Imputation of full birth histories from census data: a rediscovered method for detailed fertility analysis in sub-Saharan Africa

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This article examines an extension to the own-children method for estimating trends in age-specific fertility from single-round inquiries. It converts listings of women's own children into full birth histories using answers to the summary birth history questions about fertility (i. e. the questions about women's children ever-born and surviving). Birth histories reconstructed from census and similar data can potentially be used to investigate detailed patterns of fertility, including parity progression and birth interval dynamics. This method for imputing full birth histories from census data was first proposed more than 30 years ago (Luther and Cho, 1988) but has seldom been applied except by its developers and their collaborators at the East-West Center in Hawaii. Since their retirement, it seems to have fallen out of use (though see Retherford *et al.* 2005; Choe and Retherford 2009).

With the increased availability of sample census microdata, such as those distributed by IPUMS-International, it seems timely to revisit this approach to estimating fertility. Most fertility surveys, such as Demographic and Health Surveys (DHS), interview too few women for it to be possible to examine parity progression and birth intervals in detail without combining the data from multiple surveys and modelling the data (for example, Timæus and Moultrie 2020). Because of the large size of census microdata samples (often 10 per cent of the national population), they can be used both to study the family building process by parity in detail and to produce estimates for small geographical areas and population groups. In addition, most fertility surveys only collect birth histories from women aged less than 50. Thus, the retrospective estimates of fertility become increasingly truncated by age as one works back in time from when the data were collected. In contrast, censuses that collect summary birth history data typically ask all adult women the questions, avoiding truncation of the retrospective fertility estimates by age. Thus, the strengths of the microdata samples complement those of the DHS.

The article is divided into three parts: its first section outlines Luther and Cho's method for reconstructing birth histories and proposes some extensions to it that take advantage of advances in statistical methods and computer processing power during the last three decades; the second section assesses the performance of the method by applying it to a large fertility survey, the 2006 National Family Health Survey of India, that collected full birth histories with which the reconstructed histories and fertility estimates can be compared; and the third section applies the method to IPUMS-International sample microdata for several Southern and Eastern African countries (Botswana, Rwanda, Tanzania, Zambia) and illustrates the types of analysis that can be conducted on the reconstructed birth histories it produces.

Reconstruction of birth histories from census data

The Luther and Cho (1988) method uses the fact that most children and teenagers live in the same households as their mothers. Thus, by linking these 'own children' to their mothers in a census or household survey dataset, one can calculate the mother's age at the time each such child was born. By reverse-surviving women's own children to allow for children who have died or are living apart from their mother, one can estimate annual counts of births by age of mother at birth that can be used calculate period age-specific fertility rates for about the 15 years prior to the collection of the data.

The conventional Own-Children Method for estimating fertility adjusts the counts of own children for mortality and children who live apart from their mothers (often termed 'non-own' children) at the aggregate level (Cho *et al.* 1986). If the inquiry asked about women's children ever-born and surviving, one can produce life table estimates of the mortality of the children of each five-year cohort of mothers by the indirect or Brass method (Hill 2013). Alternatively, one can use other life table estimates of mortality in the population concerned. The number of children of each age that are living apart from their mother can be tabulated from the dataset to which the Own-Children Method is being applied and their mothers' ages pro-rated to those of the mothers of own children of that age.

Censuses that have included the summary birth history questions about women's children ever-born and surviving provide information on how many living and dead children individual women have borne in total, and therefore on how many additional living children each woman has apart from own-children who reside with her. This makes it possible to adjust for these missing children at the individual level, rather than in aggregate as in the Own-Children Method. By imputing ages to a woman's dead and non-own children and adding them to the list of ages of her own children, one can reconstruct the woman's full birth history.

Luther and Cho (1988) proposed a probabilistic method for making these estimates for each cohort of women. For a dead child, by multiplying the age-specific probabilities that the child has died, $1-L(a)$, where a is the years since birth or 'age' of the child, by the age-specific fertility of the cohort of mothers a years ago, $f(x-a)$, where x is the current age of the mother, one can estimate the probability distribution that the dead child is each possible age a:

$$\Pr\left(D(a,x)\right)=\frac{f_i(x-a)\left(1-L_i(a)\right)}{\sum_a f_i(x-a)\left(1-L_i(a)\right)}$$

Similarly, the probability that a child that was living elsewhere was each age a can be estimated by multiplying the appropriate cohort age-specific fertility rate, $f(x-a)$, by the probability that the child was still alive and by $n(a)$, the probability that a living child aged a was living elsewhere at time that his or her mother was interviewed:

$$\Pr\left(N(a,x)\right)=\frac{f_i(x-a)L_i(a)n(a)}{\sum_a f_i(x-a)L_i(a)n(a)}$$

Luther and Cho suggest that one can use the Own-Children Method to estimate aggregate fertility schedules for each cohort that can be substituted into these equations. However, women have almost no chance of having a birth within a year of another birth. Thus, before one can calculate the probability distributions for $D(a,x)$ and $N(a,x)$, the age-specific fertility distribution of each women aged x at the time of data collection needs to be adjusted to avoid children whose ages are being imputed being assigned the same age as a child with a known age. Luther and Cho did this by creating a notch in the age-specific fertility distribution around each age $x-z_i$, where z_i is the current age of one of a woman's own children. They suggest that a notch of 2.5 years is appropriate, but that this assumption could be tailored to the population in question if some information already existed on the length of birth intervals in the country.

Having calculated probability distributions for the ages of women's dead and non-own children (i. e. living children are not co-resident with their mothers), ages can be randomly imputed to both groups of children child drawn randomly drawn from the appropriate distribution. When a woman has more than one child who is not an own child, Luther and Cho impute the ages of the living and dead children sequentially in a random order, inserting an additional notch into the woman's fertility distribution after the age of each child has been determined. As a refinement, a small proportion of the dead and non-own children can be randomly paired with a child of known age, rather allocated a different age, to allow for multiple births.

One feature of Luther and Cho' approach to imputing ages to those of a women's children who are not living with her is that the only source of heterogeneity between women that it takes into account is that between age cohorts of women. No attempt is made to allow for other sources of variation in the women's fertility or their children's mortality. However, typically censuses or similar inquiries collect a variety of information on women's characteristics. For example, many inquiries collect information on women's ages at marriage and, in societies in which childbearing is largely confined to marriage, this defines the maximum age that a woman's children can have attained by the time that she (or the head of her household) was interviewed. Moreover, individual-level microdata will almost certainly include information on where each woman lives and on various of their socio-economic characteristics such as their level of schooling. By modelling the impact of such individual-level characteristics on women's age-specific fertility using Poisson regression for rates or similar methods, one can tailor the estimates of $f(x)$ to the woman and improve the accuracy of the ages that are imputed to her children. Equally, by modelling the children's mortality relative to a standard life table at an individual level, one ought to be able to produce more accurate estimates of $L(a)$ for particular subsets of children than one would obtain by using the same life table for all the children in a cohort.

Of course, to model women's fertility and their children's mortality in detail requires a full birth history, which is what we wish to impute. Having initially reconstructed the women's full birth histories using the Own-Children Method, however, one can model fertility in the imputed histories and iteratively reconstruct the birth histories several times using increasingly refined estimates of fertility. In practice, the results stabilise rapidly – iterating five times is ample.

For the analysis presented here, I fitted an Age-Period-Cohort (APC) model to the fertility rates calculated from the reconstructed birth histories using cubic splines but omitted the linear effect of cohort, which is collinear with age and period (Cartensen 2007). I also modelled spatial variation in the rates by province or district, differentials by women's level of schooling (none, primary only, secondary or higher), and the impact of having an above average or below average family size for one's age. As the purpose of the exercise is to measure variation between women in their age pattern of fertility, rather than the level of fertility, the model includes interactions between the main effects of each of these indicators and the linear splines for age and period.

One obstacle to using the Luther-Cho method, or the more elaborate version of it just described, to impute full birth histories to women is that the responses to the summary birth history questions are missing for a non-trivial number of women in many developing country censuses. Often, far more data are missing for young women than for older women. This typically results when enumerators leave the relevant field on the census form blank when the woman is childless, rather than filling it with zeros. While one does not need to impute birth histories to childless women, counting them as accurately as possible matters for the calculation of rates and statistics such as the median age at first birth. Thus, prior to using the Luther-Cho method, it is often advisable to apply El-Badry's (1961) method to the data to estimate how many of the women with missing data are childless and stochastically recode them as such.

The best approach to adopt to the remaining women that lack summary birth history data, but are imputed not to be childless, depends on how many of them there are. If they are few in number, they can be excluded from the analysis without there being any risk that this will bias the results. However, it is unlikely that the summary birth history data are missing completely at random. Instead, the probability that women failed to answer these questions is likely to vary according to factors such as their education and where they live. Thus, when one is applying the Luther-Cho method iteratively, using age patterns of fertility and child mortality that are differentiated according to women's place of residence and socio-economic characteristics, it may also be worth stochastically imputing numbers of children ever-born and dead to women who do not report them that vary with these characteristics, together with the woman's age.[1]

One limitation of the conventional Own-Children Method for estimating fertility relates to estimating the ages of non-own children who live apart from their mothers. Children enumerated in a census in a household or establishment in which their mother does not live comprise both non-own children, whose mothers are living somewhere else, and maternal orphans. The two groups of children have different age distributions, because the prevalence of orphanhood increases rapidly with children's age and estimating the ages of non-own children from those of the two groups combined can distort the resulting estimates of the age pattern of fertility (Timæus 2021). Thus, it is necessary to adjust the census age distribution of children living apart from their mother for orphanhood before using it to impute ages to women's non-own children (Timæus 2021).

Assessment of the method using the 2006 India NFHS

The National Family Health Surveys (NFHS) are large national surveys of India conducted as part of the Demographic and Health Surveys (DHS) programme. Each of them collected full birth histories which included the dates of birth of all of a woman's children, including those that had died or were living apart from their mother. By using the Luther and Cho approach to impute ages to the latter groups of children, making use only of the data on own-children, one can examine the performance of the method.

The analysis uses the 2006 survey, rather than the most recent one, as it collected information on a period when fertility in India was higher than it is today and so should yield results that are more relevant to countries that still at a relatively early stage of fertility transition. The 2006 NFHS obtained information on about 200,000 births born to about 124,000 women aged 15-49, including information on nearly 26,000 dead children and about 31,000 who were not living in the same household as their mother. By 2006 these births ranged between 0 and 36 years in age.

[1] In principle, one could apply multiple imputation (Rubin 1987; Little and Rubin 2019) to all stages of the procedure for constructing the full birth histories and quantify the uncertainty in the estimates that results from the process. In practice, as the census samples are large, the main source of error in the final fertility estimates is likely to be deficiencies in the reporting of ages and children ever-born. The results obtained from analyses of different sets imputed birth histories produced from the same census are invariably close to identical.

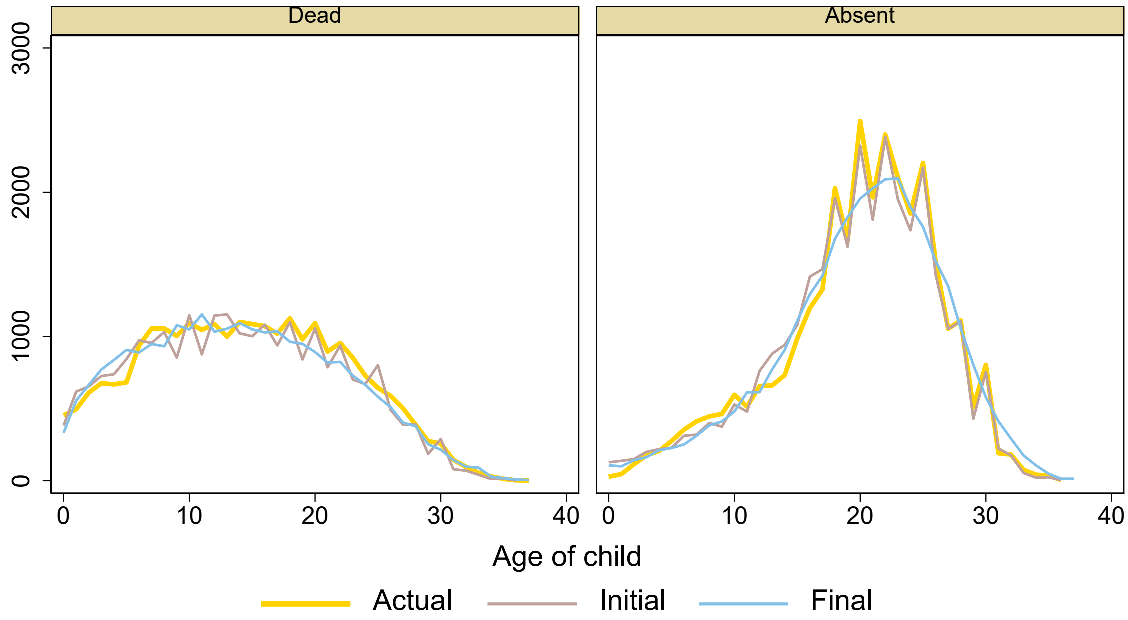

Figure 1: Actual and imputed ages of dead children and those living elsewhere, National Family Health Survey of India, 2006.

Figure 1 compares initial and final imputed age distributions for the dead children and those living elsewhere with the actual ages of these two groups of children as reported by their mothers. The overall agreement at the aggregate level between the imputed ages and reported ones is high. The imputed age distributions smooth out the dents at ages 4 to 5 in the reported age distribution of the dead children and at ages 14 to 17 in the age distribution of non-own children. The overall distribution of the ages imputed to children after five further iterations resembles that produced initially using the Own-Children Method estimates of fertility. However, the variance of the resulting ages of mothers at the birth of their dead and non-own children is larger. In the final estimates, for example, the mean age imputed to women giving birth to children that had either died or were no longer living with them by 2006 is 2.6 years higher on average for women with secondary or higher education than it is for other women.

Figure 2 compares estimates of parity progression and the median length of birth intervals for three successive periods made from the full birth histories reported in the 2006 NFHS with those calculated from the final set of imputed birth histories. The solid lines represent estimates based on reported dates and the broken lines those made using imputed ages for the dead and absent children. The estimates show that the proportion of women who progress to another birth in India fell at all parities between the beginning of the 1990s and mid-2000s, with disproportionate drops in progression from the second to the third birth and third to the fourth birth. One would expect to observe this pattern in a population practicing family size limitation.

As one might expect from the results in Figure 1, the estimates of parity progression based on the reconstructed birth histories are close to those calculated from the reported histories. For the period 2–11 years before the survey, they are almost identical. However, the imputed dataset somewhat overestimates the higher-order progression ratios in the most distant period. This is probably because women aged less than 50 who had already had fifth and higher order births more than 12 years previously are select sub-group of all women who eventually have five or more births. One would probably need to fit several separate APC models of fertility to women of different parities to represent their birth histories adequately. In applications to census samples which include data on the fertility of older women, the model that I adopted is likely to perform better than in this slightly artificial application to DHS data.

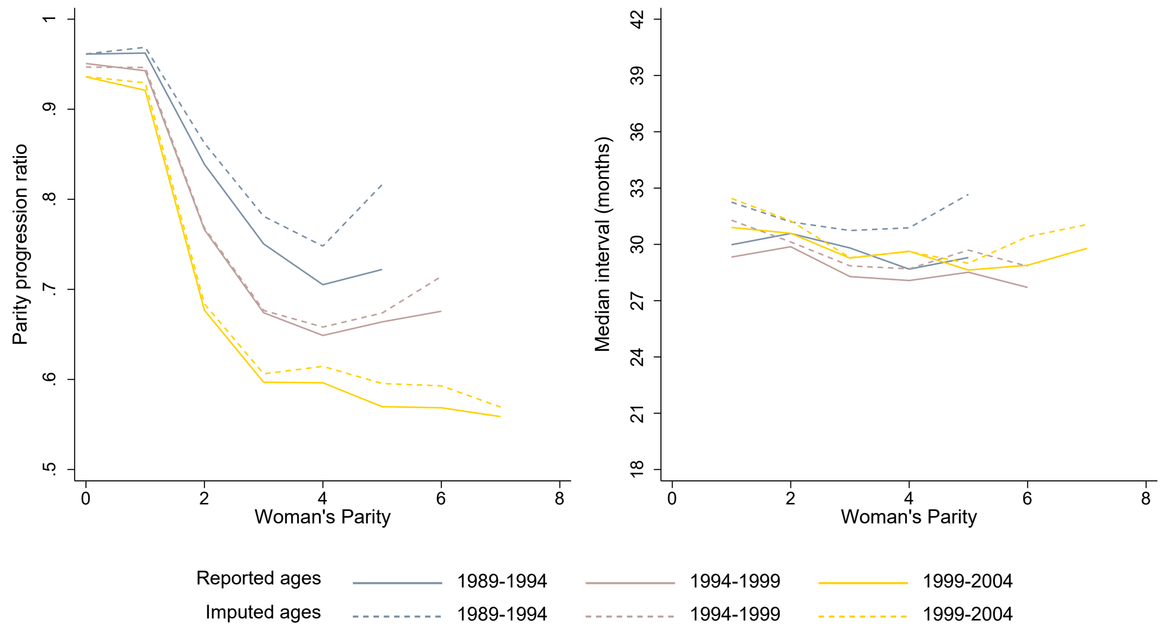

Figure 2: Parity progression and the median length of closed intervals by parity for three five-year periods, India, 2005-6 National Family Health Survey, reported and imputed ages of dead and non-own children

The estimates of the median length of birth intervals based on the reported imputed ages of women's children also agree rather closely. The median length of the intervals is about 30 months. It varies little by birth order and also changed very little over the 15-year period between 1989 and 2004. The median imputed intervals are slightly longer than the reported ones with the greatest upward bias again being for the most distant period. Unfortunately, however, they diverge increasingly from the estimates based on women's reports in successive iterations, rather than converging on them. Having said this, it is only fifth and higher order birth intervals in the most distant set of estimates that the discrepancies between the series exceed one or two months and once again the APC model of fertility may perform better on census samples that include data on older women.

Estimates for Eastern and Southern Africa

Table 1 provides basic information on the number of women and births reported in the 10 per cent sample census microdata for Botswana, Rwanda, Tanzania and Zambia that has been deposited with IPUMS-International (Minnesota Population Center 2019). Samples are available from three censuses in Botswana and from two censuses in the other three countries. The censuses were all conducted at intervals of ten years, and I discarded the data on infants and one-year old children as they appear to have been severely under-enumerated in most of the censuses. Thus, estimates for a period of more than 12 years before one of the later censuses refer to the same period as more recent estimates from the earlier census. To assess the performance of the method, I present estimates for the four five-year periods falling 2-21 years before each census or even for a 25-year interval. However, estimates for 17 or more years before a census are probably less accurate than more recent ones because the proportion of children who have left the parental home on marriage or for other reasons rises rapidly with age.

Table 1: Basic details of the IPUMS-International 10 per cent sample census microdata files

Country	Year	Women (15–79)	Own-children	Dead children	Absent children
Botswana	1991	38,919	86,784	14,665	56,596
	2001	54,607	111,141	16,545	68,651
	2011	68,792	133,961	17,269	77,195
Rwanda	2002	250,290	646,373	219,348	184,244
	2012	319,787	837,935	178,465	242,509
Tanzania	2002	1,089,573	2,654,317	718,778	1,542,961
	2012	1,299,036	3,195,754	626,988	1,858,693
Zambia	2000	271,942	660,400	167,907	254,446
	2010	367,280	975,881	186,420	293,821

Figure 3 presents 25-year long series of estimates of total fertility computed from the different censuses in each country, together with estimates of the same measure for three-year periods prior to each of the DHS conducted in the countries taken from StatCompiler (ICF 2012). During periods when the estimates from the different censuses overlap, they are highly consistent. Moreover, the census-based estimates agree closely with those from the DHS.

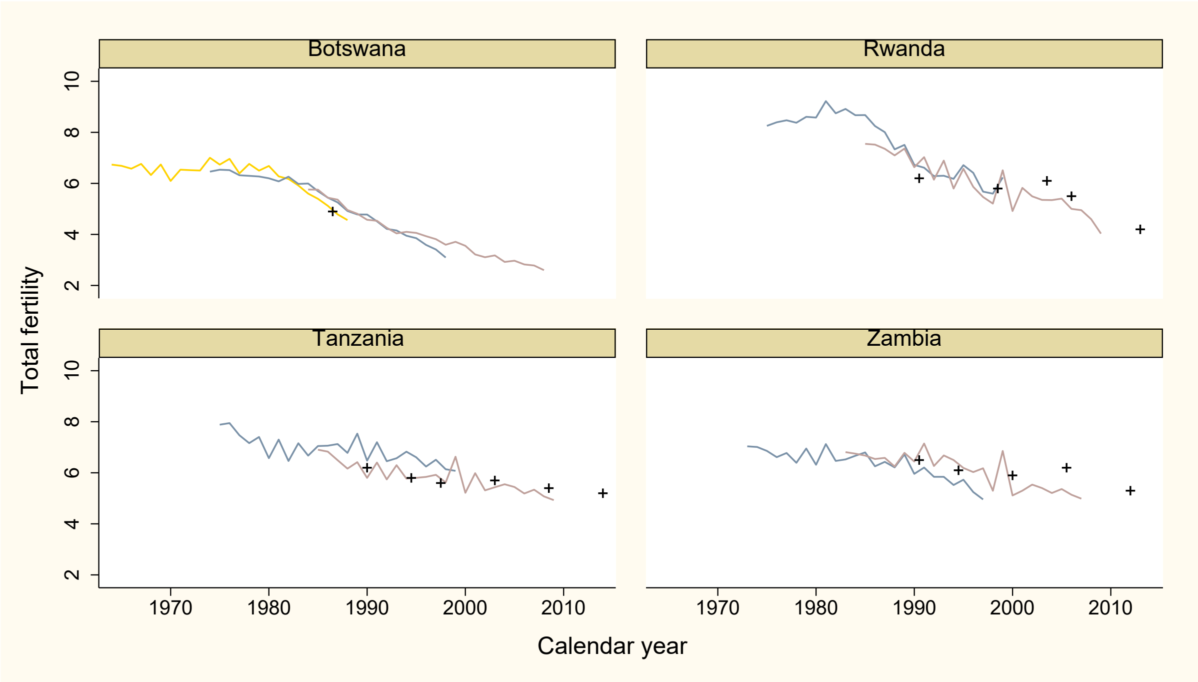

Figure 3: Trend in total fertility according to successive censuses in four Eastern and Southern African countries and to Demographic and Health Surveys (indicated by plus signs)

The early onset of fertility transition in Botswana at the beginning of the 1980s is evident. Total fertility declined steadily and, according to these estimates, dropped to about 2.7 by the end of the first decade of this century. Thus, fertility in Botswana may be as low as, or lower than, in South Africa. Rwanda had very high pre-transitional fertility till the mid-1980s but is also the country in which fertility has dropped fastest. According to the 2002 census, fertility dropped below the long-term trend during the civil war in the early 1990s before rebounding. However, considering the cataclysmic events of the time, the trough in fertility is quite shallow.[2] According to the census-based estimates, the onset of fertility decline dates to about 1990 in Tanzania and Zambia and the decline has proceeded rather slowly.

[2] Note that fertility estimates made from retrospective reports only reflect the experience of women who survived.

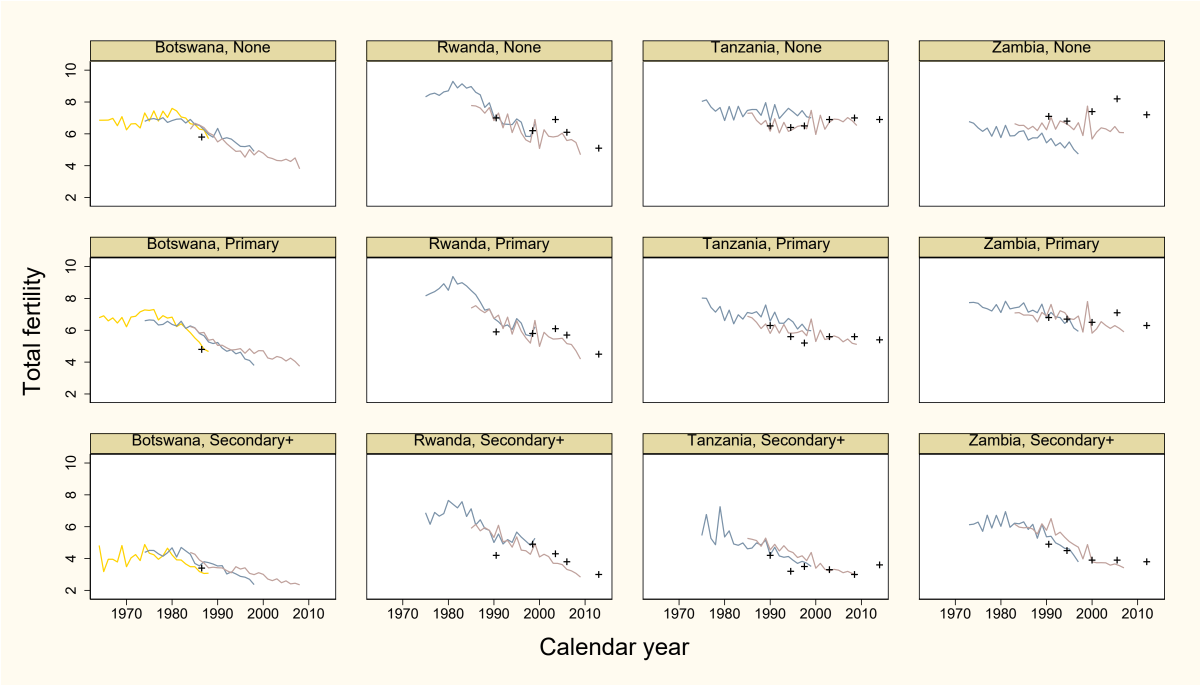

Figure 4: Trend in total fertility according to successive censuses in four Eastern and Southern African countries and to Demographic and Health surveys (indicated by plus signs)

Figure 4 depicts similar estimates of total fertility in the four countries to those in Figure 3 disaggregating them according to the level of schooling of the women. Even after splitting up the women by their educational background, the estimates from different censuses remain highly consistent with each other and estimates from the DHS. Only among the minority of women in Zambia who never attended school is the trend in fertility somewhat unclear.

It is evident that women with secondary schooling already had lower fertility than other women at the onset of fertility transition and one factor in the national declines in fertility has been growth in the proportion of young women with secondary schooling. Figure 4 also reveals numerous noteworthy differences between the countries. For example, fertility is less differentiated according to women's education in Rwanda than elsewhere. Fertility decline began at about the same time in all three educational groups in Botswana and Rwanda but had not yet begun in 2010 among uneducated women in Tanzania and Zambia. Also, whereas the fertility of the small group of women with secondary education began to fall in Tanzania at about the same time as in Botswana and Rwanda, fertility decline among this group only began in Zambia a decade later.

Figure 5 maps regional differentials in total fertility in Tanzania in about 2007. StatCompiler can produce an equivalent map, but it is worth recalling that the regional estimates provided by the DHS are based on samples for each region of just a few hundred women, and sometimes just a few score of them. Certainly, their map looks rather different from this one. These estimates reveal a clear regional divide within Tanzania: at this time total fertility remained above 6.25 in the whole of the north-western half of the country, which includes the densely-populated regions around Lake Victoria but had dropped to at least a child less than this in the whole of the rest of the country excepting Pemba. According to these estimates, total fertility in Dar es Salaam had dropped to about 3 children per woman in 2007, while in Kilimanjaro, on the border with Kenya, and Mtwara, in the south of the country, it was about 4 children per woman.

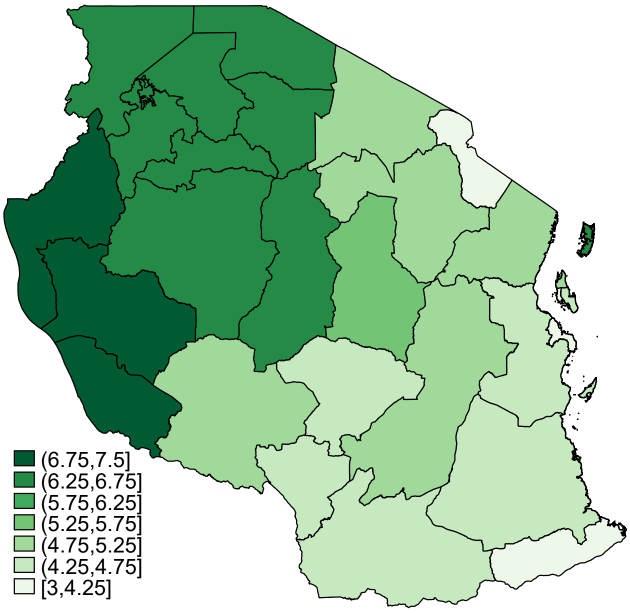

Figure 5: Total fertility in the regions of Tanzania, 2007

Figure 6 presents parity progression ratios and the median duration of closed birth intervals by parity according to the three census samples from Botswana. Estimates for the same five-year period from two different censuses are coloured identically. All the pairs of sets of overlapping estimates of both parity progression and the median length of the intervals agree fairly closely.

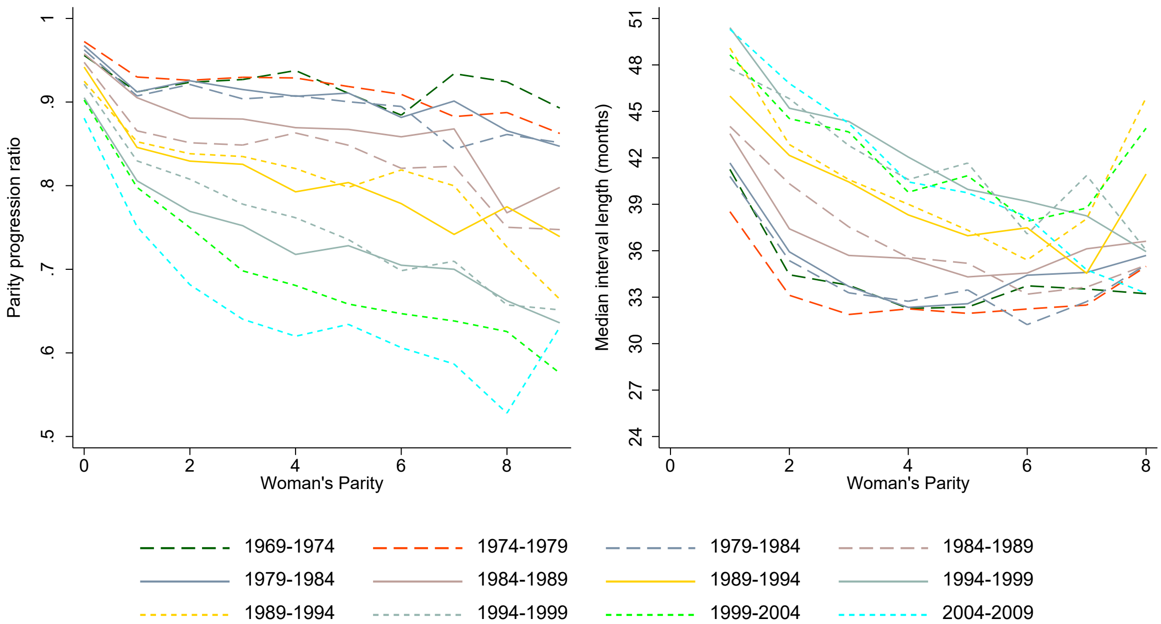

Figure 6: Parity progression and the median duration of closed birth intervals by parity according to three successive censuses, Botswana

There has been a big drop in parity progression as one might expect given the low level of total fertility in 2004–9. However, while Figure 2 revealed that birth intervals hardly changed at all over time in India, in Botswana their median duration lengthened substantially between 1985 and the late–1990s, particularly at the lower parities, before stabilising again this century. There are also intriguing differences between the changes in parity progression in Botswana and India. Notably, the proportion of women remaining childless or having only one child has increased somewhat in Botswana, whereas almost all women in India still have at least two children.

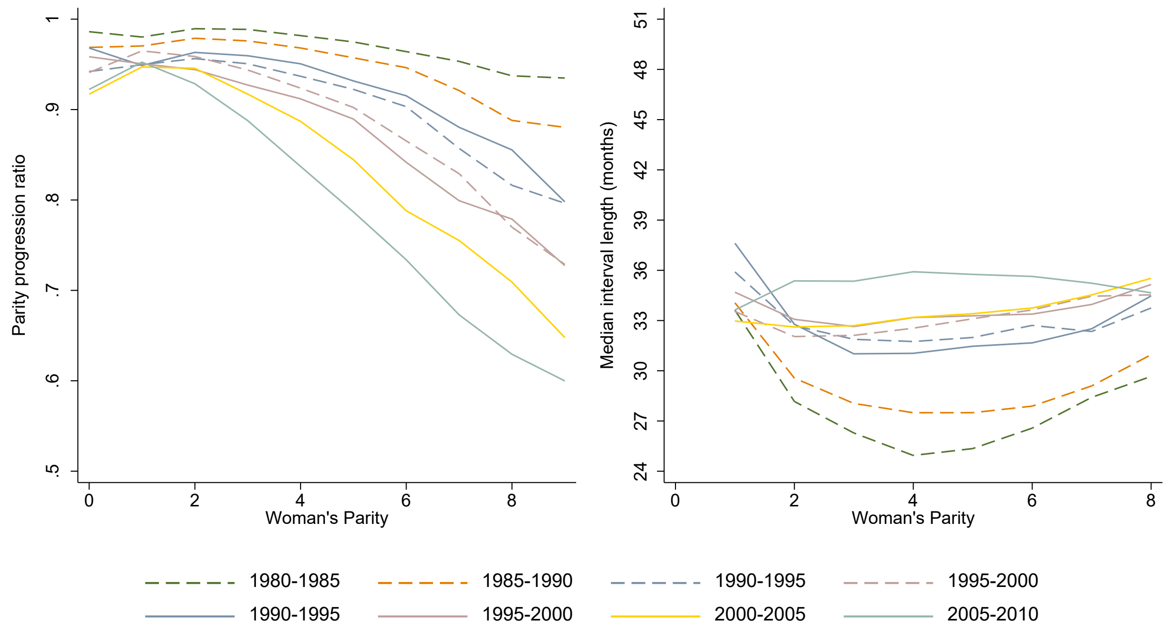

Figure 7: Parity progression and the median duration of closed birth intervals by parity according to two successive censuses, Rwanda

Figure 7 refers to Rwanda, where only two census samples are available. They again yield rather consistent series of estimates. The country has also seen a large drop in parity progression over time. It differs from Botswana, however, in that no evidence exists that women are limiting their families to just a few children, although childlessness has become more common over time. Instead, the more children a woman has had, the more likely she is to stop childbearing. Birth intervals were very short in Rwanda before the transition began, explaining why fertility was exceptionally high. They lengthened rapidly between the mid-1980s and late-1990s before stabilizing again for another decade. Even in 2007, the median length of birth intervals in Rwanda was only slightly longer than it had been in Botswana 25 years earlier.

Figure 8 examines parity progression and the median length of closed intervals in Zambia according to women's level of schooling. Problems clearly exist with the reporting of childlessness by uneducated women in Zambia. In other respects, the pattern of family building among this group has not changed at all. Only the fertility of women with secondary schooling has only dropped significantly. Moreover, for this group, the drop in parity progression was concentrated in the 1990s and stalled at the beginning of this century. Note that, as in the national data for Rwanda, the progression ratios for women with secondary schooling fanned out over time, with the drop in progression being larger the higher the parity of the women.

Lastly, Figure 9 examines parity progression in Tanzania by region. There have been large drops in parity progression in Dar es Salaam, Kilimanjaro and Mtwara, and somewhat smaller ones in other parts of southern and eastern Tanzania. Parity progression in large parts of north-western Tanzania has hardly changed at all. The ratios also show no evidence of any change in Pemba. Everywhere that parity progression has dropped, the size of the fall increases with parity, leading to a fan-like pattern of ratios.

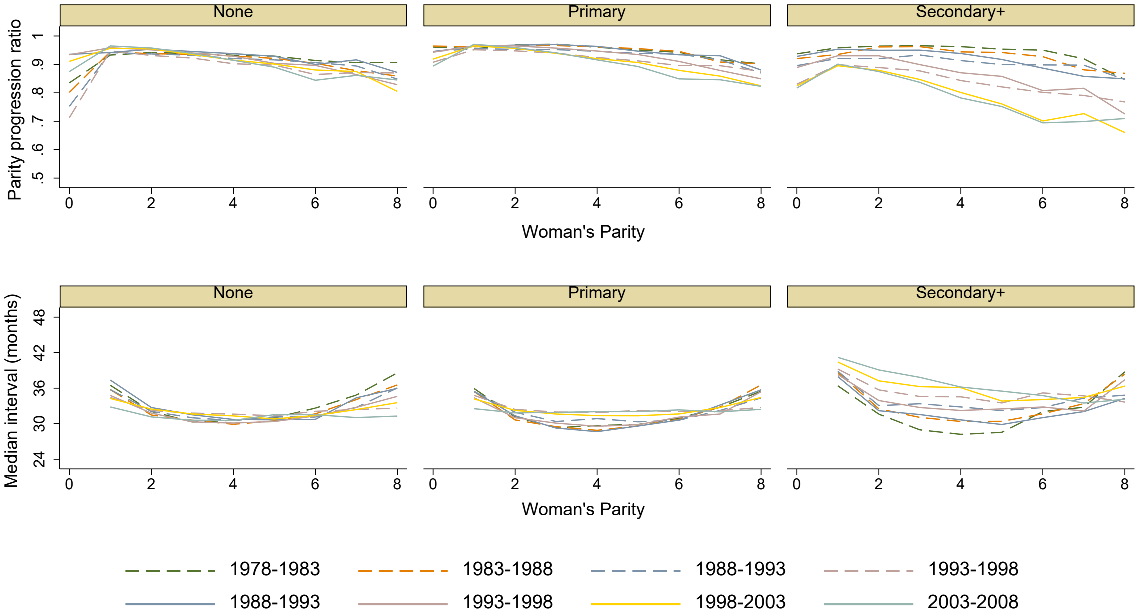

Figure 8: Parity progression and the median duration of closed birth intervals by parity and women's level of schooling according to two successive censuses, Zambia

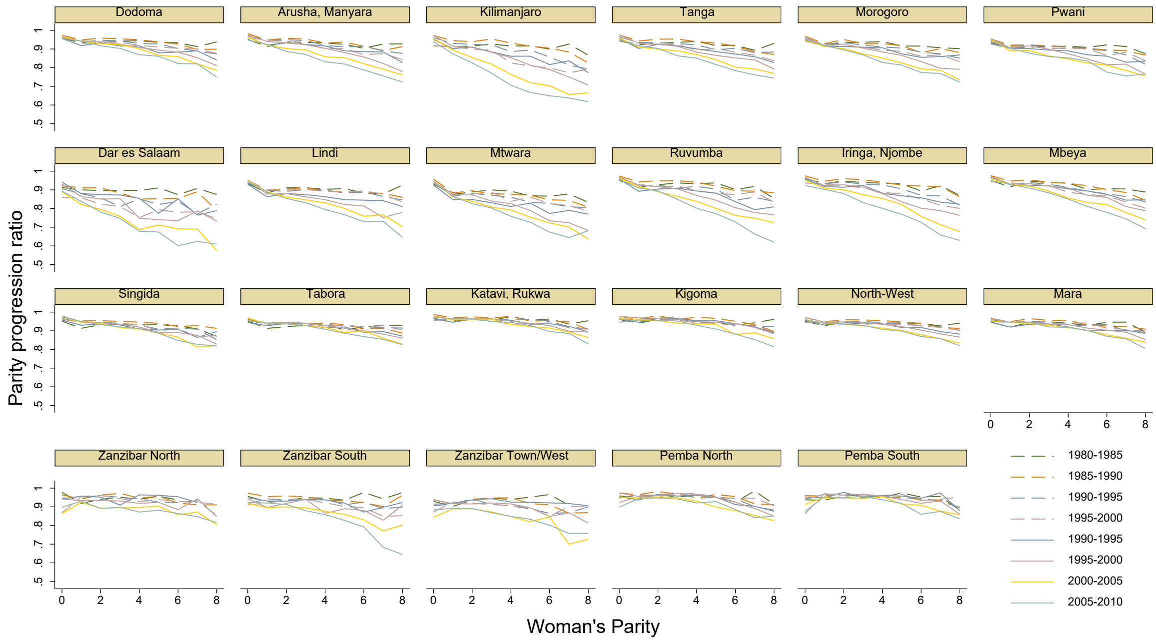

Figure 9: Parity progression by parity and region according to two successive censuses, Tanzania

Discussion

Sample census data microdata represent an important resource for the study of fertility transition in sub-Saharan Africa. Both the validation study using Indian data and the high degree of consistency between fertility estimates made from successive censuses of the same country suggest that the iterative version of Luther and Cho's method for reconstructing full birth histories from such data that is proposed here performed well in these applications.

The census microdata provide information on the fertility of far larger samples of women than are available from DHS surveys. For example, the datasets available for Tanzania comprise about 1.2 million women aged 12-65 in 2002 and about 1.4 million such women in 2012. There are 277,000 and 343,000 such women in the sample microdata from the Rwandan censuses in the same two years and 298,000 and 4005,000 such women in the 2000 and 2010 sample census microdata for Zambia. These datasets offer the potential to analyse fertility patterns in detail, both for relatively small geographical units within a country and for relatively small groups of women, including those who may be pioneering the transition to low fertility.

Imputing full birth histories to women using sample census microdata should make it possible to use these data to move beyond the estimation of levels and trends in age-specific and total fertility in sub-Saharan Africa and permit the investigation of birth interval dynamics. Detailed information on women's family building patterns of this type are of vital importance to gaining insights into the factors that are shaping the fertility transition in sub-Saharan Africa and into the specificities of the need for reproductive services among different groups of women within a country (Timæus and Moultrie 2008; Moultrie *et al.* 2012; Timæus and Moultrie 2020).

The initial results for Botswana, Rwanda, Tanzania and Zambia presented in this paper have already revealed new insights into the pathways toward low fertility being pursued by these countries. Fertility transition in sub-Saharan Africa is following diverse paths. Fertility transition in Botswana has been characterised by family size limitation, but also by lengthy postponement of births. In contrast, while Rwanda has experienced rapid fertility decline since the 1980s, this is because women are curtailing childbearing rather than beginning to limit their families to just 2 or 3 children. Thus, women's propensity to stop childbearing increases with their family size. A similar pattern of change is found in Tanzania and Zambia, although fertility decline began later and has proceeded more slowly in both countries than in Botswana and Rwanda. Birth intervals have lengthened in all four countries

The results presented here have also started to reveal new insights into differentials within the countries in patterns of fertility decline. A clear split exists in Tanzania between the northern and western half of the country, where fertility has declined only slightly, and the less densely populated southern and eastern regions, which have experienced a more rapid decline in fertility and where total fertility is at least a child lower. In Zambia, however, education seems to be more salient than place: even as late as 2010, fertility had only just begun to drop among women with primary education and the overall decline was driven by women with secondary schooling.

Nobody would dispute the long-term importance of improving the civil registration of birth and deaths in sub-Saharan Africa. Quite apart from providing the basis of a demographic information system that can be used to monitor progress in relation to the Strategic Development Goals and other policy objectives, legal certification of vital events is crucial to sound administration and maintenance of the rule of law. National censuses, however, and the samples of microdata drawn from them, are vitally important sources of statistical information that have already been collected and are available for analysis. Moreover, they can be used to examine past trends in vital rates that will never be captured by future data collection initiatives. For example, although the sample sizes involved are too small to engage in highly disaggregated fertility analysis, the sample microdata from the 1991, 2001 and 2011 censuses of Botswana can be used to study fertility in the country over a 40-year period commencing well before its fertility transition began (Rutenberg and Diamond 1993; Diamond and Rutenberg 1995).

The evidence available suggests that the vision that led national statistical organisations and IPUMS-International to make sample census microdata widely available to interested analysts, combined with the widespread availability today of the computing power needed to process them, mean that the Luther and Cho (1988) method for reconstructing full birth histories from censuses that only asked summary questions about fertility deserves to be rescued from obscurity. Although the programming involved in the imputation of the missing ages of children is fairly complex, as a companion to this paper *Stata* code will be distributed on *GitHub* that can be used to produce imputed files from any standard IPUMS-I census dataset using their standard variable names. The potential exists to reconstruct full birth histories for the women in any census that collected summary birth histories. Analysts can take into account heterogeneity between women on whatever variables they wish and use the full birth histories to conduct whatever further analyses interest them.

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