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ORIGINAL ARTICLE

Decomposition of official population projections in Brazil

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Brazil's population has continually changed over time. However, the effects of each demographic component on official population projections are still unclear. In this research, we replicate the *Population Projections Revision 2018* of the Brazilian Institute of Geography and Statistics using a projection matrix model and the cohort-component method by sex, age and geographic regions. Thereafter, we established four alternative scenarios to decompose the official benchmark scenario into four demographic effects (fertility, age structure, mortality, and migration) and one residual effect. The results reveal that fertility and age structure effects have been the main drivers of the population dynamics between 2010 and 2060. On the one hand, the negative effect of fertility below replacement level has been mostly offset by the still positive effect of the age structure, even across regions in the country. On the other hand, age structure effect has been decreasing over time. By 2048, the effects of age structure, mortality and migration will no longer counterbalance fertility effects, resulting in a population decline.

Keywords: Population projection. Cohort-component method. Demographic decomposition.

Introduction

Brazil's population has changed continually over time. Particularly, the onset of the demographic transition in the country has driven changes in population size and age structure since the decline in mortality rates in 1930s and the subsequent decline of fertility rates in the 1960s (Carvalho, 1974; Brito *et al.*, 2007; Carvalho; Wong, 2008; Potter *et al.*,

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2010; Gonçalvez *et al.*, 2019). With population stability still distant, population projection with time-varying fertility and mortality has become a great challenge. Past fertility rates, for example, have been overestimated and revised downward (Carvalho; Brito, 2005; Wong; Bonifacio, 2009). Even if vital rates returned to a constant level over time, the age structure would still hold a memory of the destabilization for a long time (Preston *et al.*, 2001), and a non-zero net migration over projection horizon could yet impact the expected population (Andreev *et al.*, 2013).

Accurate population projections are vital for public service planning (such as health, education, transportation and social security), financial resource allocation and demand forecasting (Isserman; Fisher, 1984; Miller, 2006; IBGE, 2018). Brazil's National Immunization Program (PNI) and the National Education Plan (PNE) use population estimates to determine vaccine distribution and to plan school enrollment, respectively (Brasil, 2003, 2015). The Participation Fund of States and Federal District (FPE) and the Participation Fund of Municipalities (FPM) also rely on population estimates to allocate resources to beneficiary entities (Brasil, 1989). Jannuzzi (2007) also states that population estimations and projections have been central for the development and monitoring of Urban Master Plan and Multi-Year Investment Plan, for impact assessment of major urban projects, and the allocation of resources in participatory planning processes. For Preston *et al.* (2001, p. 117), population estimation and projection is "probably the demographic technique that is most frequently requested by demography's 'clients'".

In Brazil, the Brazilian Institute of Geography and Statistics (IBGE) is the nation's federal institute accountable for publishing population statistics. Since 1973, IBGE releases population projection for the country and, since 1975, for federation units and municipalities (Mendes *et al.*, 1994; IBGE, 2024). Projection revisions occur at any time that real demographic outlook looks different from the assumptions in current projections, after population census or counts, or after a methodological change (IBGE, 2018). The *Population Projections Revision 2018* is the latest available revision, showing the population projections for Brazil and its Federation Units over a 50-year period since the 2010 demographic Census.

Methodologically, the cohort-component method has been the main method for population projections among demographers and national statistics institutes since its formalization and implementation (Leslie, 1945; Notestein, 1945; IBGE, 2018). This method relies on the concept of a 'cohort', a group of individuals born in the same time period and experiencing similar demographic events over the life cycle, usually disaggregated by sex and age. In addition, this method has been commonly used in a matrix-based model framework, particularly using the Leslie matrix (Leslie, 1945; Preston *et al.*, 2001; Keyfitz; Caswell, 2005).

Around the world, the Population Division of the United Nations has published estimates and projections for countries and regions since 1951 (Heilig *et al.*, 2009; UN, 2022a). The organization framework includes benchmark and alternative scenarios for the demographic components (UN, 2022b). Andreev *et al.* (2013) used that set of scenarios to disentangle the effects of fertility, mortality, migration and age structure for a better understanding of future population trends. Beyond the benchmark scenario, the U.S. Census Bureau has also released three alternative scenarios to analyze outcomes of immigration levels (U.S. Census Bureau, 2023). In turn, Spain's National Statistics Institute has published seven alternative scenarios to show central projections sensitivity to fertility and migration assumptions (INE, 2022). In Brazil, official population projections only consider a benchmark scenario, and therefore, the implicit contribution of each demographic component in the population dynamics remains unclear.

For Lee and Zhou (2017a, 2017b), counterfactual comparisons are the gold standard method to study demographic sources of population aging, although there is also a broader debate using stable population models and mathematical decomposition of population change (Horiuchi; Preston, 1988; Preston *et al.*, 1989; Preston; Stokes, 2012; Myrrha *et al.*, 2017; Murphy, 2017, 2021; Preston; Vierboom, 2021; Fernandes *et al.*, 2023). By analytic simulations for a set of countries, the authors revisited the question of whether the main driver behind continuing population aging was fertility or mortality. Bengtsson and Scott (2005, 2010, 2011) also used alternative scenarios with fixed fertility to find the main reason for population aging in Sweden. However, Murphy (2021) highlighted the weaknesses in the counterfactual population approach for assessing the demographic determinants of population aging, including that conclusions were sensitive to the choice of base year and that the method was not transitive (sub-interval results did not add up to the whole interval).

In this research, we have two objectives. First, we replicate the *Population Projections Revision 2018* benchmark scenario for Brazil and regions using official data and methodology. Then, we establish alternative scenarios through counterfactual population projections to assess the sensibility of the official model to varying levels and trajectories of fertility, mortality, and migration. Particularly, we create four alternative scenarios (residual, natural, replacement, and momentum) to disentangle population growth between 2010 and 2060 into the effects of fertility, age structure, mortality, migration and residuals at national and subnational levels. We also show a year-over-year decomposition in order to highlight the effects' dynamics during the period.

Data and methods

The *Population Projections Revision 2018* covers a 50-year time horizon from 2010 to 2060 with population by sex (male and female) and age (single ages from 0 to 90 years or more) at national, broader geographic regions, and federation units (IBGE, 2018). The official database includes annual life tables by sex, geographic region, and age groups (0, 1, 5, 10, ..., 85, 90+ years old), annual fertility rates in five-year age groups from 15 to 49 years old, and also annual migration balance by geographic region only.

The initial process of our estimation and projection required the definition of a base population and the delimitation of expected trajectories for fertility, mortality, and migration over the time horizon. The 'cohort-component method' (Preston *et al.*, 2001) was then used to apply region-, sex-, and age-specific vital rates and migration over the base population in order to project the population in the next calendar year. As this research aims to replicate the official projections to implement alternative scenarios beyond the benchmark scenario, the inputs in the replication model should be similar – ideally equal – to official data/inputs. Therefore, we set a successive process of projections starting with the population of 2010 (base population) until 2060.

The base population in 2010 and the expected trajectories for fertility and mortality over the time horizon were publicly available by region, age, and sex, and can therefore be used directly in the replication model. However, the national institute only provided abridged (incomplete) life tables by broader age groups. The 'lt_abridged2single' function in the R package DemoTools (Riffe *et al.*, 2019), commissioned by the Population Division of United Nations, was then used to recover complete life tables by single ages from 0 to 90 years or more. Fertility rates were also available for single year and 5-age groups, with rates repeated for single ages within the same age group.

As the projected populations should match official population projections, region-, sex- and age-specific migration were used as a *balancing item* between our projections (without migration) and official projections. If the total difference between our model and official projections was higher or lower than the official migration balance, the difference was considered a residual term. This replication methodology followed the cohort-component method via a projection matrix model (as shown in the Appendix).

Once we have the base population in 2010 and year-over-year trajectories for fertility, mortality, and migration by sex, age, and regions between 2010 and 2060, we were able to replicate official benchmark scenario perfectly. Based on Andreev *et al.* (2013), we decomposed population growth in the benchmark scenario using alternative scenarios. In our study, from the benchmark scenario, we successively added cumulative restrictions in each alternative scenario (residual, natural, replacement, and momentum, respectively). Firstly, in the residual scenario, residuals were set to zero, and thus the difference between the benchmark and residual scenario was the contribution of residuals to population growth. In the natural scenario, migration was set to zero in all projection horizons. Therefore, the difference between the natural and residual scenario was the contribution of net migration to population growth in each year of projection. In the replacement scenario, the level of fertility rate was set to replacement level in each year. To that end, age-specific fertility rates in each year and region were divided by the net reproduction rate, keeping the age structure of benchmark fertility. In this case, the difference between natural and replacement was the effect of fertility above or below replacement level on population growth. In the momentum scenario, the mortality rates in 2010 were constant over the entire projection period, and therefore the difference between this scenario and replacement was the contribution of mortality to population growth. Finally, the difference between the initial population in 2010 and momentum scenario was the contribution of the initial age structure of the population.

Results

In 2010, there were 194.9 million people in Brazil, and that number is projected to reach 228.3 million by 2060, an increase of 33.4 million (Figure 1, panel a). The fertility rate below replacement level (around 2.1 children per woman) in the country had a downward pressure on the population growth. If this were the only component, the population would decrease by 39.9 million people by 2060. Nevertheless, the other three demographic components offset this fertility effect.

Age structure in Brazil had by far the largest effect on population due to the still relatively young age structure, with larger cohorts of women in reproductive ages. Although the fertility rate is below replacement level, the age structure effect would result in an increase of 54.6 million people. This increase alone was sufficient to offset the negative fertility effect, thereby ensuring a positive population growth rate during the period. Moreover, the increase in life expectancy over the years implies a larger population due to fewer mortalities at birth and also more people surviving to older ages, resulting in a higher population at the end of projection horizon. The mortality effect is expected to increase the population by 17.6 million people between 2010 and 2060. Finally, migration had a minor effect on population compared to the other demographic components.

However, these four demographic effects reveal the total effect during 2010 and 2060. A year-to-year decomposition shows the components' trend over time (Figure 1, panel b). The fertility effect, for example, is relatively stable until 2025, reducing the population by over 500 thousand people a year. But in the following decades, this effect is expected to more than double. The mortality and migration effects are not expected to offset the fertility effects by themselves. Migration shows residual relevance throughout the entire period, whereas the mortality effect increases population, but to a much lesser magnitude than the decrease caused by fertility. The primary driver of population dynamics during the entire period has been the age structure. However, its effect is clearly decreasing: it will add 2.2 million people to the country in 2011 compared to only 0.1 million in 2060. In 2048, the combined effects of age structure, mortality, and migration will not be able to offset fertility effect, resulting in a projected population decline from that year onwards.

Furthermore, the trend in the age structure is expected to reach negative levels after 2060, which will further contribute to the population decline. Even if the fertility rate returned to replacement level, a negative effect of the age structure would still exert downward pressure on the population. This negative age structure effect will reflect the below-replacement levels of fertility over the recent past in Brazil since the 2000s.

There is still heterogeneity across regions in the country (Table 1). Roraima is the only state with positive fertility effect between 2010 and 2060, although its fertility rate is expected to reach replacement level around 2.1 by 2025. The Federal District has the most significant effect of fertility: the population would reduce by 26.5% over the years due to its lower fertility rate levels. On average, the fertility effect of 39.9 million people would mean a 20.5% decline of the country's population over time. Even though the age structure effect is sufficient to offset the fertility effect on average, this is not true for all regions in the country.

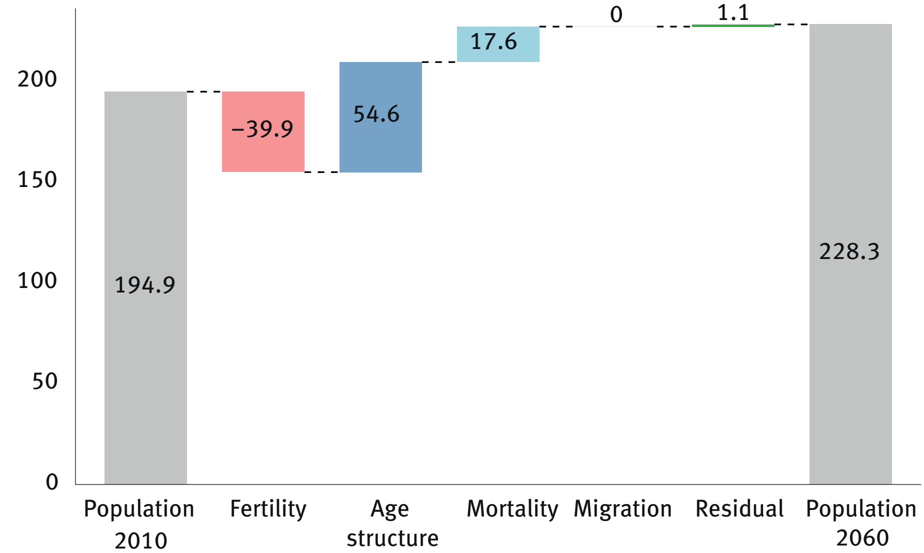
Minas Gerais, Rio de Janeiro, and Rio Grande do Sul reveal that the persistent low fertility rates below replacement levels in the past years have impacted their age structure, which is expected to be insufficient to offset the negative fertility effects. On the other hand, the North region shows a high level of age structure effect: the population could grow by 47.1% until 2060 due to this effect alone. In Amapá, this population growth could reach 59.7%. The mortality effect is more homogenous across regions, with all states expected to experience higher life expectation over the years, and consequently a positive mortality effect on population growth. The lower levels of mortality over the years would represent an average population growth of 9.0%. The highest and the lower population growths due to mortality effect are expected in Roraima (12.8%) and Goiás (7.3%), respectively.

The migration effect across regions is interesting because it potentially reveals two phenomena: international and internal migration. In Roraima, the migration effect is projected to increase the population by 50.6%, primarily driven by international migration. In the official projection, Roraima was the only geographic region with international migration balance different from zero, totaling a migration inflow of 79 thousand between 2015 and 2022 (IBGE, 2018). In other regions, internal migration is expected to be the predominant component. On average, the Northeast is the only region with a negative effect during the reference period. In Maranhão, emigration is projected to reduce the population by 28.5% between 2010 and 2060. Although immigration prevails in other states, negative effects are also observed in Acre, Pará, Paraná e Rio Grande do Sul. The Middle-West region exhibits the higher positive effect of migration. Beyond Roraima and Amapá, the main federation units with significant positive migration effect include Goiás, Federal District, Santa Catarina, and Espírito Santo.

Finally, the residual effect was more pronounced at regional levels. Two main uncertainties explained the presence of the residuals. Firstly, IBGE provided only rounded values for age-specific fertility rates, which impacted the estimated number of births. Secondly, we had no access to official life tables by single ages (only by age groups), which also accounted for some variation in the estimated number of deaths.

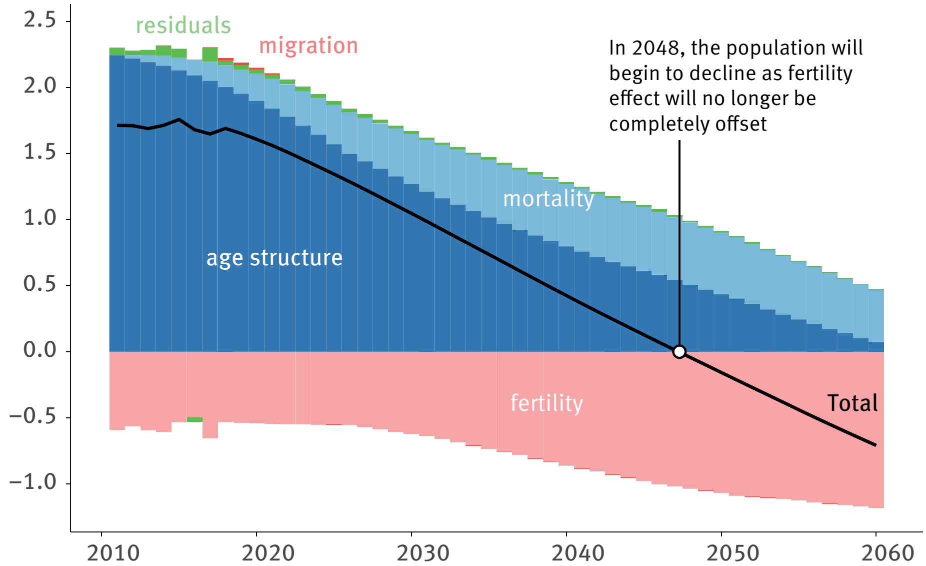
FIGURE 1
Population growth by demographic components
Brazil – 2010-2060

Panel (a): change from initial to final population, in millions of people



Note: Migration effect is positive and less than 0.0 million.

Panel (b): year-over-year change, in millions of people



Source: Own calculation based on data by IBGE.

TABLE 1
Decomposition of population growth, by geographic region and demographic components
Brazil – 2010-2060

	Population 2010	Contribution relative to total population in 2010 (in percentage)						Population 2060
		Fertility	Age structure	Mortality	Migration	Residual	Total	
Brazil	**194,890,682**	**-20.5**	**28.0**	**9.0**	**0.0**	**0.5**	**17.1**	**228,286,347**
North	16,246,130	-11.9	47.1	8.7	0.9	1.0	45.8	23,682,134
Rondônia	1,598,634	-18.4	35.9	8.4	5.5	1.3	32.6	2,120,212
Acre	765,325	-7.3	55.6	9.8	-5.7	3.4	55.8	1,192,647
Amazonas	3,553,148	-2.2	50.5	9.7	4.4	1.2	63.7	5,815,537
Roraima	458,820	1.5	48.4	12.8	50.6	1.2	114.6	984,511
Pará	7,762,953	-15.9	46.9	7.9	-7.6	1.6	33.0	10,321,412
Amapá	694,261	-11.0	59.7	9.2	30.3	0.8	89.0	1,312,240
Tocantins	1,412,989	-15.8	40.3	9.1	2.5	0.9	37.0	1,935,575
Northeast	54,215,569	-23.6	33.8	9.5	-14.9	0.5	5.3	57,115,649
Maranhão	6,710,964	-16.8	42.8	11.5	-28.5	0.6	9.6	7,357,617
Piauí	3,192,643	-23.2	32.3	8.0	-25.0	0.2	-7.7	2,948,119
Ceará	8,623,766	-25.3	34.6	7.8	-9.2	0.4	8.4	9,345,192
Rio Grande do Norte	3,239,939	-25.1	33.8	6.8	1.7	0.5	17.8	3,815,691
Paraíba	3,840,796	-23.4	28.5	9.9	-10.0	0.4	5.4	4,048,336
Pernambuco	9,000,873	-22.5	29.6	12.0	-9.3	0.7	10.5	9,945,508
Alagoas	3,195,720	-23.4	38.5	12.3	-26.9	0.7	1.1	3,230,875
Sergipe	2,108,297	-24.5	35.4	9.6	0.4	2.3	23.2	2,598,353
Bahia	14,302,571	-26.2	32.5	8.2	-18.2	0.4	-3.3	13,825,958
Southeast	82,155,595	-21.5	21.9	8.9	3.4	2.1	14.8	94,332,464
Minas Gerais	19,957,444	-25.8	24.2	8.3	0.4	-1.1	6.0	21,160,005
Espírito Santo	3,596,057	-17.0	27.8	9.2	14.3	2.7	37.0	4,927,795
Rio de Janeiro	16,303,188	-21.2	16.1	9.8	1.4	2.2	8.2	17,647,842
São Paulo	42,298,906	-20.1	22.7	8.7	5.9	2.3	19.6	50,596,822
South	27,921,126	-19.0	21.3	10.2	1.6	1.7	15.7	32,302,669
Paraná	10,653,276	-17.6	24.2	10.6	-8.8	7.5	15.9	12,342,362
Santa Catarina	6,353,055	-19.6	24.7	10.3	23.9	2.6	41.9	9,015,090
Rio Grande do Sul	10,914,795	-20.1	16.6	9.6	-9.2	3.4	0.3	10,945,217
Middle-West	14,352,262	-17.9	31.2	8.6	22.1	1.4	45.3	20,853,431
Mato Grosso do Sul	2,494,745	-8.6	30.4	9.0	5.9	1.2	37.9	3,440,594
Mato Grosso	3,106,513	-8.6	33.2	9.6	6.5	2.0	42.7	4,433,798
Goiás	6,111,792	-22.1	28.4	7.3	35.4	1.4	50.4	9,189,311
Distrito Federal	2,639,212	-26.5	37.6	8.8	22.4	1.3	43.6	3,789,728

Source: Own calculation based on data by IBGE.

Discussion

The population growth has drawn attention over the years due to its potential impact on economy, environment and society (Lutz; Sanderson; Scherbov, 2001; Bloom, 2011;

Bongaarts; Sinding, 2011). After WWII, fast population growth – especially in developing countries – became important in the international political agenda (Carvalho; Brito, 2005). In the 1940s, Brazil started a huge population increase due to mortality decline and higher fertility rates (Prata, 1992; Schramm *et al.*, 2004; Duarte; Barreto, 2012; Borges, 2017; Martins *et al.*, 2021). By that time, there was no expectation of a natural fertility decline in the short and medium term (Carvalho; Brito, 2005).

Nevertheless, beyond the decline from higher to lower mortality rates, since the 1960s, women on average have also started to have fewer babies (Carvalho, 1980; Berquó; Cavenaghi, 2005; Gonçalves *et al.*, 2019; Martins; Verona, 2019). Consequently, the lower mortality was counterbalanced by a lower fertility and therefore the country would show lower rates of population growth. Between 1960 and 1980, the geometric rate of population growth decreased from 3.0% to 2.5% a year (IBGE, 2023). Nowadays, the population growth is less than 1.0% a year and is expected to have negative rate from 2048 onwards (IBGE, 2018). Before fertility transition, demographic growth rate was the basic reference for socioeconomic planning as the age structure remained constant. Nevertheless, the population started an ageing process as the relative number of births continuously decreased, and the age structure change also became a key element for socioeconomic planning in the short, medium and long terms (Carvalho, 1980). In this context, accurate population projections have been vital for public service planning, financial resource allocation and demand forecasting (Isserman; Fisher, 1984; Miller, 2006; Jannuzzi, 2007; IBGE, 2018).

Therefore, the drivers behind population dynamics over the years have been especially associated with fertility, age structure, mortality, and migration effects, although they do not necessarily have the same weight on driving population change (Bengtsson; Scott, 2005, 2010, 2011; Andreev *et al.,* 2013; Lee; Zhou, 2017; Murphy, 2017, 2021; Fernandes *et al.*, 2023). The understanding of each demographic component can shed light on population changes in the past, present and future. Had demographers predicted the fertility transition during the 1950s, there would be a different expectation about population growth in following decades. Nowadays, the current age structure can also be informative about expected population in the next decades as it still preserves information about important changes in vital rates from the recent past (Preston *et al.*, 2001).

Since 2000s, the fertility rate has been below replacement-level fertility (around 2.1 children per woman), fostering a population decline. Between 2010 and 2060, our estimates indicate that population would decrease by 20.5% due to this fertility effect. This scenario is widespread throughout the country, except for Roraima, which is projected to maintain a positive – but relatively small – fertility effect during the same period. In turn, the Brazilian age structure still reflects higher fertility rates in the past, resulting in a relatively younger population and a sufficient number of women in reproductive ages to generate a number of births higher than deaths. On average, the age structure is projected to increase population by 28.0% between 2010 and 2060. Therefore, most states and the country as a whole will likely face positive population growth in the period.

However, the age structure effect has been reducing over time. As fertility rate has remained below replacement levels since 2000s, the number of women in reproductive ages will not be able to counterbalance the persistent low fertility rate in the future. In 2048, the population in Brazil will start a continuous decline process. The yearly effect of age structure should be close to zero by 2060 and, in the decades right after 2060s, there is an expectation that the age structure will have a negative effect on yearly population growth. Even if fertility rates return to replacement level, the population will have negative growth for a longer period because of an inertial component embedded in the age structure.

Regionally, federation units face the same population trend: fertility and age structure as the leading demographic components, although in different intensities. If international migration has a residual impact on national dynamics, the stronger influence of internal migration among geographic regions is worth noting. The continuous net emigration in Northeast states has been discussed in the literature (Ojima; Fusco, 2015), and it seems to continue in the future. Between 2010 and 2060, that regional population would reduce 14.9% due to migration effect.

For Andreev *et al.* (2013), migration effects also had a minor effect in explaining population growth between 2010 and 2100 in Brazil. Moreover, the positive age structure effect partially offset the negative fertility effect. In our study, although the age structure effect completely offset the fertility effect between 2010 and 2060, the year-over-year decomposition highlighted that the negative effect of fertility is expected to prevail by 2048. Therefore, our results are consistent with Andreev *et al.* (2013). Furthermore, Myrrha *et al.* (2017) also found that fertility decline had a primary role in explaining population aging between 1950 and 2100 in Brazil, while the mortality transition had a secondary role. Although in our study we focused on population growth and exhibited an age structure component, we also found that fertility effect prevailed over mortality effect in explaining population growth.

In summary, the demographic transition has changed the size and composition of the population in the country, and the timing of this transition has varied among different geographic regions. Our study identified and measured the main demographic drivers of population growth between 2010 and 2060. Our projection model decomposed official population projections into fertility, age structure, mortality, and migration effects. The results helped explain the trajectory of population growth over time and across different regions of the country. Fertility rates below replacement level have contributed to a population decline, but it has been damped on average by the age structure effect. However, the impact of age structure effect is decreasing over time, and it is expected that it will no longer completely counterbalance the negative fertility effect in the future.

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Resumo

Decomposição das projeções oficiais de população no Brasil

A população brasileira está em constante mudança ao longo do tempo. Contudo, os efeitos de cada componente demográfica nas projeções populacionais oficiais ainda não são claros. Nesta pesquisa, replicamos as *Projeções de População Revisão 2018* do Instituto Brasileiro de Geografia e Estatística usando um modelo matricial de projeção e o método das componentes por coortes por sexo, idade e região geográfica. Em seguida, estabelecemos quatro cenários alternativos para decompor o cenário *benchmark* oficial entre quatro efeitos demográficos (fecundidade, estrutura etária, mortalidade e migração) e um efeito residual. Os resultados mostram que a fecundidade e a estrutura etária têm sido os principais impulsores da dinâmica populacional entre 2010 e 2060. De um lado, o efeito negativo da fecundidade abaixo do nível de reposição tem sido compensado em maior parte pelo efeito ainda positivo da estrutura etária, mesmo por regiões do país. De outro lado, o efeito da estrutura etária está diminuindo com o tempo. Em 2048, os efeitos da estrutura etária, mortalidade e migração não serão mais suficientes para contrabalançar os efeitos da fecundidade, resultando em declínio populacional.

Palavras-chave: Projeção de população. Método de componentes por coortes. Decomposição demográfica.

Resumen

Descomposición de las proyecciones oficiales de población en Brasil

La población brasileña cambia constantemente a lo largo del tiempo. Sin embargo, los efectos de cada componente demográfico en las proyecciones oficiales de población aún no están claros. En esta investigación, replicamos las Proyecciones de Población Revisión 2018 del Instituto Brasileño de Geografía y Estadística (IBGE) utilizando un modelo de proyección matricial y el método de componentes por cohortes por sexo, edad y región geográfica. Luego, establecimos cuatro escenarios alternativos para descomponer el escenario de referencia oficial en cuatro efectos demográficos (fecundidad, estructura de edad, mortalidad y migración) y un efecto residual. Los resultados muestran que la fecundidad y la estructura por edad parecen ser los principales impulsores de la dinámica de la población desde 2010 con proyección a 2060. Por un lado, el efecto negativo de la fecundidad debajo del nivel de reemplazo ha sido compensado en gran medida por el efecto todavía positivo de la estructura por edad, incluso por regiones del país. Por otro lado, el efecto de la estructura de edad está disminuyendo con el tiempo. Así, en 2048, los efectos de la estructura de edad, la mortalidad y la migración ya no serán suficientes para compensar los efectos de la fecundidad, lo que provocará una disminución de la población.

Palabras clave: Proyección de población. Método de componentes por cohortes. Descomposición demográfica.

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Appendix

In the cohort-component method, via a projection matrix model, the population vector $P_t = [P^w_{0,t}, P^w_{1,t}, \dots, P^w_{90,t}, P^m_{0,t}, P^m_{1,t}, \dots, P^m_{90,t}]^T$ for calendar-year t with the population of women w and men m at single ages from 0 to 90 is multiplied by a two-sex Leslie matrix L_t (LESLIE, 1945) of dimensions 182 x 182 as shown below. The matrix exhibits the survivorship ratio $s_{i,t} = \frac{L_{i+1}}{L_i}$ at time t, which is the probability of a person (woman or man) at age to survive to the next age i, where L_i is the number of person-years lived at age i from the complete life table of time t. We assume that the age structure is stationary beginning at age 89, allowing the computation of the survivorship ratio at the last (open) age of 90. Additionally, there is a fertility component $f_{i,t} = k.\ F_{i,t}$ representing the number of births F by each woman at each age i in time t, where k is a factor to distribute births into male ($k = \frac{SRB}{1+SRB}$) and female ($k = \frac{1}{1+SRB}$) births according to the sex ratio at birth (SRB). Based on the official assumptions by the Brazilian Institute of Geography and Statistics, reproductive ages are considered to range from 15 to 49 years old, and the sex ratio at birth is assumed to be 1.05 over projection horizon (IBGE, 2018).

$$P_{t+1} = L_t.\ P_t + M_t + R_t$$

$$L_t = \begin{bmatrix} f^w_0 & f^w_1 & f^w_2 & \dots & f^w_{90} & 0 & 0 & \dots & 0 & 0 \\ s^w_0 & 0 & 0 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & s^w_1 & 0 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & s^w_{89} & s^w_{90} & 0 & 0 & \dots & 0 & 0 \\ f^m_1 & f^m_2 & f^m_3 & \dots & f^m_{90} & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & s^m_0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & s^m_1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & s^m_{89} & s^m_{90} \end{bmatrix}_{182\text{x}182}$$

The multiplication of the base population vector and the Leslie matrix at time result in the projected population for time $t + 1$, which should align with the official population projection. Otherwise, the difference between estimated and official projection is allocated to a migration vector $M_t = [M^w_{0,t}, M^w_{1,t}, \dots, M^w_{90,t}, M^m_{0,t}, M^m_{1,t}, \dots, M^m_{90,t}]^T$ representing the number of immigrants (positive values) or emigrants (negative values) by sex and age. If the total migration by year differs from official migration balance, the difference is proportionally allocated to a residual vector $R_t = [R^w_{0,t}, R^w_{1,t}, \dots, R^w_{90,t}, R^m_{0,t}, R^m_{1,t}, \dots, R^m_{90,t}]^T$. Then, this projected population becomes the reference population for the next projection period, and is multiplied by a Leslie matrix for time $t + 1$ in order to project population in year $t + 2$. The difference between estimated and official projection is again allocated to a migration and a residual vector in $t + 2$. This process is repeated successively until 2060. This method ensures model calibration and captures detailed migration data by age and sex.