Reconciliation of Australian demographic data to study immigrant population change across space and time

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ABSTRACT

The study of immigrant population change is hindered by data sources that capture international migration flows separately from other demographic process and population stock data. In this paper, we illustrate this by gathering detailed demographic data and estimates for the Australia-born population and 18 immigrant populations in Australia, according to their country or region of birth. We then develop a methodology for reconciling differences in these data sets to study the sources of quinquennial immigrant population change from 1981 to 2016 by age, sex, and geographic area. Reconciliation refers to the process of ensuring consistency between the demographic components of change (i.e., births, deaths and migration) and total population change. We validate the methodology by how well it predicts the population five years later by age and sex using a multiregional cohort-component prediction model. Once the data are reconciled for every five-year period from 1981 to 2016, we then see how well the reconciled data reproduces the 2016 population data using the 1981 population as a starting point. This research is useful for improving our understanding of the mechanisms and subsequent spatial contributions of immigration to population change over time. We demonstrate such value by examining the reconciled sources of regional population change for populations born in Australia, the United Kingdom and China over time.

Key words: spatial demography, immigration, population change, Australia

RECONCILIATION OF AUSTRALIAN DEMOGRAPHIC DATA TO STUDY IMMIGRANT POPULATION CHANGE ACROSS SPACE AND TIME

1. INTRODUCTION

This study is about understanding the specific contributions made by international migration to long-term demographic change. Like many developed countries, Australia has experienced considerable amount of demographic change over the past 35 years (Khoo and McDonald 2003). The population has grown by 10 million persons. Female life expectancy at birth increased by six years. The modal age at which women have babies increased by six years. The propensity to migrate within the country has declined (Bell et al. 2018). There has been both increased levels and diversity of immigration (Markus et al. 2009; Wilson and Raymer 2017; Raymer et al. 2018). And, state capital cities have increased their attractiveness as places to live and work (Raymer and Baffour 2018). Moreover, with continued increases in life expectancy at birth and below replacement level fertility, international migration will no doubt continue to influence population growth and redistribution for years to come.

In this paper, we document our efforts to create a complete, consistent and detailed account of spatial population change in Australia so that we may assess the contributions of immigration over time. Our objective is to place international migration in the context of demographic change for specific subpopulations and geographic areas. To accomplish this objective, we first obtained available data on population stocks, fertility, mortality, internal migration and international migration by age, sex, geographic area and birthplace for the period 1981 to 2016 from the Australian Bureau of Statistics (ABS). Second, we developed and applied demographic and statistical techniques to overcome inadequacies in the available demographic event data, including overall immigrant population change (Raymer et al. 2018), internal migration and mortality, (Raymer and Baffour 2018; Baffour and Raymer

2109), and sub-state immigration and emigration flows (Raymer et al. 2019). Third, as documented in this paper, we (i) construct a multiregional demographic accounting model (Rogers 1995) to identify the discrepancies between the sources of population change data and the corresponding change found in the official population stock estimates; (ii) reconcile the discrepancies by adjusting the reported immigration and emigration flow totals; and (iii) assessed the results by age and sex for 19 birthplace-specific groups and 11 subnational areas from 1981 to 2016. Finally, we present the results with a focus on populations born in Australia, the United Kingdom (UK) and China. We believe these three populations provide a useful comparison of the methodological results as they represent the majority population, a large and long-established immigrant population, and a large but relatively new immigrant population, respectively.

The absence of reconciled demographic sources of growth data hinders the study of immigrant population change. It also prevents one from placing international migration in the context of overall population change. Moreover, it limits our ability to study the subsequent demographic behaviours of immigrants, such as emigration, internal migration, fertility and mortality. Thus, this research increases the capacity to identify and assess the demographic consequences of migration to, from and within Australia for a range of immigrant and non-immigrant populations over a 35-year period of time.

In the next section, a brief background on the importance of demographic accounting models for studying migration is provided. This is followed by a description of the estimated resident populations, births, deaths, internal migration and international migration data by age, sex and geography that were used as inputs for developing our methodology and analyses. In Section 4, we present the methodology for reconciling the demographic accounts for 18 immigrant populations and the Australian-born population across eleven geographic areas and seven time periods. In Section 5, we present the results of from the reconciliation,

focusing on the populations born in Australia, United Kingdom and China. The paper ends with a discussion and conclusion.

2. BACKGROUND

Migration acts to add or subtract people of specific origins, ages and sexes to populations. What distinguishes migration from the other demographic mechanisms of change (fertility and mortality) is that it involves two populations simultaneously, i.e., an in-migrant to one place is an out-migrant from another. Furthermore, migration alters the social structure of both populations by adding or subtracting people with specific characteristics, such as high or low levels of education, majority or minority ethnicity, or young or old ages. In the destinations, migrants may later have children which also add to the population (or die which has the opposite effect).

Since the Commonwealth of Australia was established in 1901, immigration has been an important aspect of Australian society, and immigration policy has long sought to control the types and characteristics of people coming to Australia (Richards 2008). However, a major gap in our knowledge of migration concerns the long-term demographic consequences of these flows and policies on population growth and redistribution. We also know little about the corresponding consequences of domestic migration, which tend to involve larger numbers of people than international migration. In a demographic accounting model framework, consequences include those that are direct, such as changing the size and age-sex composition of specific populations through immigration or emigration, and indirect, such as those involving subsequent generations (Edmonston 2010; Lomax et al. 2019; Rees et al. 2013; Scott and Stanfors 2010) and other demographic processes (see, e.g., Kulu 2005, 2006; Kohls 2010; Milewski and Kulu 2014; Raymer and Baffour 2018). Further, migrants from poorer areas of the world tend to bring with them their higher levels of fertility, and because

migration involves a selection process, they also tend to be young, ambitious and with skills needed for the labour market. Not all migrants remain to retire in the host country but many do, and this has implications for the health sector in an ageing society.

In Australia, there have been many studies that have examined international and internal migration flows (Bell and Hugo 2000; Stillwell et al. 2001; Markus et al. 2009; Hugo 2010). Some have examined the determinants of internal and international migration (Flood et al. 1991; Hugo 2004) and the description of social change caused by international migration (Markus et al. 2009), including the linkages between immigration and internal movements (Burnley 1996). There have also been compilations describing various aspects of Australia's changing demography (Hugo 1986; Khoo and McDonald 2003). What these studies have not attempted is to quantify the long-term demographic consequences of international migration or to place it in a consistent population accounting framework. Having a consistent and detailed time series of demographic event and population stock data, disaggregated by age, sex, geographic area and birthplace, allows one to assess the relative contributions of migration to demographic change for areas within Australia. This information is important to planners and policy makers who are interested in understanding the mechanisms behind population change, and for assessing the effectiveness of past or current migration policies.

Demographic data reconciliation is conducted by most national statistical offices after new census results come out to ensure the demographic components of change between census years match the population totals. These efforts are typically focused on ensuring consistency in the demographic components for the total population by age, sex and geographic location. In Australia, the ABS adjusts its estimated resident population numbers, interstate migration and net overseas migration estimates to ensure consistency between censuses every five years (ABS 2017). Births and deaths data are not adjusted. In the

academic literature demographic reconciliation and estimation has been used to study the long-term contributions of immigration to the United States (Gibson 1975, 1992), foreign-born and native-born regional population change in the United States (Rogers et al. 1999), subsequent immigrant generations in Canada (Edmonston 2010), and ethnic population change across local authority districts in England (Rees et al. 2018).

In this paper, demographic reconciliation is applied to study population change across 18 immigrant populations according to their country or region of birth and the Australian-born population. We chose birthplace as the defining feature population because of the consistency in measurement over time and relative abundance of available data in Australia. Note that children of immigrants born in Australia are considered ‘Australia-born.’ The study of ethnic population change, on the other hand, is considerably more complicated because persons can change their ethnic identify and/or can have children comprised of a different or mixed ethnic background. Also, aside from Aboriginal or Torres Strait Islander, Australia does not gather data on the ethnic identity of its population.

In Australia, fertility and mortality are obtained from administrative registers, internal migration flows are obtained from quinquennial censuses and changes of address notified to Medicare, and immigration and emigration are obtained from administrative data on border crossings. Population characteristics are available from censuses as enumerations and the ABS as official estimates (estimated resident population). The above information can be brought together using a demographic accounting model where a population in location i and at time $t+1$ is equal to a population at time t plus the births, in-migration and immigration that occurred during the year less the deaths, out-migration and emigration that occurred during the year. However, before doing so, it is important to align the measurement of the demographic components to fit the population statistic of interest (Rees 1985; Rees and Willekens 1986; Raymer et al. 2015). Finally, due to time and budget constraints of the data

providers, the demographic outputs made available to users rarely consider all the different types of population present in location i and at time t let alone their components of demographic change. More often, they refer to just one type of population, such as those considered to be usual residents. This may have implications for the availability and quality of detailed or demographic data.

3. DATA

We gathered data on five demographic components of change for immigrant populations by age, sex, birthplace and geographic area in Australia. These data represent a time series of five-year periods from 1981-1986 to 2011-2016 disaggregated by birthplace (Australia and 18 overseas countries or regions of birth, shown in Appendix 1), geography (47 and 11 consistently-classified sub-national regions in Australia), five-year age group (0-4 years, 5-9 years, ..., 80-84 years, 85+ years) and sex (male, female). The following description provides an overview of how each demographic component time series was refined prior to use in a demographic accounting equation.

In general, for each demographic component, we first identified any inconsistency or missing data issues in the available data. For example, with some areas, there were issues with small cell values and general data sparseness, especially when disaggregated by birthplace, geographic area and age. To overcome the weak or missing data, we developed and implemented strategies for each demographic component (summarised below).

Sometimes, the solutions were relatively simple and involved aggregation of geographic units, or the application of smoothing techniques (e.g. to mortality and internal migration). In other situations, we had to use methods for extrapolating the trends backwards in time (e.g., births, deaths, immigration and emigration) or for combining data to produce sub-state levels of immigration and emigration.

The estimated resident population (ERP) is the official measure of the Australian population provided by the ABS. It is based on census counts of usual residents, and adjusted for net undercount in each census, residents temporarily overseas on census night, and the small timing difference between census night (9 August) and the ERP (30 June) reference date (ABS 2019). In this research, we consider the total estimated resident populations by sex, birthplace and geographic area to be the true estimates of the Australian population. These data were commissioned from the ABS for each census year from 1981 to 2016 by age group and sex. The geographic information represented Statistical Divisions for the 1981 to 2011 data and SA3 for the 2016 data. Details of the geographic harmonisation into 47 harmonised regions based on Statistical Divisions are provided in Raymer and Baffour (2018). The national estimated resident population counts by birthplace and sex by were disaggregated into subnational regions by using region-to-national proportions calculated from census data (Raymer et al. 2019). Further, due to small immigrant population counts in most of these regions, the 47 geographic areas are aggregated into 11 areas representing a mixture of large state capital cities and regions (see Appendix 2).

Annual numbers of births were obtained from registration data provided by ABS from 1981 to 2016, disaggregated by geography (Statistical Division or SA3 geographic classifications), birthplace of mother and five-year age group of mother. The annual numbers of births were aggregated into five-year totals from 1981-1986 to 2011-2016. Then, for each five-year period, the total births were divided by mid-period female estimated resident populations to calculate five-year average age-specific fertility rates by birthplace of mother and region of residence in Australia. These age-specific fertility rates were then used as inputs for estimating the number of Australia-born births contributed by both Australia-born and overseas-born females in Australia (see Section 4.3).

Annual numbers of deaths from 1981 to 2016 were obtained from registration data provided by ABS. Similar to births, annual numbers of deaths were added together for five year periods from 1981-1986 to 2011-2016 and the geographic units were harmonised at the Statistical Division level into 47 regions and 11 broader regions. To obtain age- and sex-specific mortality rates for each subpopulation and five-year period, we divided the number of deaths by the average of estimated resident populations for each time period. One issue we had to overcome was sparseness in the deaths data for immigrant populations, many of which have arrived in Australia in only the past 10-15 years and were still relatively young (i.e., low risk of death). We used P-splines (Carmada 2012) to smooth the age-specific mortality rates for each of the 18 overseas-born populations (Baffour and Raymer 2019). These smoothed mortality rates were then combined with probabilities of interregional migration to calculate the multiregional survivorship probabilities for the purposes of demographic prediction (refer to Section 4.3).

Interregional migration data were obtained from the quinquennial censuses in Australia administered by ABS. For each five-year period from 1981-1986 to 2011-2016, we used the census questions of place of usual residence by place of usual residence five years ago to cross-tabulate population counts by area of residence, country or regional of birth, age and sex. To deal with the issue of sparse internal migration data, we used unsaturated log-linear models to smooth the observed origin-destination population counts for the 19 birthplace-specific populations, with the exception of the relatively large Australia-born and UK-born populations (Baffour and Raymer 2019). These smoothed data were then rebased for each five-year period to match the sizes of the estimated resident populations.

Finally, the immigration and emigration flows were estimated by ABS from statistics on permanent and long-term overseas arrivals and departures that are provided by the Department of Home Affairs from various sources, such as incoming passenger cards and

visas (ABS 2018a; 2018b). Since July 2007, ABS has applied a 12 out of 16 month rule to obtain estimates of international migration in line with population change. That is, an immigrant is defined as a person coming from overseas who has lived in Australia for a total of 12 months over a duration of 16 months. Likewise, an emigrant is defined as someone who has been outside Australia for 12 out of 16 months.

The immigration and emigration data commissioned from the ABS consist of two single-year time series: one time series runs from 1981 to 2003, disaggregated by citizenship, state, age and sex, and the other time series goes from 2004 to 2016, disaggregated by country or region of birth, state, age and sex. To derive a complete and consistent time series of immigration and emigration by birthplace, region, age and sex, two steps were carried out (Raymer et al. 2019). First, the birthplace-specific immigration and emigration flows for the period of 1981 to 2003 were estimated at the state level using birthplace to citizenship ratios. Second, the estimated state-level flows of immigration and emigration from 1981 to 2016 were then disaggregated into 47 sub-state regions using region-to-national proportions calculated from census data. As with births and deaths data, annual flows of immigration and emigration data were aggregated into five-year totals from 1981-1986 to 2011-2016.

The data and methods described above represent our best attempts to complete and harmonise the individual demographic component time series data. When combined together, however, substantial errors are evident in observed birthplace-specific demographic data at both the national level (Figure 1) and regional level (Appendix 3) from 1981-1986 to 2011-2016. So, even with our best attempts to improve the data, when combined together in a demographic accounting model, the numbers do not line up to the reported change between the estimated resident population at time t and $t+5$. In the next section, we develop a method to reconcile the detailed demographic data over time so that they do line up and are able to quantify the sources of population change across regions and birthplaces.

4. RECONCILIATION METHODOLOGY

4.1 General strategy

Our methodology for reconciling demographic accounts is motivated by Rogers et al. (1999; see also Rogers and Raymer 1999, 2001) who examined regional foreign-born and native-born population change in the United States from 1950 to 1990. First, we apply a cohort-component demographic accounting model for each birthplace and sex group at the 11 region level to calculate the accounting discrepancies or error terms --- presented in Figure 1, along with the demographic components of change. Second, these error terms are distributed to immigration and emigration at the regional level. Third, a multiregional cohort-component prediction model is used to validate our reconciled data by how well it matches the estimated resident population at various time points going forward by birthplace, region, sex and age. The data validation was divided into two stages where we first applied the model to estimate the populations five years later, i.e., 1986 population from a 1981 base population, 1991 population from a 1986 base population, ..., 2016 population from a 2011 base population, and then to estimate the whole 35-year period using the 1981 birthplace-region-sex-age population as the starting point.

----- Figure 1 about here -----

4.2 Identifying and distributing error terms

For each of the 18 overseas-born populations, we used the following demographic accounting equation to calculate error terms by period, region, and sex:

$$\varepsilon_{y,i,k}^{t \sim t+5} = P_{y,i,k}^{t+5} - P_{y,i,k}^t + D_{y,i,k}^{t \sim t+5} - I_{y,i,k}^{t \sim t+5} + O_{y,i,k}^{t \sim t+5} - IM_{y,i,k}^{t \sim t+5} + EM_{y,i,k}^{t \sim t+5} \quad (1)$$

where ε denotes the error term, P denotes the population stock, D denotes deaths, I denotes in-migration, O denotes out-migration, IM denotes immigration, and EM denotes emigration. The subscript y denotes sex, i denotes one of the 11 regions in Australia, k denotes birthplace,

and t denotes a specific census year from 1981 to 2011. For example, the error term for UK-born females who resided in Sydney in the period of 1981-1986 was calculated as:

$$\begin{aligned}
\varepsilon_{F,Syd,UK}^{1981\sim1986} &= P_{F,Syd,UK}^{1986} - P_{F,Syd,UK}^{1981} + D_{F,Syd,UK}^{1981\sim1986} - I_{F,Syd,UK}^{1981\sim1986} + O_{F,Syd,UK}^{1981\sim1986} \\
&\quad - IM_{F,Syd,UK}^{1981\sim1986} + EM_{F,Syd,UK}^{1981\sim1986} \\
&= 113,041 - 118,567 + 5,147 - 5,958 + 10,969 - 17,336 + 8172 \\
&= -4,532.
\end{aligned}$$

For the Australia-born population, births were added to Equation 1:

$$\begin{aligned}
\varepsilon_{y,i,Aus}^{t\sim t+5} &= P_{y,i,Aus}^{t+5} - P_{y,i,Aus}^t - B_{y,i,Aus}^{t\sim t+5} + D_{y,i,Aus}^{t\sim t+5} - I_{y,i,Aus}^{t\sim t+5} + O_{y,i,Aus}^{t\sim t+5} - IM_{y,i,Aus}^{t\sim t+5} + \\
&\quad EM_{y,i,Aus}^{t\sim t+5},
\end{aligned} \tag{2}$$

where B denotes births contributed by both the Australia-born and overseas-born populations. Note, in this case, IM denotes Australia-born persons who have returned to Australia and EM denotes Australia-born persons who migrated abroad.

For both the Australia-born and overseas-born populations, we assumed that error terms were attributed to misreporting in the immigration and emigration data. In reality, error could come from any of the demographic components or even the estimated resident populations used as a basis for calculating the error. Our reasoning for attributing error to international migration is as follows. First, international migration is, by far, the largest component of change for the 18 immigrant populations. Second, the estimation of immigration and emigration flows by ABS are not aligned to the concept of usual residence as closely as the other demographic components are. Third, adjusting immigration and emigration totals provided the simplest solution. For the Australia-born population, internal migration is the likely to be the other main contributor to error but since this demographic component comes from census data, we believe it is relatively well-aligned with the estimated resident populations.

The following equations were used to adjust the reported immigration and emigration flows:

$$\widehat{IM}_{x,y,i,k}^{t \sim t+5} = \frac{IM_{x,y,i,k}^{t \sim t+5}}{IM_{y,i,k}^{t \sim t+5}} \times (IM_{y,i,k}^{t \sim t+5} + \varepsilon_{y,i,k}^{t \sim t+5} \times \frac{IM_{y,i,k}^{t \sim t+5}}{IM_{y,i,k}^{t \sim t+5} + EM_{y,i,k}^{t \sim t+5}}) \text{ and} \quad (3)$$

$$\widehat{EM}_{x,y,i,k}^{t \sim t+5} = \frac{EM_{x,y,i,k}^{t \sim t+5}}{EM_{y,i,k}^{t \sim t+5}} \times (EM_{y,i,k}^{t \sim t+5} - \varepsilon_{y,i,k}^{t \sim t+5} \times \frac{EM_{y,i,k}^{t \sim t+5}}{IM_{y,i,k}^{t \sim t+5} + EM_{y,i,k}^{t \sim t+5}}), \quad (4)$$

where x denotes five-year age groups, $\widehat{IM}$ denotes reconciled immigration, and $\widehat{EM}$ denotes reconciled emigration. Using these two equations, we first reconciled immigration and emigration at the regional level by distributing the total error terms by sex, birthplace and region to the corresponding total immigration and total emigration flows. We then proportioned the reconciled immigration and emigration across age groups based on the age patterns originally reported by ABS. For example, the reconciled immigration and emigration flows for UK-born females aged 20-24 years in Sydney during the period of 1981-1986 were calculated as:

$$\begin{aligned} \widehat{IM}_{20,F,Syd,UK}^{1981-1986} &= \frac{IM_{20,F,Syd,UK}^{1981-1986}}{IM_{F,Syd,UK}^{1981-1986}} \\ &\times \left(IM_{F,Syd,UK}^{1981-1986} + \varepsilon_{F,Syd,UK}^{1981-1986} \times \frac{IM_{F,Syd,UK}^{1981-1986}}{IM_{F,Syd,UK}^{1981-1986} + EM_{F,Syd,UK}^{1981-1986}} \right) \\ &= \frac{2,140}{17,336} \times \left(17,336 - 4,532 \times \frac{17,336}{17,336 + 8,172} \right) = 1,760 \\ \widehat{EM}_{20,F,Syd,UK}^{1981-1986} &= \frac{EM_{20,F,Syd,UK}^{1981-1986}}{EM_{F,Syd,UK}^{1981-1986}} \\ &\times \left(EM_{F,Syd,UK}^{1981-1986} - \varepsilon_{F,Syd,UK}^{1981-1986} \times \frac{EM_{F,Syd,UK}^{1981-1986}}{IM_{F,Syd,UK}^{1981-1986} + EM_{F,Syd,UK}^{1981-1986}} \right) \\ &= \frac{1,041}{8,172} \times \left(8,172 + 4,532 \times \frac{8,172}{17,336 + 8,172} \right) = 1,226 \end{aligned}$$

Several special cases on distributing the errors are worth noting. If both immigration and emigration turned out to be zero at the regional level, we distributed positive error terms to immigration and negative error terms to emigration. As immigration and emigration were constrained to be positive at the regional level, error terms were distributed only to immigration if reconciled emigration turned out to be negative and only to emigration if reconciled immigration turned out to be negative. Finally, the observed age patterns of immigration and emigration at the national level were used to disaggregate reconciled immigration and emigration at the regional level if either observed immigration or observed emigration at the regional level was zero.

4.3 Multiregional cohort component prediction model

4.3.1 Multiregional life tables without and with emigration

To apply the multiregional cohort component prediction model to our reconciled data, we first needed to obtain survivorship matrices from the multiregional life table (Rogers 1995, Chapter 4). Given that immigration and emigration data are considered the major sources of the mismatch between population stock data and demographic event data, we constructed two sets of multiregional life tables: one based on probabilities of dying and internal migration and one based on probabilities of dying, internal migration and emigration.

The multiregional life tables constructed without emigration were based on age-specific rates of mortality and conditional survivorship proportions of internal migration (i.e., Option 2 method in Rogers 1995, pp. 97-100). As mentioned in Section 3, to reduce the effects of sparseness in the data, we smoothed the internal migration counts (except for the Australia-born and UK-born populations) and mortality rates (except for the Australia-born population) before calculating the conditional survivorship proportions and the multiregional life tables (Baffour and Raymer 2019). Further, to prevent implausible results, we adjusted

the formulas for the probability of migrating (p_{ij}) and probability of staying (p_{ii}).

Specifically, we forced p_{ij} to be zero if $\sum p_{ij}$ was larger than or equal to 0.4. The rationale behind this adjustment is that we believe p_{ii} normally stands at 0.6 or higher in the absence of emigration. For p_{ii} , we changed the formula from $1 - \sum p_{ij} - q_x$ to $1 - q_x$, where q_x denotes the probability of dying, when the results were negative, and set p_{ij} to be zero.

The multiregional life table with age-specific probabilities of emigration (EM_x) required further adjustments to the calculation of p_{ii} . The calculation of EM_x used estimated resident populations and reconciled emigration as its inputs, and followed the same formula for calculating q_x , except that the last age group was not closed. Here, the formula for p_{ii} is changed to $1 - \sum p_{ij} - q_x - EM_x$, with the values of p_{ii} constrained to be no less than 0.001 (except for the North America-born population, whose p_{ii} values were constrained to be no less than 0.1). Without these constraints, it was not possible to calculate the multiregional life table with emigration.

In Table 1, we present the multiregional life expectancies for UK-born and China-born females aged 20 years based on the 2011-2016 data. The life expectancies are expressed as percentage of remaining life. For example, a UK-born female who is 20 years old and lives in Sydney is expected to spend 7% of her remaining life in Sydney, 13% in other regions in Australia, and 80% elsewhere overseas. This can be compared to a corresponding China-born female which is expected to spend 25% of her remaining life in Sydney, 7% in other regions in Australia, and 69% elsewhere overseas. Note, these figures were obtained by combining the two multiregional life tables: without emigration and with emigration. The number of remaining life years spent within Australia (i.e., retention and other regions) were drawn from the life table with probabilities of emigration included. The number of remaining life years expected to be spent overseas for each region was obtained by subtracting the total regional life expectancies with emigration from the total regional life expectancies without emigration.

----- Table 1 about here -----

With the two sets of multiregional life tables, we calculated multiregional survivorship matrices without emigration, $\mathbf{S}_{x,y,i,k}^{t \sim t+5}$, and with emigration, $\hat{\mathbf{S}}_{x,y,i,k}^{t \sim t+5}$. In both cases, we used the conventional life table formula $\mathbf{S}_{x,y,i,k}^{t \sim t+5} = \mathbf{L}_{x+5,y,i,k}^{t \sim t+5} (\mathbf{L}_{x,y,i,k}^{t \sim t+5})^{-1}$ for all but the last age group (see Rogers 1995, p. 101). For the last open-ended age group, we used the following equation from Rogers (1995, p. 107):

$$\mathbf{S}_{(80)} = \frac{2}{5} \left[\frac{2}{5} (\mathbf{I} + \bar{\mathbf{S}}_{(80)})^{-1} (\mathbf{I} - \bar{\mathbf{S}}_{(80)}) + \mathbf{M}_{(85)} \right]^{-1} \mathbf{p}_{(80)} (\mathbf{I} + \mathbf{p}_{(80)})^{-1} \quad (5)$$

where $\mathbf{I}$ is an identity matrix and $\mathbf{p}_{(80)} = \frac{1}{3} (2 \times \bar{\mathbf{S}}_{(75)} + \bar{\mathbf{S}}_{(80)}) \mathbf{p}_{\sigma(80)}$. Here, $\mathbf{p}_{\sigma(x)}$ is a diagonal matrix of survival probabilities that unconditionalises the conditional survival probability matrix: $\bar{\mathbf{S}}_{(x)} = (\mathbf{I} + \frac{5}{2} \times \bar{\mathbf{M}}_{(x+5)})^{-1} (\mathbf{I} - \frac{5}{2} \times \bar{\mathbf{M}}_{(x)})$. Note, $\bar{\mathbf{M}}_{(x)} = \mathbf{M}_{(x)} - \mathbf{M}_{d(x)}$, where $\mathbf{M}_{d(x)}$ is a diagonal matrix of regional mortality rates. $\mathbf{M}_{(x)}$ is a matrix defined as follows:

$$\mathbf{M}_{(x)} = \begin{bmatrix} M_{1d(x)} + \sum M_{1j(x)} & -M_{21(x)} & \cdots & -M_{m1(x)} \\ -M_{12(x)} & M_{2d(x)} + \sum M_{2j(x)} & \cdots & -M_{m2(x)} \\ \vdots & \vdots & \ddots & \vdots \\ -M_{1m(x)} & -M_{2m(x)} & \cdots & M_{md(x)} + \sum M_{mj(x)} \end{bmatrix} \quad (6)$$

where the subscript m is the number of regions, $M_{id(x)}$ is the age-specific annual mortality rate for region i , and $\sum M_{ij(x)}$ is the sum of age-specific migration rates between regions i and j for all values of j ($j \neq i$). The equation with emigration included is the same as above, except emigration rates are added to the diagonal elements in $\mathbf{M}_{(x)}$.

4.3.2 Cohort component prediction model with immigration

To validate the reconciled immigration and emigration data for demographic accounting, we first applied the multiregional cohort component prediction model to each five-year period separately, using the regional birthplace-specific populations by age and sex at the beginning

of each period to estimate the corresponding populations at the end of that period. The predicted regional populations were then compared with the observed populations in the same year. Two multiregional cohort component prediction models were considered:

- (i) A model with zero immigration to provide a baseline for comparison. This model is specified as

$$\hat{\mathbf{P}}_{x+5,y,i,k}^{t+5} = \mathbf{G}_{x,y,i,k}^{t \sim t+5} \mathbf{P}_{x,y,i,k}^t, \quad (7)$$

where $\mathbf{G}$ is the growth matrix that includes the probabilities of survivorship and emigration.

- (ii) A model with immigration, specified as

$$\hat{\mathbf{P}}_{x+5,y,i,k}^{t+5} = \mathbf{G}_{x,y,i,k}^{t \sim t+5} (\mathbf{P}_{x,y,i,k}^t + 0.5 \widehat{\mathbf{IM}}_{x,y,i,k}^{t \sim t+5}) + 0.5 \widehat{\mathbf{IM}}_{x,y,i,k}^{t \sim t+5}, \quad (8)$$

where 0.5 of the period immigration is added to the beginning population (subject to mortality and emigration) and 0.5 of the period immigration at the end of period (not subject to mortality and emigration).

To illustrate the results, in Figure 2, we present comparisons between the observed and predicted (with and without immigration) age-specific female populations born in the UK and China and living in Sydney and Adelaide in 1986, 2001 and 2016. The corresponding mean absolute percentage errors are presented in Table 2.

----- Figure 2 and Table 2 about here -----

For predicting the Australia-born population, a birth vector was added to Equation 8, i.e.,

$$\hat{\mathbf{P}}_{x+5,y,i,AUS}^{t+5} = \mathbf{G}_{x,y,i,AUS}^{t \sim t+5} (\hat{\mathbf{P}}_{x,y,i,AUS}^t + 0.5 \widehat{\mathbf{IM}}_{x,y,i,AUS}^{t \sim t+5}) + 0.5 \widehat{\mathbf{IM}}_{x,y,i,AUS}^{t \sim t+5} + \hat{\mathbf{B}}_{0,y,i,AUS}^{t \sim t+5}. \quad (9)$$

To derive the birth vector, we first summed the numbers of births contributed by both Australia-born females and females born in the 18 overseas birthplaces, i.e.:

$$\hat{\mathbf{B}}_{0,i,Aus}^{t \sim t+5} = \sum_{k=1, x=15}^{k=19, x=45} (\hat{\mathbf{P}}_{x,F,i,k}^t b_{x,F,i,k}^{t \sim t+5}), \quad (10)$$

where

$$b_{x,F,i,k}^{t \sim t+5} = \frac{5}{2} \frac{L_{0,F,i,Aus}^{t \sim t+5}}{5l_{0,F,i,Aus}^{t \sim t+5}} \times (f_{x,F,i,k}^{t \sim t+5} + f_{x+5,F,i,k}^{t \sim t+5}) \hat{S}_{x,F,i,k}^{t \sim t+5} \quad (11)$$

$\hat{B}_{0,i,Aus}^{t \sim t+5}$ denotes estimated total Australia-born births by period and region, $L_{0,F,i,Aus}^{t \sim t+5}$ denotes the number of person-years lived between age 0 and age 5 by Australia-born females obtained from the multiregional life table without emigration, $l_{0,F,i,1}^{t \sim t+5}$ denotes a matrix with 100,000 in the diagonal and zeros elsewhere, and $f_{x,F,i,k}^{t \sim t+5}$ denotes age-specific fertility rates. The total number of births were then multiplied by the 105 / 100 male-to-female sex ratio at birth to get the numbers of Australia-born male babies. Note that the births contributed by Australia-born females were calculated using the multiregional population prediction model for the Australia-born population and the overseas-born births were calculated separately using the 18 overseas-born prediction models.

In Figure 3, we present some selected results from the second stage of our data validation process, where the 2016 populations are predicted based on the 1981 base data and the five-year reconciled demographic components from 1981-1986 to 2011-2016. We find that both the age profiles and regional totals resulting from our multiregional population predictions in 2016 are reasonably close to the observed values by age, sex, birthplace and region, giving support to the reconciliation methodology we applied.

----- Figure 3 about here -----

5. RESULTS

5.1 Results at the national level

Reconciled demographic accounts at the national level are presented in Figure 4. These results can be compared to the observed (not reconciled) data presented in Figure 1. In examining the reconciled components of population change, notable differences are found both between the Australia-born and overseas-born populations and amongst the 18 overseas-

born populations. While births have remained the largest contributor to the growth of the Australia-born population over the past 35 years, demographic changes of overseas-born populations in Australia have mainly been driven by immigration and emigration.

----- Figure 4 about here -----

There are two contrasting sources of growth patterns exhibited by the 18 overseas-born populations. The first is represented the immigrant populations born in the UK, South-East Europe and, to a lesser extent, other North-West Europe. These populations are affected by relatively large numbers of deaths and all have witnessed near-zero or even negative population growth in recent years. This is due to many of them arriving under the White Australia policy prior to 1975. The second pattern is represented by the non-European groups, which by contrast do not exhibit significant numbers of deaths but instead have exhibited increasing levels of immigration and emigration flows over the last three and a half decades. These flows are a result of dismantling the discriminatory White Australia migration policy in the 1970s in favour of a skilled-based migration program (Markus et al. 2009).

5.2 Sources of regional population growth for populations born in Australia, UK and China

To examine demographic changes at the regional level, the reconciled demographic accounts for the Australia-born, UK-born and China-born populations are presented in Figures 5, 6 and 7, respectively (refer to Appendix 3 for corresponding unreconciled data). The reconciled demographic data for the Australia-born population shows that overall change remained positive in each of the 11 broad regions for the most of the past 35 years, albeit with differences in the size and patterns. Sydney and Melbourne witnessed relatively large increases in population growth, particularly over the last two decades, contributed mainly by rising immigrant births and declining out-migration flows. Brisbane, by contrast, experienced

steady population growth throughout the period, receiving large in-migration flows and births. Population growth in NSW Coast has been declining since the early 1990s, driven by a combination of several demographic factors but mostly increasing emigration and deaths.

----- Figures 5, 6, and 7 about here -----

One problem identified in the reconciled data for the Australia-born population concerns Adelaide during the 2011-2016 period. In this case, we find a substantial increase in the emigration flows. The reason behind this relatively large increase was due to the negative error term being much larger than the reported immigration and emigration flows. This resulted in all the error being distributed to the emigration flow. When examining the demographic components of change prior to reconciliation (Appendix Figure 3a), the patterns appear relatively stable, suggesting that the problem may be due to error in the estimated resident population for Adelaide or due to a geographical concordance issue associated with matching the SA3 geography to the Statistical Division geography in the most recent period.

In contrast to the Australia-born population, the UK-born population exhibited near-zero or negative growth in most of the 11 broad regions over the past three and a half decades, as illustrated in Figure 6. This demographic pattern is most remarkable in Sydney and Melbourne, where population growth has remained negative throughout the 35 years, except between 2006 and 2011. Brisbane, Perth and Regional Australia are the only three regions that exhibited substantial growth the UK-born population over the past 35 years, and it was driven primarily by increased levels of immigration. That said, population growth in these three regions fluctuated considerably and even touched zero or turned negative for certain periods, for example, Brisbane in 2011-2016.

The reconciled sources of growth for the China-born population are presented in Figure 7. This population exhibited positive and increasingly rapid growth in all regions,

except Remote Australia. The growth was contributed almost entirely by rising immigration levels, particularly in the state capital cities of Sydney, Melbourne, Brisbane and Perth.

5.3 Age-sex compositions

In this section, we illustrate the age patterns of the reconciled demographic components for females born in Australia (Figure 8), UK (Figure 9) and China (Figure 10) and living in Sydney and Adelaide. Note that the reconciliation was carried out on data aggregated across age groups, i.e., the model does not enforce the sources of demographic change to match the reported age-cohort differences between the estimated resident populations (represented by the diamonds in the figures). Early in the research, we tried adjusting the age-specific immigration and emigration flows so that they would match exactly the age-cohort differences but the resulting age profiles proved to be unrealistic. Thus, we believe there is also some error in the age profiles of the immigrant populations and designed the prediction model to include some flexibility by allowing the demographic components to vary from the age patterns of the estimated resident populations.

----- Figures 8, 9 and 10 about here -----

Australia-born females aged 0-4 years in Sydney (Figure 8a) exhibited significant population growth over the past 35 years, due largely to increasing numbers of births contributed by overseas-born mothers. Other age groups, except 15-19 year olds, exhibited negative population growth. Patterns of demographic changes in the Australia-born population in Adelaide (Figure 8b) are similar to the patterns in Sydney, except that population growth of females aged 0-4 years in Adelaide did not increase until the mid-2000s and that sizeable increases in emigration were observed in the most recent five-year period, especially amongst children and young adults. Note, as mentioned previously, the substantial increases in emigration from Adelaide during 2011-2016 were due largely to the large

negative error observed and the reconciliation methodology that redistributed it all to emigration. Fortunately, we did not discover other similar (implausible) results amongst other regions or immigrant populations.

Compared to Australia-born females, UK-born females in Sydney and Adelaide (Figures 9a and 9b, respectively) witnessed positive population growth of both children and young adults. While population growth of UK-born children in Sydney has been relatively stable over the past three and a half decades, growth of UK-born young adult females in Sydney have been increasing rapidly. Population changes in UK-born females in Adelaide, however, fluctuated with the largest growth observed in the period of 2006-2011. Also, there were considerable numbers of deaths amongst UK-born females aged 70 years and older in both Sydney and Adelaide, which is not surprising considering the UK-born population is an established migrant group with a long history in Australia.

In contrast to the demographic changes experienced by UK-born females, China-born females in Sydney and Adelaide (Figures 10a and 10b, respectively) displayed continuous population expansion in the last 35 years, notably over the past decade. This expansion was driven almost entirely by young adult immigration. This demographic pattern, along with very few deaths, reflects the China-born population's status as an emerging source of immigration to Australia.

6. DISCUSSION AND CONCLUSION

The study of demographic change provides researchers and policymakers with information about the fundamental sources of population change and subsequent impacts on the age and sex composition of the population. It also provides information on how the population is redistributing itself across the country, allowing one to assess where the areas of growth or decline are (or will be) and whether this growth or decline is affecting particular population

groups. In Australia, there have been very few studies on the geographical dimensions of migrant groups during the past two decades, aside from highly specific studies of individual groups. This is surprising considering the large scale of migration and the impacts it has on social change. Our research provides further insights on how immigration, emigration and internal migration act to shape population change across Australia.

In order to fully understand the consequences of internal and international population movements, researchers and policy makers need to overcome the limitations of the currently available data sources on population stocks and demographic components of change, including inconsistencies in data availability, definitions and quality. This topic of research is particularly important for Australia, where the main source of numbers on immigration and emigration come from arrival and departure cards collected at major entry points with uncertainty about the destinations and origins within the country. This research has addressed these issues by first developing a conceptual framework for population change and matching that framework to the available data through a population accounting model. Demographic estimation techniques and statistical modelling have been applied to reconcile the measurement differences between the framework and the data, and to overcome other limitations, such as inadequate demographic or geographic detail and irregularities in the observed data caused by random or sample-based variation. Future improvements to the modelling approach could incorporate uncertainty in the reconciliation process and could build off recent developments utilising Bayesian techniques (see, e.g., Bryant and Graham 2013; Bryant and Zhang 2018; Wheldon et al. 2013).

The advantages of having a consistent and reliable data set of demographic change are numerous. Detailed migration and population estimates are needed so that governments have the means to improve their planning policies directed at supplying particular social services or at influencing levels of migration. This is important because international migration and

domestic migration are major contributors to population change at subnational levels in Australia. By applying demographic estimation and data harmonisation techniques to reconcile and augment available data, we are now able to better understand the dynamics of population change that has occurred since 1981. Our research included the Australia-born population plus 18 immigrant groups for 11 geographic areas to provide a richer picture of population change across Australia. The estimation of the components of population change has been embedded within a demographic accounting framework, one that allows groups to be tracked as they are born, enter or exit a particular area within and outside of Australia, and ultimately die.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Table 1. Multiregional life expectancies (percent) for UK-born and China-born females aged 20 years, 2011-2016

Birthplace	Region	Retention	Other regions	Overseas
UK-born				
	Sydney	7	13	80
	NSW Coast	3	16	81
	Melbourne	10	12	78
	Country Victoria	5	16	80
	Brisbane	13	12	75
	Adelaide	18	15	67
	Perth	18	13	69
	Greater Hobart	8	19	73
	Canberra	5	23	73
	Regional Australia	5	21	74
	Remote Australia	2	27	71
China-born				
	Sydney	25	7	69
	NSW Coast	6	27	68
	Melbourne	25	8	67
	Country Victoria	9	23	69
	Brisbane	12	14	73
	Adelaide	7	24	69
	Perth	15	14	71
	Greater Hobart	7	23	69
	Canberra	3	28	70
	Regional Australia	9	17	74
	Remote Australia	8	9	84

Table 2. Mean absolute percentage errors for the multiregional cohort component prediction models with and without immigration: UK-born and China-born population predictions for 1986, 2001 and 2016

Birthplace	Year	With Immigration	Without Immigration
UK	1986	10%	17%
	2001	12%	16%
	2016	9%	18%
China	1986	25%	40%
	2001	31%	37%
	2016	20%	41%

Figure 1. Observed birthplace-specific demographic accounts at the national level, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in population stocks during each five-year period.

A. UK-born

B. China-born

Figure 2 Comparison between predicted and observed populations (in thousands) for UK-born and China-born females in selected regions in 1986, 2001 and 2016

Notes: 1. The x-axis in graphs for Sydney and Adelaide denotes age groups, and the x-axis in graphs for regional totals denotes region codes.
2. See Appendix 2 for the correspondence between region codes and names.

Figure 3 Comparison between predicted and observed populations (in thousands) for Australia-born, UK-born and China-born females in selected regions in 2011-2016

Notes: 1. The x-axis in graphs for Sydney and Adelaide denotes age groups, and the x-axis in graphs for regional totals denotes region codes.
2. See Appendix 2 for the correspondence between region codes and names.

Figure 4 Reconciled demographic accounts by birthplace at the national level, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in population stocks during each five-year period.

Figure 5. Reconciled demographic accounts by region for the Australia-born population, 1981-1986 to 2011-2016
*Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.
 2. The diamond in each bar represents the change in population stocks during each five-year period.*

Figure 6. Reconciled demographic accounts by region for the UK-born population, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in population stocks during each five-year period.

Figure 7. Reconciled demographic accounts by region for the China-born population, 1981-1986 to 2011-2016
*Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.
 2. The diamond in each bar represents the change in population stocks during each five-year period.*

Figure 8a Reconciled demographic accounts of Australia-born females by age in Sydney, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Figure 8b Reconciled demographic accounts of Australia-born females by age in Adelaide, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Figure 9a. Reconciled demographic accounts of UK-born females by age in Sydney, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Figure 9b. Reconciled demographic accounts of UK-born females by age in Adelaide, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Figure 10a. Reconciled demographic accounts of China-born females by age in Sydney, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Figure 10b. Reconciled demographic accounts of China-born females by age in Adelaide, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016.

2. The diamond in each bar represents the change in the reported estimated resident population stocks during each five-year period.

Appendix 1. Classification of Australia and 18 overseas birthplace groups

No.	Birthplace
1	Australia
2	New Zealand
3	Other Oceania and Antarctica
4	United Kingdom
5	Other North-West Europe
6	South-East Europe
7	North Africa and the Middle East
8	Vietnam
9	Philippines
10	Malaysia
11	Indonesia
12	Other South-East Asia
13	China (excludes SARs, Taiwan)
14	Other North-East Asia
15	India
16	Other Southern and Central Asia
17	North America
18	South America
19	Sub-Saharan Africa

Appendix 2. Map of the eleven geographic areas for Australia

Appendix 3a. Observed demographic accounts at the regional level for the Australia-born population, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016; 2. The diamond in each bar represents the change in population stocks during each five-year period.

Appendix 3b. Observed demographic accounts at the regional level for the UK-born population, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016; 2. The diamond in each bar represents the change in population stocks during each five-year period.

Appendix 3c. Observed demographic accounts at the regional level for the China-born population, 1981-1986 to 2011-2016

Notes: 1. In each bar group, the seven bars from left to right represent the seven five-year periods from 1981-1986 to 2011-2016; 2. The diamond in each bar represents the change in population stocks during each five-year period.

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Author/s:

Raymer, J;Bai, X;Liu, N;Wilson, T

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