The outlook for maternal orphanhood in the context of the HIV/AIDS epidemic

Evidence from formal demographic analysis

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Abstract

The HIV/AIDS epidemic has led to an unprecedented orphanhood crisis in sub-Saharan Africa. This article formally discusses the relationships between the demographic change induced by a generalized HIV/AIDS epidemic, and age-specific probabilities of maternal orphanhood. Classic results from the stable theory of kinship are extended to model situations in which demographic rates change over time, and to account for heterogeneity in the population. A methodology to estimate and project orphanhood probabilities from schedules of demographic rates is offered. The methods are applied to data provided by the United Nations World Population Prospects, to obtain estimates for all countries. The results from the projections indicate that the prevalence of maternal orphanhood is decreasing in most countries. The number of orphans, however, may continue to increase for several decades in some countries affected by the HIV/AIDS epidemic, in particular in those countries where fertility will remain high. As the adult HIV prevalence rate decreases, the intensity of the of orphanhood crisis shifts from young children to adolescents.

INTRODUCTION

The HIV/AIDS epidemic has led to an unprecedented orphanhood crisis in sub-Saharan Africa. There has been some progress in the containment of the epidemic worldwide. However, orphanhood remains one of the most challenging problems for societies affected by generalized HIV/AIDS epidemics. In this article, I use formal demographic analysis to evaluate the extent of the orphanhood crisis and to generate projections of number and prevalence of maternal orphans for the future.

The first part of the article provides the theoretical framework. I discuss classic results from the theory of stable populations and extend the formal analysis of maternal orphanhood in two main directions. First, I consider the situation of demographic rates changing over time. Second, I analyze the effect of heterogeneity, and correlations of risks of mortality between mothers and children, on prevalence of maternal orphanhood.

In the second part of the article, I apply the methods discussed in the theoretical section to generate projections of the number and fractions of orphans for countries with a generalized HIV/AIDS epidemic. The combination of formal methods with the largest collection of demographic rates across countries (the United Nations World Population Prospects 2010) gives us an extremely powerful tool to evaluate the prospects for maternal orphanhood in a large number of countries and under different scenarios.

This article focuses on demographic analysis that relies on aggregate rates. It shows how macro-level formal analysis is useful to improve our understanding of key demographic processes. The article complements case-studies that focus on a specific country and provide a lot of detailed information for a specific geographic region or social context (e.g., microsimulation). Here the goal is to use comparative data for a large number of countries to obtain insights on current and future trends in maternal orphanhood in areas affected by the HIV/AIDS epidemic.

THE THEORETICAL FRAMEWORK

The formal demography of maternal orphanhood has a long history and it is the result of the finest demographic modeling. Keyfitz and Caswell (2005) discussed the stable theory of kinship with reference to the work of Lotka (1931), Burch (1970), Coale (1965), Le Bras (1973), and Goodman, Keyfitz and Pullum (1974). An important result from the formal demography of kinship is the analytic representation of the probability that a girl aged a

has a living mother $M_1(a)$, under a given regime of mortality and fertility (see Keyfitz and Caswell (2005)):

$$M_1(a) = \int_{\alpha}^{\beta} \frac{l_{x+a}}{l_x} e^{-rx} l_x f_x dx \qquad (1)$$

where l_x is the probability of survival to age x, f_x is the fertility rate at age x (intended as daughters-only), and r is the Lotka's intrinsic growth rate for the stable population.

The impact of the epidemic on limiting probabilities of maternal orphanhood

Equation 1 can be used to evaluate the probabilities of maternal orphanhood that result from the persistence of given schedules of mortality and fertility rates. For specific countries, we can compute the limiting stable probability of maternal orphanhood at age a $(1 - M_1(a))$ that we would observe if the regime of mortality and fertility of a given year would not change in the future.

Figure 1 shows estimates and projections of limiting maternal orphanhood probabilities for Zimbabwe. The estimates for each year in time are generated assuming that the age-specific mortality and fertility rates for the year considered will persist unchanged in the future. The figure shows the considerable impact of the HIV/AIDS epidemic on the probability of maternal orphanhood. For instance, the estimated probability of maternal orphanhood at age 10 is 0.04 in 1990. With the rapid increase in the number of AIDS-related deaths, this probability rapidly grows to 0.12 in 1995, 0.29 in 2000, up to 0.34 in 2004, before slowly decreasing, in accordance with the projected demographic rates. The same pattern characterizes the probability of maternal orphanhood at other ages.

HIV/AIDS epidemics have a strong impact on maternal orphanhood, through their effects on mortality. Figure 2 shows estimated probabilities of maternal orphanhood at age 5, 10 and 15, respectively, associated to values of life expectancy between 40 and 65. Higher levels of life expectancy are associated to lower orphanhood probabilities. It is interesting to note that the slope of the lines is higher when evaluated at lower levels of life expectancy. This means that an improvement in life expectancy of one year, from a starting level of 40 years, generates a larger reduction in probabilities of orphanhood than an analogous improvement from a starting level of 60 years of life expectancy.

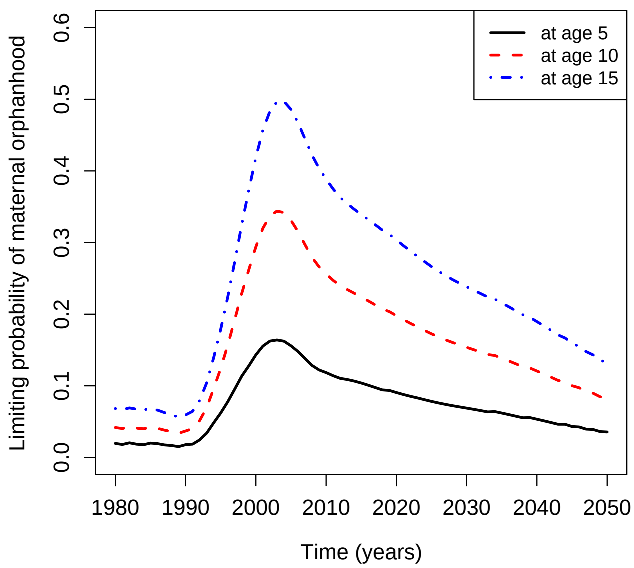

Figure 1: Estimates and projections of limiting stable probabilities of maternal orphanhood implied by mortality and fertility rates for selected years and ages in Zimbabwe. Data source: own elaborations on UN World Population Prospects, 2006 Revision.

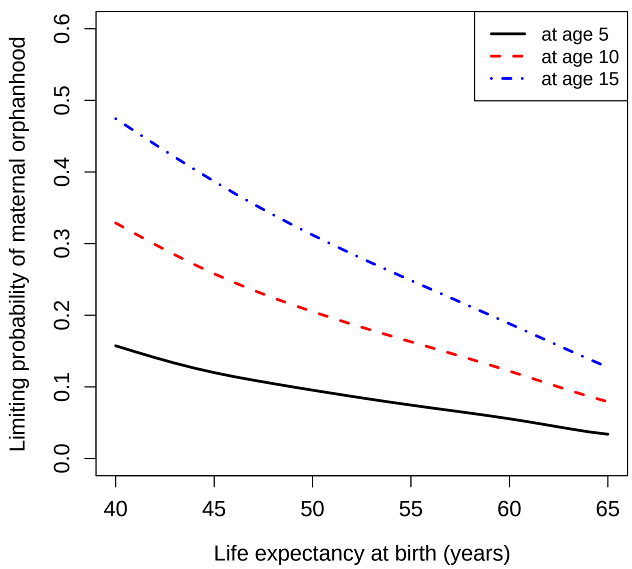

Figure 2: Estimates of limiting stable probabilities of maternal orphanhood associated to different levels of AIDS-related life expectancy at birth in Zimbabwe. Data source: own elaborations on UN World Population Prospects, 2006 Revision.

Probabilities of maternal orphanhood when vital rates change over time

Keyfitz and Caswell (2005) show that the problem of evaluating the probability of orphanhood at a given age may be approached using a renewal equation. In particular, the number of living mothers for girls aged a at time t is given by:

$$\int_{\alpha}^{\beta} B(t-a-x) l_x f_x f_{fab} \frac{l_{x+a}}{l_x} l_a dx \tag{2}$$

where $B(t-a-x)$ stands for female births at time $t-a-x$. For the same birth function, the number of daughters, or, in other words, girls born a years ago and surviving to the reference time t is:

$$B(t-a) l_a \tag{3}$$

Starting from the ratio of expression 2 to expression 3, that is the average number of mothers per daughter at time t, and assuming that mortality and fertility rates are constant over time, Goodman, Keyfitz and Pullum (1974) obtain an analytical expression for $M_1(a)$ (see equation 1).

If we consider demographic rates that change over time, and we have estimates and projections of these rates for a rather long period of time, we can build on the same type of renewal equation described in 2 and 3 to obtain an expression for probabilities of orphanhood when rates change over time. We can use different sets of fertility and survivorship schedules to account for the fact that mothers and daughters at different periods of time experience different fertility and mortality conditions. For instance, the number of living mothers to girls aged a at time t becomes:

$$\int_{\alpha}^{\beta} B(t-a-x) l_x(t-a-x) f_x(t-a-x) f_{fab} \frac{l_{x+a}(t-a-x)}{l_x(t-a-x)} l_a(t-a) dx \tag{4}$$

The elements between parentheses in expression 4 are to be intended as the year of birth of the cohort members to which the rates apply.

The approach described in the previous paragraph is appealing, but its practical application is limited due to data requirements. The approach is dependent on the availability of cohort data, which require time series of demographic rates that extend far in the past and future. For instance, we need to know the number of births of prospective mothers in the past, their survival probabilities and fertility schedules, and the survival probabilities of recently born children up to the age of interest. It is therefore desirable to express probabilities of maternal orphanhood over time in a more compact way, that has lower data requirements.

The United Nations World Population Prospects provide data on number of births by age of mothers, in addition to rectangular arrays of fertility and mortality rates, from where data along the cohort dimension can be extracted. The probability that, at time t, a child of age a randomly selected from the population has a living mother is the probability that the mother survives a years past giving birth, weighted by the probability of the age at childbearing for the woman:

$$M_1(a,t) = \int_{x=12}^{49} \frac{l_{x+a}(t-x-a)}{l_x(t-x-a)} \times P(A_b = x, t-a) \tag{5}$$

where $P(A_b = x, t-a)$ is the probability that, at time t, the age at giving birth for a woman is x. The quantity $P(A_b = x, t-a)$ is the fraction of total births at time $(t-a)$ to women of age x at time $(t-a)$. Equation 5 is presented in continuos form. However, in practical applications it is evaluated in discrete terms.

It is interesting to observe the close resemblance between $M_1(a,t)$ and a classic approximation for $M_1(a)$. Keyfitz and Caswell (2005) show that, in a stable population, $M_1(a)$ can be roughly approximated using a Taylor expansion of l_{x+a}/l_x around κ, the mean age at childbearing:

$$M_1(a) \approx \frac{l_{\kappa+a}}{l_\kappa} \tag{6}$$

Expression 5 gives the probability that a child standing in front of us has a living mother. It is a weighted average of the probabilities of surviving a years past childbearing, where the weights are the probabilities of giving birth at a specific age. The approximation in equation 6 can be thought of as a specific case of the more general equation 5, when births are concentrated around the mean age at childbearing and when the age structure of mothers does not change over time.

Figure 3 shows estimates and projections of maternal orphanhood probabilities over time for a randomly selected child of age 5, 10 and 15, in Zimbabwe. It is interesting to note how the creation of orphans is a process with a lag, with respect to the generation of HIV cases. In the previous section, we observed the probabilities of orphanhood implied by the persistence of specific conditions over time. We saw that the highest probabilities of orphanhood are implied by the persistence of the conditions at the peak of the HIV epidemic. Here we see how the consequences of a peak in the HIV

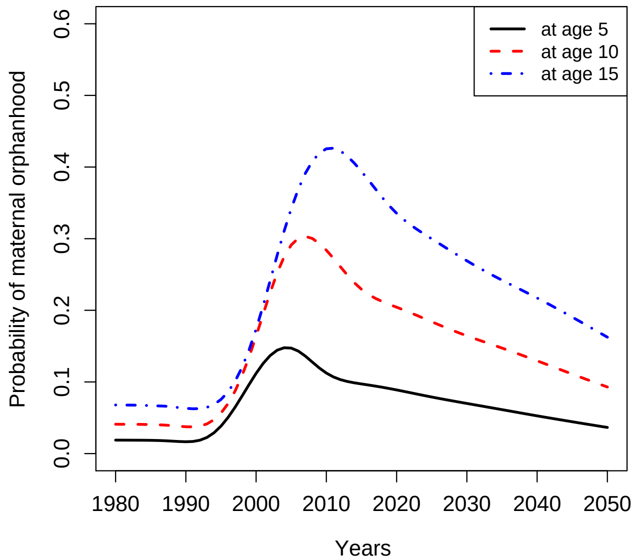

Figure 3: Estimates and Projections of maternal orphanhood probabilities for children, given that they are alive, at age 5, 10 and 15 in Zimbabwe (1980-2050). Data source: own elaborations on UN World Population Prospects, 2006 Revision.

epidemic on generation of orphans persist for a rather long period of time past the reduction in HIV prevalence. After reaching its peak, the probability of being orphan at age 5 decreases more quickly than the probability of being orphan at age 15. With the reduction in AIDS-related deaths, the most recently born cohorts of children are less likely to become orphaned. For the older children, the probability of being orphan is more related to the conditions in the past, as the probability of being orphan at a specific age is the cumulative result of the probabilities of being orphan at previous ages. These results indicate that with the containment of the epidemic, the scale of the orphanhood problem may become smaller for young children, but may continue to be a pressing problem for teenagers.

The effect of heterogeneity and selection

Stable population theory and the formal demography of kinship are built on the implicit assumption that the population is composed of homogeneous individuals. The same set of rates apply to everyone who is in a specific age group. In the context of an HIV/AIDS epidemic, the assumption of homogeneity is strongly challenged. In this section, I deal with the issue of incorporating heterogeneity in mathematical models that rely on aggregate demographic quantities. I show that ignoring heterogeneity leads to underestimation of the probability of having a living mother.

A typical strategy to model heterogeneity is based on the idea that each person may be subject to an individual-specific hazard rate. Some people may be weaker than others and experience higher probability of death throughout their entire lives. Some people may be stronger and experience probabilities of death consistently lower than the average. The hazard rate observed at the population level is an average of all individual-specific rates. In the context of an HIV/AIDS epidemic, we may expect that some people are more at risk of dying than others because they may be at higher risk of becoming infected with HIV, they may live in unhealthy environments, the may be poorer, etc.. The risk of mortality for their children is likely to be higher too: the children share the same environment of the parents, they may have higher probabilities of becoming infected with HIV (e.g., through perinatal transmission) or they may be more vulnerable because they are likely to be orphans or to spend a portion of their childhood with little resources and a sick parent.

In order to introduce heterogeneity in models of kinship demography, I allow for hazard rates to be different across individuals, according to proportionality factors that are individual-specific. These scaling factors have become popular under the name of 'frailties', after Vaupel, Manton and Stallard (1979) formalized some ideas on using frailties for survival analysis, to get insights on the dynamics of mortality and aging populations. Some developments of the pioneering approach allow for correlated frailties (e.g., Yashin, Vaupel and Iachine 1995): the idea is that there may be correlations between individuals in the factors that multiply hazard rates. To model heterogeneity and selection I use correlated frailties.

Keyfitz and Caswell (2005, section 15.1.1) show that the probability of having a living mother at age a, $M_1(a)$, in a stable population, can be obtained using the 'counting method'. The expression for $M_1(a)$ in equation 1 is derived from the ratio of surviving mothers of surviving daughters, to surviving daughters, at time t. The quantity on the numerator, the number of surviving mothers of surviving daughter at time t, is:

$$Numerator = \int_{\alpha}^{\beta} B(t-a-x) f_x l_{x+a} l_a dx \tag{7}$$

The quantity on the denominator, the number of surviving daughters at time t, is:

$$Denominator = B(t-a) l_a \tag{8}$$

It is important to note that, in the numerator, the survivorship of mothers a years past giving birth (l_{x+a}) is independent of the survivorship of daughters (l_a). The correlations between survivorship of mothers and daughters can be modeled using frailties. Assume that the hazard rate for each child and each mother in the population are proportional to the average hazard rate that we observe at the population level, for the respective groups, and that the coefficients of proportionality are positive random variables, z_c and z_m for children and mothers respectively. The expected value of the frailties z_c and z_m, for each cohort of newborns has to be equal to 1, so that the average hazard rates for the overall population are consistent with the aggregate ones, as in the standard case in Vaupel, Manton and Stallard (1979). We also expect the frailties z_c and z_m to be positively correlated: higher mortality risk for mothers is likely to be associated with higher mortality risk for their children.

The product of mother and child survivorship can be expressed in terms of hazard rates: $l_{x+a} l_a = e^{-{}_{x+a}H_0 - {}_aH_0}$, where ${}_xH_0$ is the cumulative hazard rate of death from age 0 to age x. In presence of heterogeneity, we have that $l_{x+a} l_a = e^{-(z_m)_{x+a}H_0 - (z_c)_aH_0}$. To obtain the expected value of the joint survivorship, we use a Taylor expansion around zero for the exponential function in the two variables z_m and z_c. Since the expected value for the two frailties is equal to 1, we have:

$$\begin{aligned} E[e^{-(z_m)_{x+a}H_0 - (z_c)_aH_0}] &\approx 1 - {}_{x+a}H_0 - {}_aH_0 + \\ &+ \frac{1}{2}({}_{x+a}H_0)^2[\mathbf{Var(z_m)} + 1] + \frac{1}{2}({}_aH_0)^2[\mathbf{Var(z_c)} + 1] + \\ &+ ({}_{x+a}H_0 \times {}_aH_0)\mathbf{Cov(z_m, z_c)} \end{aligned} \tag{9}$$

We observe that the expected value of $e^{-(z_m)_{x+a}H_0 - (z_c)_aH_0}$ is positively related to the variances of the frailty terms and to their covariance. In other words, the larger the heterogeneity in the population and the larger the covariance between the frailty of the mother and the one of her children, the higher the proportion of births that survive to age a with a living mother. If the variances and covariances of frailties were zero, then the Taylor expansion in equation 9 would reduce to the Taylor expansion for the situation with independent risk of mortality. Positive values of variances and covariances inflate the probability of joint survivorship of mothers and daughters, therefore increasing the value of the numerator (equation 7) used in the counting method to evaluate $M_1(a)$. The result is a larger value for $M_1(a)$ compared to the one obtained under the assumption of homogeneous population. When high risks of mortality are clustered in subgroups of the population, that is when there are positive correlations between mothers and children, then it is more likely to observe that either both the mother and the child survive or they both die within a years from the birth of the child. The probability of maternal orphanhood (the child survives, but not the mother) is reduced in the context of a heterogeneous population with positively correlated frailties, compared to a homogeneous population.

The size of the effect is noticeable, but not extremely large. The magnitude of the effect depends on the life table considered and relative values of variances and covariances of frailties, for which we do not have empirical measurements. However, some tests using the Zimbabwean life table show that the effect of heterogeneity may be up to a few percentage points. In other words, when we consider the joint survivorship of mothers and children, the difference between extremes cases (correlations near 0, or correlations near 1) is about 5%.

PROJECTION OF THE NUMBER AND PREVALENCE OF MATERNAL ORPHANS

In the first part of this article I addressed the problem of estimating the probabilities that a child of a particular age has lost his or her mother. It is also important to quantify the scale of the orphanhood crisis and to provide estimates and projections of absolute numbers of orphans. In this section, I develop on the ideas that I discussed earlier in the context of stable population theory. The United Nations World Population Prospects 2010 provide demographic rates for virtually all countries in the world in a standardized format. I propose a method to use these data to estimate and project the number of maternal orphans over time, and I show some projections under different scenarios.

The United Nations World Population Prospects provide estimates and projections for a number of demographic quantities, including population counts by age and sex, age-specific fertility and mortality rates, and number of births to mothers of age x at time t ($B_x(t)$). The data are available for each country and under different scenarios, called variants. For instance, for countries with a generalized HIV/AIDS epidemic, both a medium scenario and a scenario under the assumption of No-AIDS mortality are provided.

Orphans of age a at time t are children who were born a years before time t, who survived a years and whose mothers have not survived a years past giving birth to them. The number of maternal orphans of age a at time t (MO_a^t) can be expressed as a weighted average of the number of births a years before time t, where the weights are the survival probabilities of children and their mothers:

$$MO_a^t = (1 - {}_aq_0(t-a)) \sum_{x=15}^{49} B_x(t-a) \times {}_aq_x(t-x-a) \qquad (10)$$

The indexes between parentheses refer to the year of birth of the members of the cohort to which the demographic quantities apply. The idea behind this estimation procedure is to follow the same group of people over time and age in order to have demographic rates that give a longitudinal (or cohort) representation of life histories.

It is often relevant to know the overall number of maternal orphans for a particular age group, in a specific year. For instance, UNICEF and other international organizations report recent estimates of orphans in the age group 0-17 years. This quantity, MO_{0-17}^t, can be easily computed as:

$$MO_{0-17}^t = \sum_{a=0}^{18} MO_a^t \qquad (11)$$

I applied equations 10 and 11 to data from the World Population Prospects 2010. Figure 4 shows estimates and projections of the number of maternal orphans (age 0-17) in South Africa, Zimbabwe, Malawi and Zambia during the period 2000-2100. For each country, three scenarios are shown. The black line is computed using mortality and fertility rates from the UN medium scenario with AIDS. The blue line is computed using mortality and fertility rates from the UN medium scenario in absence of AIDS. The red line mimics the complete and sudden elimination of AIDS in 2015: the rates for the medium scenario with AIDS are used until 2015, then there is a sudden switch to the medium scenario in absence of AIDS.

Figure 4 offers important insights. First, we observe that in some countries, like South Africa and Zimbabwe, a peak in the number of orphans is reached before 2015. In other countries, like Malawi and Zambia, the

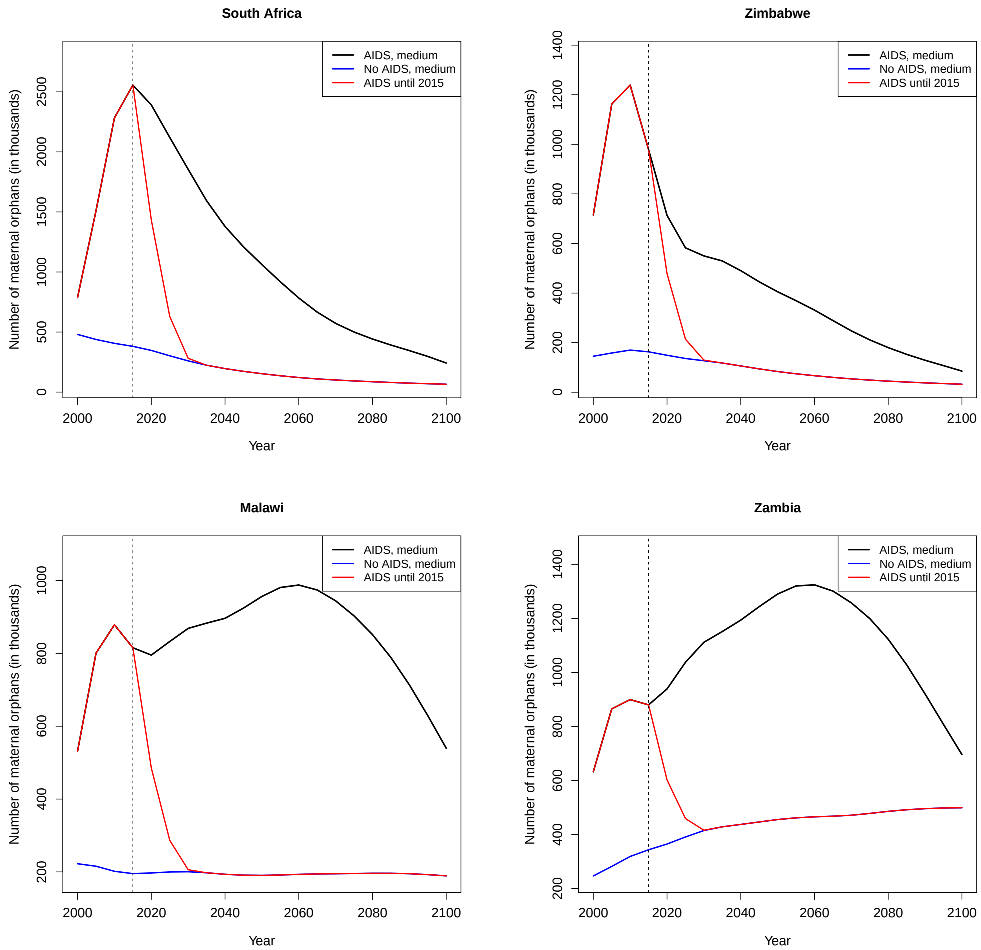

Figure 4: Estimates and projections of the number of maternal orphans (age 0-17) for four countries in sub-Saharan Africa for the period 2000-2100. For each country, three scenarios are shown. The black line is computed using mortality and fertility rates from the UN medium scenario with AIDS. The blue line is computed using mortality and fertility rates from the UN medium scenario in absence of AIDS. The red line is obtained using the rates for the medium scenario with AIDS until 2015, then there is a sudden switch to the medium scenario in absence of AIDS. Data source: own elaborations on UN World Population Prospects 2010.

number of orphans is expected to increase during the next decades. In Zambia, the number of maternal orphans is expected to increase even under the scenario of No-AIDS. Although the fraction of children who are orphans is expected to decrease, the high levels of fertility in Zambia and Malawi explain the rising number of orphans in these countries. The UN projects that the TFR of Malawi will not go below 4 until after 2050, and the one of Zambia will not go below 4 until after 2060. Countries like Zimbabwe and South Africa have much lower levels of fertility, with TFRs between 2 and 3, and fertility expected to be below replacement level in the next few decades. Second, even if we could eliminate all the AIDS-related deaths, there are large numbers of young children that are already orphans and will become adolescents without at least one parent. The consequences of the epidemic on orphanhood will be felt for decades. In an optimistic scenario of gradual eradication of the epidemic, the number of orphans will continue to be high. We can think of this phenomenon as a momentum of the epidemic.

UNICEF publishes estimates of the number of orphans for countries affected by the HIV/AIDS epidemic, but does not publish projections of maternal orphans. For the year 2005, the UNICEF estimates (UNICEF 2006) of number of maternal orphans are the following: 540,000 maternal orphans in Malawi, 1.3 million in South Africa, 860,000 in Zambia and 1.1 million in Zimbabwe. These statistics are very much in line with the values shown in figure 4. For the following years, UNICEF reports in the statistics section of the its website the number of total orphans (both mother and father dead), which are not directly comparable with the values in figure 4. It is possible that our method slightly overestimate the number of orphans because we do not account for heterogeneity (see the previous section on heterogeneity and correlated frailties). However, general trends should not be affected by that.

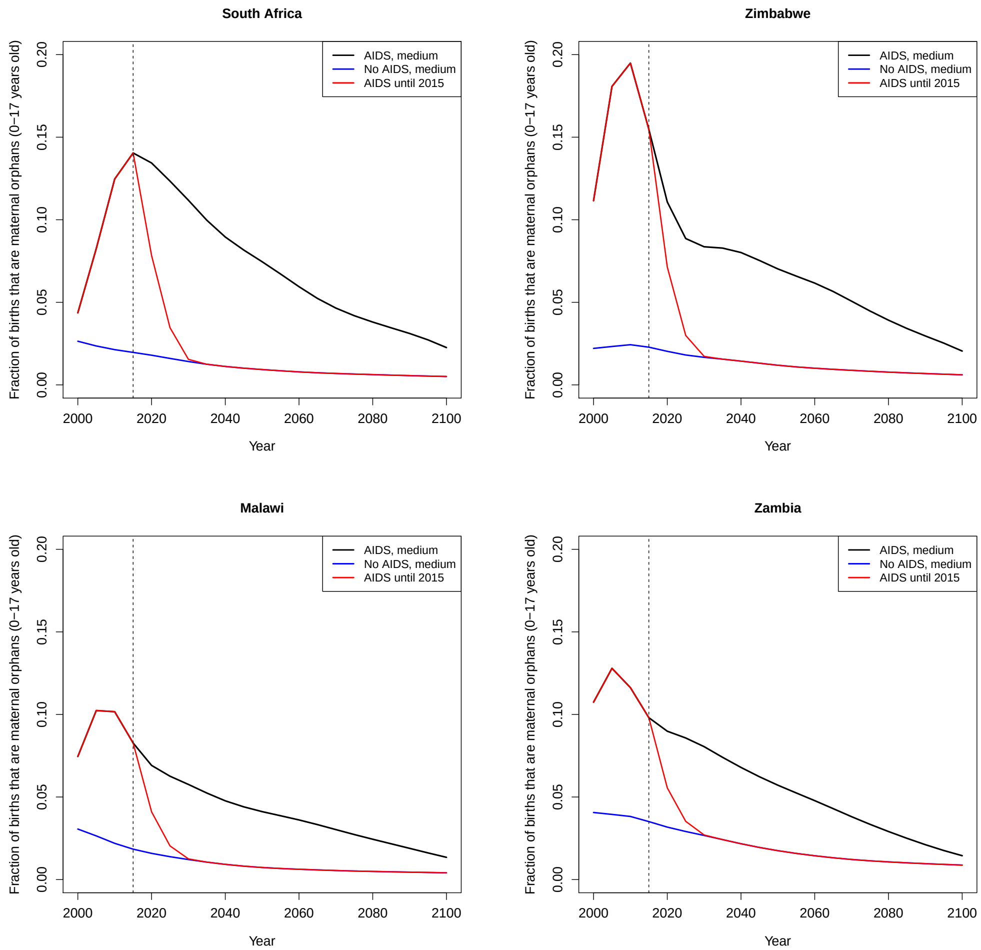

Figure 5: Estimates and projections of fraction of birth cohorts, in the age group 0-17 years old, who are maternal orphans, by calendar year. These measures of prevalence of orphanhood are shown for four countries in sub-Saharan Africa for the period 2000-2100. For each country, three scenarios are considered. The black line is computed using mortality and fertility rates from the UN medium scenario with AIDS. The blue line is computed using mortality and fertility rates from the UN medium scenario in absence of AIDS. The red line is obtained using the rates for the medium scenario with AIDS until 2015, then there is a sudden switch to the medium scenario in absence of AIDS. Data source: own elaborations on UN World Population Prospects 2010.

CONCLUSIONS

This article discussed the insights that we can obtain from formal demographic analysis to understand the impact of mortality shocks, such as the one generated by the HIV/AIDS epidemic, on prevalence and number of maternal orphans. The article highlights the importance of formal demographic methods to evaluate the prospects of maternal orphanhood in countries affected by a generalized HIV/AIDS epidemic. The application and extension of classic methods from the demographic theory of kinship, together with the availability of comprehensive and comparative demographic rates (United Nations World Population Prospects, 2010 Revision), generate a very powerful tool to evaluate the consequences of current demographic trends.

The article is intended to complement microsimulation studies, which have much larger data requirements, and produce a lot more information on kinship structure, but are limited to specific settings. For instance, Zagheni (2011) used the microsimulator Socsim to reconstruct and project the entire kinship structure of Zimbabwe, in order to evaluate the impact of the HIV/AIDS epidemic on the availability of kin support for children. In this article, the output of the analysis is not as rich as the one of microsimulations. Hovewer, the methods can be easily applied to all countries in the world and therefore are particularly useful for comparative purposes and to understand the dynamics of maternal orpanhood.

The formal analysis shows that the consequences of mortality crises persist for a long time. Improvements in the containment of the HIV/AIDS epidemic reduce the prevalence of very young orphans more quickly than the prevalence of orphanhood for teenagers. Population heterogeneity and correlated risks of mortality between mothers and children tend to reduce the probability of orphanhood. Positive correlations between hazard rates of mother and child imply a higher likelihood that either both survive or both die within a given number of years. Empirical analysis indicates that the impact of heterogeneity is noticeable, but not very large.

Projections for the future show that the prevalence of maternal orphanhood is expected to decline, at a different pace, in virtually all countries. Conversely, the number of orphans is not expected to decrease everywhere. In several countries, in particular where fertility is expected to remain high, the number of orphans is projected to increase during the next few decades. The comparison of number and prevalence of orphans between the 'AIDS' and 'No-AIDS' variants show the very large impact of the epidemic on maternal orphanhood.

UNICEF publishes estimates of number of orphans, but does not generate projections. Estimates can be obtained from surveys and give a picture of the orphanhood situation at one point in time. The main advantage of introducing a formal model is that it greatly improves our understanding of processes. Here I showed that it is relatively straightforward to apply formal methods to existing UN rates to evaluate the implications of current trends. These projections are particularly important to inform policy-relevant decisions. As the World Population Prospects move towards probabilistic projections, it will become possible to produce probabilistic projections of maternal orphanhood, in addition to scenario-based projections. I believe that formal methods will become more and more relevant complements to detailed surveys, like the Demographic and Health Surveys, and to microsimulation. In particular, the combination of classic methods from the formal theory of kinship, with microsimulation and with information from sample surveys is a promising area for future research.

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