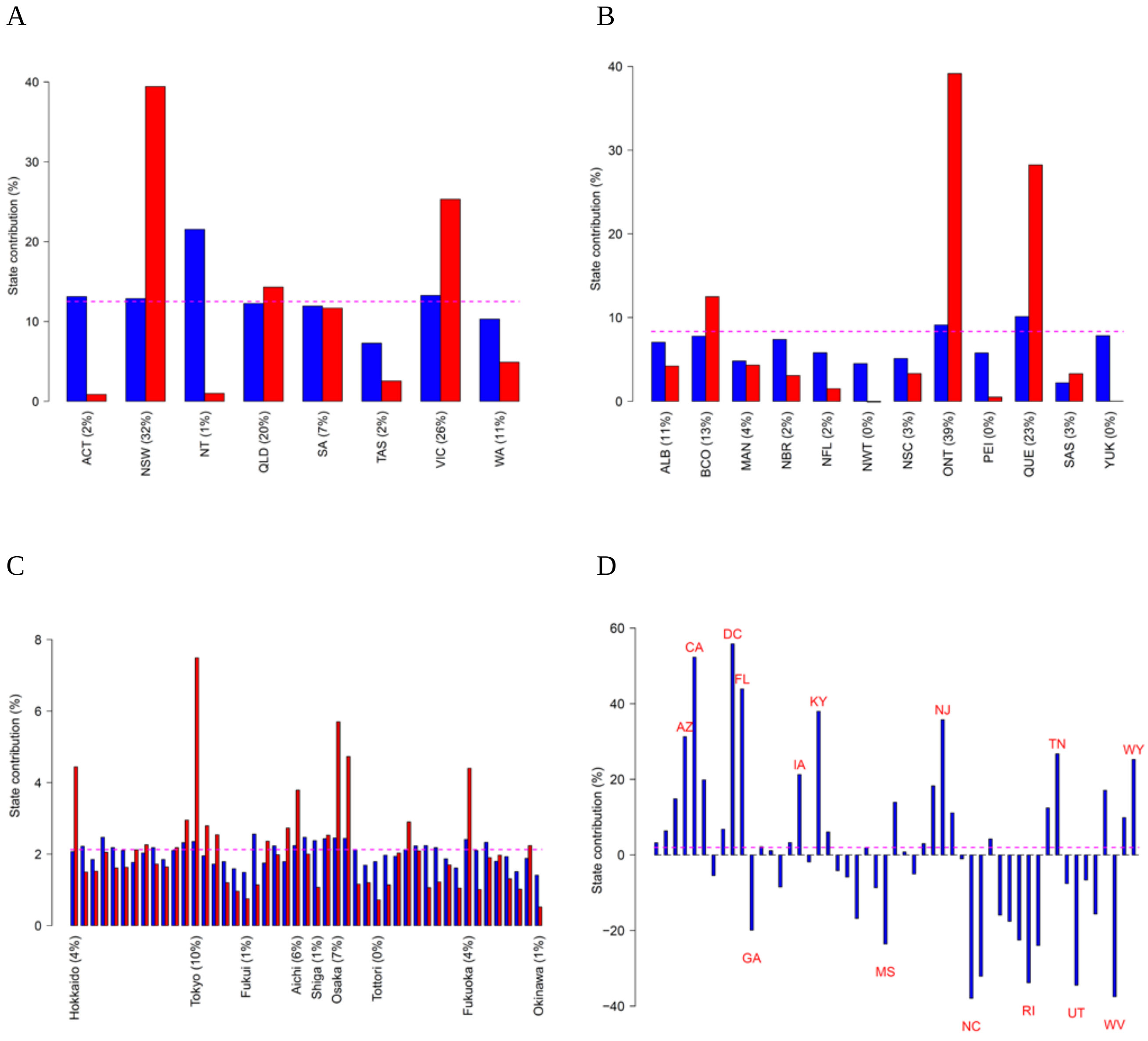
Source: subnational HMD for Australia, Canada, Japan and the USA

Figure 2. Gap in national life expectancy from the HMD and calculated from subnational life tables, females and males combined, for Australia, Canada and Japan from available years between 1970 and 2017.



Source: authors' calculations derived from HMD and subnational HMDs.

Figure 3. Subnational contributions to the national life expectancies changes in the last 10 years of available data under two scenarios (i) equal number of population across all subnational populations shown in the blue bars, and (ii) actual contribution, for females and males combined, for Australia (A), Canada (B), Japan (C) and the USA (D).



Note: a magenta line is shown for the scenario with all subpopulations of equal number representing the values that should have been if all subpopulations contributed equally to the increase in national life expectancy.