Empirical evidence for the severe but localized impact of AIDS on population structure

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Despite considerable speculation on the demographic impact of AIDS, there has been, until now, little scientific evidence to establish its existence or scale. Because of the widespread implications of these predictions, methods to combine demography and epidemiology to study empirical situations have been an urgent priority. This study derives the extent and mechanisms of demographic impacts of AIDS from routine data (the 1991 census) in a severely affected country, Uganda. Three characteristics are of particular note: first, the emergence of demographic impacts much earlier than previously estimated; second, their localization with negative population growth at parish but not at district or national scales; third, a greater impact on the number of children than previously predicted[1,2], due as much to changes in population fertility as mortality. The emergence of demographic impacts at this stage highlights original aspects of the interdependence of HIV infection and demographic growth not previously recorded and the need to target preventive interventions to youth in developing countries.

Unprecedented population growth in many developing countries presents perhaps the most dramatic modern conditions for spread of infectious diseases of humans. Research has focused on demography and AIDS (ref. 1–3), which is claimed to have a greater potential to depress population growth rates in several decades than smallpox or bubonic plague did previously[2,3]. Despite considerable speculation on the demographic impact of AIDS, there has been little scientific evidence to establish its existence or scale. This study derives the extent and mechanisms of demographic impacts of AIDS from the 1991 census in Uganda, a severely affected country, and the findings have general implications for monitoring the impact and the predicted course of AIDS internationally.

The human immunodeficiency virus can significantly affect population, as it is transmitted vertically from mother to child, horizontally by sexual contact and as it results in high mortality[2]. Demographic conditions in many developing countries in turn affect the dynamics of infectious diseases, including HIV. With 50% of the population under 15 years old, increasingly larger cohorts of susceptible individuals are exposed to infection with time[4]. This may distinguish HIV epidemics in Africa from those elsewhere in the world, particularly as HIV prevalence begins to stabilize. Theoretical studies show that for many infectious diseases, infection may shift in an expanding population to younger ages with time[5], and a shift to younger cohorts is reported for HIV in some studies[4,6].

Reports from Uganda indicate considerable geographical heterogeneity in HIV prevalence, varying from 20% (and 50% HIV-attributed mortality) in some areas[7] to 13% in the Rakai and less than 2% in the Pallisa districts (Asiimwe-Okiror, G. *et al.*, Ninth Int. Conf. on AIDS and STDs in Africa, Kampala, Uganda, 1995). Indeed within Rakai, prevalence varies by parish from 1% to 40% (ref. 8). HIV prevalence in Rakai is associated statistically with trading centers[8]; but distinctly rural parishes may also have very high HIV prevalence and some of the first reports of AIDS (ref. 9,

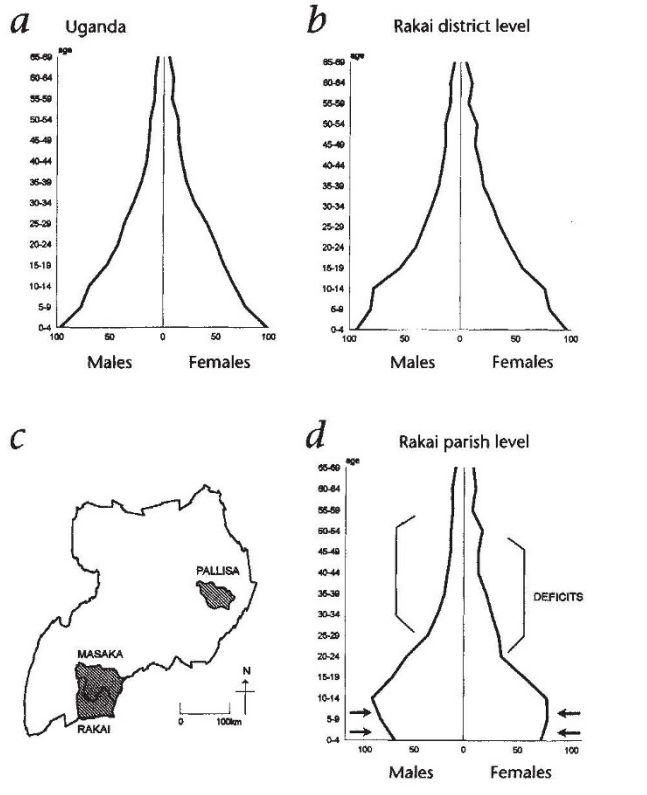

Fig. 1 Population from the 1991 Uganda census by five-year age group and sex, standardized to a population of one thousand, for *a*, Uganda national level; *b*, Rakai district; *d*, a parish with high HIV prevalence[8] in the Rakai district. *c*, Map of Uganda showing Masaka and Rakai districts with adult HIV prevalence >10% (ref. 8), and Pallisa district with HIV prevalence in pregnant women <2% (Asiimwe-Okiror, G. *et al.*, Ninth Int. Conf. on AIDS and STDs in Africa, Kampala, Uganda, 1995).

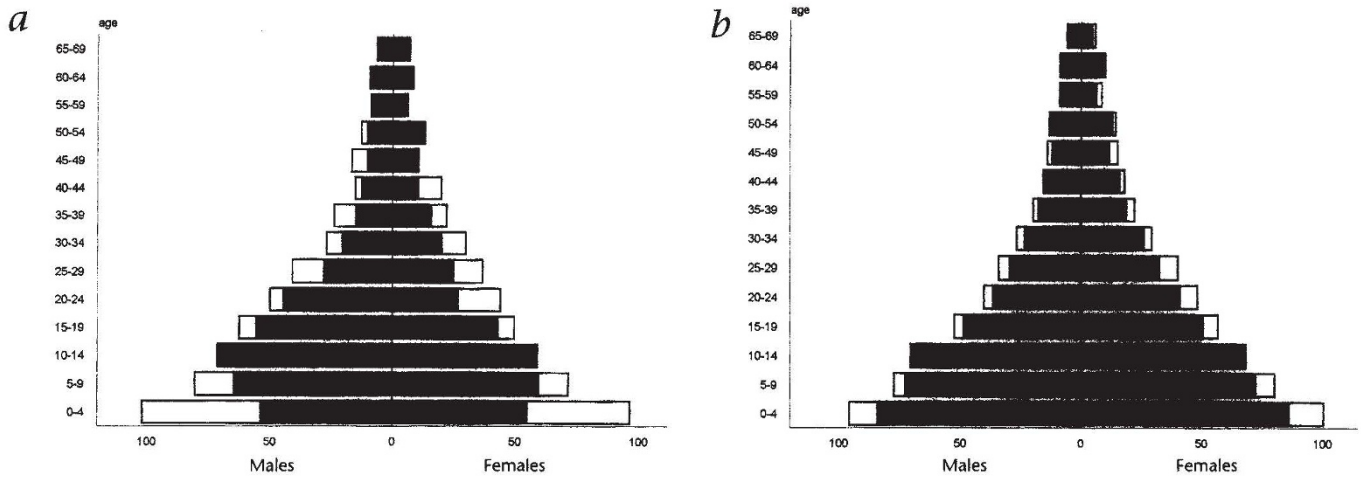

Fig. 2 *a*, Population by age and sex in a parish in Rakai with high HIV prevalence (black) standardized to a population with low HIV prevalence (from cluster sample survey[6]) (white). *b*, Rakai district population by age and sex (black) standardized to Uganda rural population (white).

10). Parishes with similar characteristics in these strata, but that differ in terms of HIV prevalence, can therefore be compared, in order to assess demographic impacts. We analyzed census data using this geographical heterogeneity in HIV prevalence (1) to identify population features that characterize areas with high prevalence from those with low HIV prevalence; (2) to standardize these populations to estimate deficits by age and sex; (3) to establish the extent of demographic impacts at parish, district and national levels; and (4) to correlate impacts to AIDS cases and census data on migration and parental death.

Results

The population structure shows a broad-based pyramid when plotted by age and sex at the national level, characteristic of countries with high population growth (Fig. 1); little difference exists at the district level. However, a distinctive structure is seen in parishes with high HIV prevalence: the pyramid contracts at the base with fewer aged 0–4 than 10–14; the 10- to 14-year-olds become the largest group and are least affected by AIDS mortality; there is a deficit of young adults. The impacts in adults are similar to model predictions over the longer term, but impacts in children are much greater than expected[2].

The population of a parish with high HIV prevalence standardized to one with low HIV prevalence is shown in Fig. 2. Large deficits occur in those born in the five years before the 1991 census, peak deficits in females aged 20–29, in males aged 25–29 and with an even sex ratio. These features could be due to AIDS, other mortality, fertility and migration. To control for other factors, parishes with similar rural characteristics but differing in HIV prevalence are plotted for comparison.

In adults, peak population deficits and reported AIDS cases occur within the same age groups and have a more similar age distribution than migration data by age (Fig. 3). These data make the results more consistent with AIDS than with migration as a cause. Furthermore, the pattern of deficits is repeated in several other parishes with high HIV prevalence in Rakai and Masaka

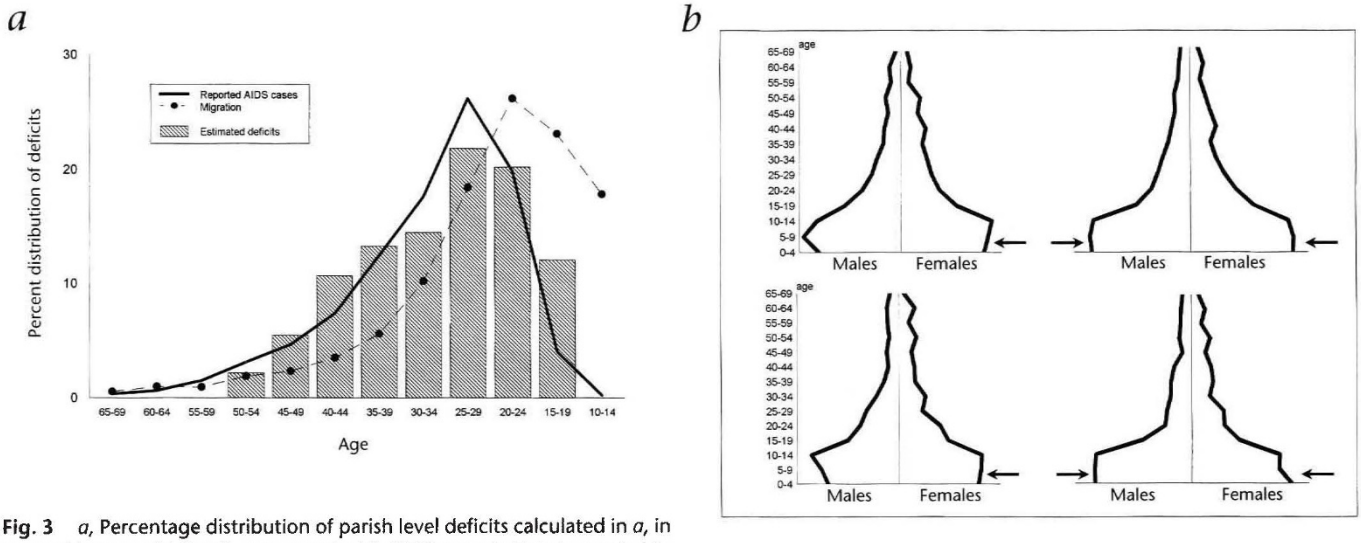

Fig. 3 *a*, Percentage distribution of parish level deficits calculated in *a*, in ages >10 years old (bars), compared with AIDS cases in Rakai reported to the Uganda National AIDS control programme, 1987–94 (solid line), and internal Uganda migration data from the 1991 Uganda census (dashed line). *b*, Examples of population distribution by age for males and females of other parishes with estimated deficits in Rakai and Masaka.

districts (Fig. 3). Although other factors may play a role, we suggest that the severity of these deficits in parishes with some of the first reported AIDS cases, and the similar distribution by age to AIDS cases, are probably due to the demographic impacts of HIV.

In severely affected parishes we estimate an overall 23% population loss, 25% among females and 22% among males. Deficits among children (33%) are greater than expected if solely due to AIDS mortality. At the district level in Rakai, the overall deficit is lower (10%) and is more difficult to distinguish from migration in younger ages. The demographic impact is less than half at the district compared with the parish level, showing how localized the impacts of HIV are in the 1991 census (Fig. 2).

From analysis of several hundred parish populations, the geographical extent of similar impacts was established for the predominantly rural districts of Rakai and Masaka, compared with Pallisa, which has low HIV prevalence (Fig. 4). Of 230 parishes in Rakai and Masaka, 5 demonstrated very severe, 9 severe and 29 moderate impacts. By comparison, in 80 parishes of Pallisa district used as controls, no similar impacts were found. In the parish with greatest demographic impacts, orphan rates were also highest, at 24%, compared with 5% in Pallisa. Orphan rates show a distribution similar to that for demographic impacts, concentrated in parishes with the earliest AIDS case reports (Fig. 4). Orphan rates are 2–6 times as high as rates from parishes without deficits due to HIV.

At the district level, no severe or even moderate impacts were observed. Possible demographic impacts were emerging at the parish level, in 7 parishes in districts close to Rakai (compared with 27 in Rakai), decreasing with distance along the trans-African highway from Rakai. The central district, Luwero, was an outlier, severely affected by civil war in 1982–83 (ref. 9), with impacts in three parishes.

Epidemiological modeling (Fig. 5) suggested severe parish population losses were consistent with HIV. A model including HIV infection dynamics and demographics defined from the 1991 census showed outputs by age and sex similar to the estimated deficits, in simulations with the following characteristics: an epidemic onset in 1980; 35% HIV prevalence within 3–5 years; a median 7-year incubation period and 1-year survival with AIDS. Ages 0–4 are initially most affected by pediatric HIV mortality (Fig. 6). Reduced fertility due to HIV mortality in women is more significant in the longer term. High deficits in ages 0–4 not previously noted help to explain why dependency ratios are not increased by HIV (ref. 3), even though we show orphan rates are increased 2–6 times. The observed demographic impacts are consistent with negative population growth in certain parishes by 1990–95. In contrast, population growth at district and national levels remains strongly positive.

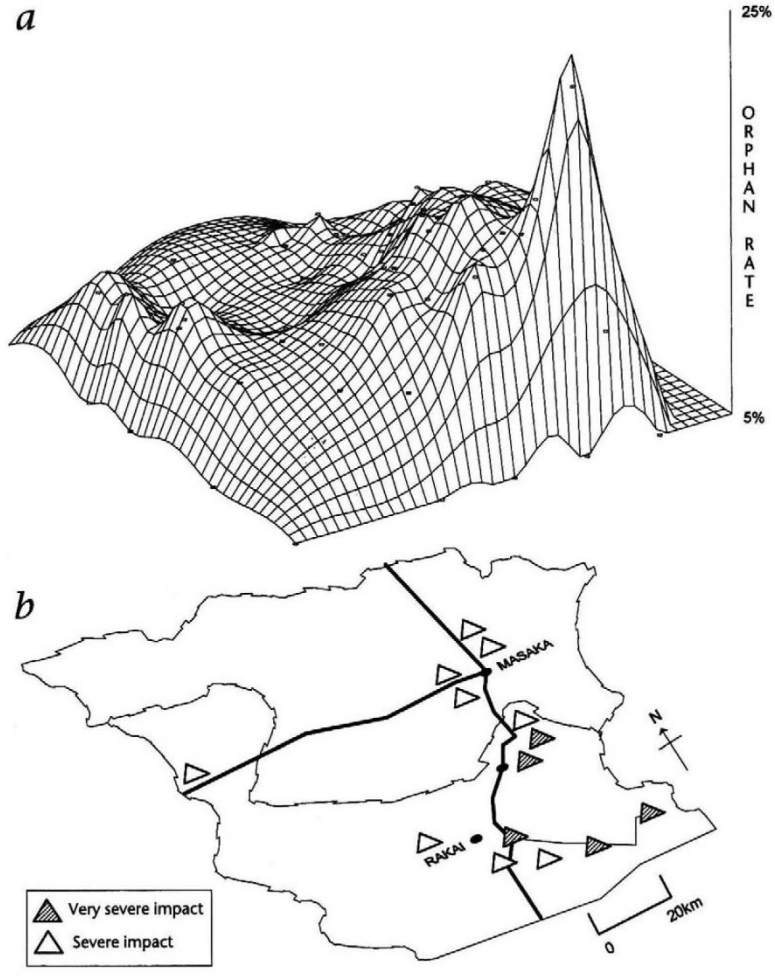

Fig. 4 Comparison of geographical distribution of orphan rates to estimated demographic impacts of AIDS in Rakai and Masaka districts. *a*, Distribution of subcounty orphan rates from the 1991 Uganda census. Data are interpolated using a negative exponential function with low tension (= *1*) around subcounty midpoints, using the Systat statistics package[21]. *b*, Distribution of estimated very severe demographic impacts of HIV (hatched triangles) and severe demographic impacts (white triangles) in Rakai and Masaka districts. Black lines mark roads from the parishes with the first reported AIDS cases in Uganda in south east Rakai, which also have the severest demographic impacts.

Discussion

The study provides some of the first empirical evidence of the structure and extent of the emerging demographic impact of HIV (ref. 9, 11, 12). It shows for the first time from census data the potential severity of the impacts as predicted previously[2,3]: the population pyramids with large sections missing and evidence of negative population growth at the parish scale. However, it also shows empirically how localized the impacts are at this stage, that they do not apply generally to population growth in Africa or even at the national or district levels.

The estimated deficits in adults by age were consistent with the distribution of reported AIDS cases, but in children the deficits were much greater. Despite underreporting of AIDS cases particularly in children, the magnitude of deficits in ages 0–4 is not fully explained by direct AIDS mortality. The model shows the important role of reduced fertility due to HIV mortality in women. The death of a young woman from HIV deprives the population of her full fertility, scheduled progressively over the following 20–30 years. This is sufficient to explain the observed deficits, but postulated declines in fertility in HIV-positive women (Gray, R. *et al.* Ninth Int. Conf. on AIDS and STDs in Africa, Kampala, Uganda, 1995) may also contribute to demographic impacts.

The methods in this paper were developed to apply to data with important sources of bias. The method of comparing

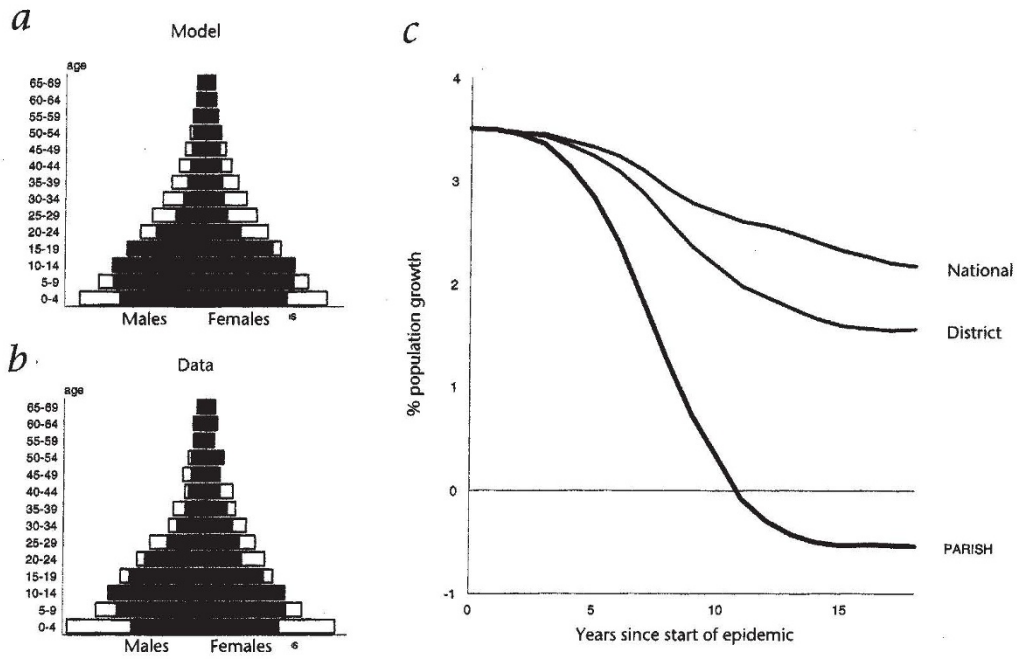

Fig. 5 The graphs show simulations of an epidemiological model, consistent with the observed demographic impacts. *a*, Model output compared with estimated deficits (*b*) in the worst affected parishes, by age for males and females. *c*, Population growth rates by year for simulations at the national level, the Rakai district, and a parish in Rakai.

parishes controls to a significant extent for the effect of census bias on the observed deficits. The 1991 census was undertaken by the Ugandan government to international standards[13] with technical assistance from United Nations organizations. The data quality is exceptional in relation to previous Ugandan censuses in 1948, 1959, 1969 and 1980, but biases may be involved in enumeration particularly in younger and mobile groups. However, sources of bias sufficient to explain the observed deficits were not apparent in populations with low HIV in Rakai and Masaka or in the 80 parishes used as a control in Pallisa (Fig. 1).

Other factors that may contribute to the deficits include other sources of mortality, fertility and migration. Deficits of this magnitude, observed in rural and town parishes, with a distribution similar to that of reported AIDS cases and orphan rates, are likely due to the demographic impact of AIDS. Furthermore, no impacts were observed among 80 parishes in Pallisa district with HIV prevalence less than 2%. Limitations to the study include that observations may be limited to a decade of the epidemic, and that patterns may develop differently in the future, and in relation to behavioral and migration patterns elsewhere. These initial observations would benefit from more focused and stratified demographic surveys. More important would be the development of similar methods to allow countries to establish empirically the scale of the demographic impacts of AIDS, as they undertake censuses in the next few years.

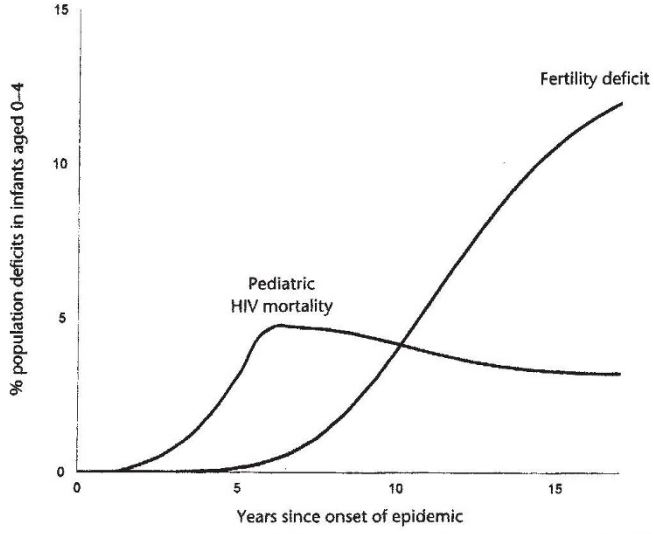

Fig. 6 Percentage population deficits in ages 0–4 by year, in a parish with very severe impacts, due to the following: direct pediatric HIV mortality and fertility loss from mortality in women of child-bearing age, calculated as the difference between simulations with and without AIDS for identical non-AIDS parameters.

The study highlighted the importance of geographical heterogeneity in infection patterns, as well as the need to identify the determinants of the severe impacts of HIV that occur alongside low impacts and HIV prevalence in neighboring parishes. The observed demographic impacts reflect explosive but relatively localized subepidemics, possibly due to specific risk behaviors[14], a period of heightened exposure, or initially high population infectivity due to increased viremia after infection[4]. The demographic impacts that are earlier than predicted are consistent with reports in Africa and Asia of stability or declines in HIV prevalence (ref. 15 and Asiimwe-Okiror, G. *et al*, Ninth Int. Conf. on AIDS and STDs in Africa, Kampala, Uganda, 1995). The HIV epidemic curve may increase and stabilize more rapidly than previous predictions of 30–100 years, and impacts may similarly be observed earlier, already in censuses in the 1990s. HIV may therefore be attuned to population growth, spreading rapidly, stabilizing or declining slightly, but established quickly to affect cohorts of increasing size in a growing population, as they age into sexual activity. Our results emphasize the need to sustain public health interventions[16] guided by surveillance, to respond early to rapidly increasing HIV prevalence, and with signs of stability to target preventive interventions to youth in developing countries.

Methods

The data from the Uganda census[13] for the census night of 11 January 1991 were analyzed to plot the male and female population by 5-year age groups

at parish, district and national levels. Census data on migration, orphan rates, and AIDS cases reported to the Uganda National AIDS Control Programme, 1987–94, were then compared with the population deficits to identify the possible impacts of AIDS. Finally a model[4] was used to confirm whether the deficits were consistent with HIV infection dynamics by age and sex.

In order to assess the impact of HIV prevalence on population and to control for sources of bias in the census, populations with high HIV prevalence were standardized to similar populations with low HIV prevalence. At the district level, the rural districts of Rakai and Masaka with adult HIV prevalence of 13% and 8%, respectively[7,8], were compared with the rural district of Pallisa with HIV prevalence in pregnant women under 2% (Asiimwe-Okiror, G. *et al*, Ninth Int. Conf. on AIDS and STDs in Africa, Kampala, Uganda,1995).

Within these districts, similar parishes that differed in terms of HIV prevalence were also matched. Parishes with distinctly rural characteristics were standardized in Fig. 2. The distribution of population deficits by age was also compared with migration and reported AIDS cases to control for other demographic factors. The populations are first converted to rates by age per 1000 population. They are then standardized so the groups aged 10–14 are the same size, because they are assumed from AIDS case data to be the group with lowest AIDS mortality. Population deficits are therefore approximated by the difference between the two populations after standardization (white bars in Fig. 2). The percentage distribution of parish level deficits by age was then compared with AIDS cases in Rakai reported to the Uganda National AIDS control programme, 1987–94, and internal Uganda migration data from the 1991 Uganda census.

To assess the geographical extent of demographic impacts, we analyzed data from 230 parish populations in Rakai and Masaka for similar deficits. We also analyzed 80 parishes in Pallisa district with low HIV prevalence as a control. To identify similar impacted populations, we used an index of the ratio of the 0- to 4-year-old age group at the base of the pyramid, to the 10- to 14-year-old age group, the one least affected by AIDS. A ratio of less than 1 in both sexes, where the base of the pyramid is contracting, is classified as a very severe impact, less than 1.1 a severe impact, and less than 1.2 a moderate impact. Above 1.2 it is assumed that the demographic impact of HIV could not be distinguished from other factors. The ratio for Uganda overall is 1.44 and for Pallisa district, with low HIV prevalence, 1.62. Using these ratios, no impacts that were defined as moderate or above were identified in the controls in the Pallisa district.

The estimated demographic impacts of AIDS in the Rakai and Masaka districts were also compared with subcounty orphan rates from the 1991 census. For comparison with other studies in Uganda, orphan rates were calculated as the proportion of children aged 0–9 missing one or both parents[17]. This reflects adult mortality and can be compared with the estimated population deficits due to AIDS and is consistent with previous definitions used in Uganda.

Finally, epidemiological modeling was used to investigate whether HIV infection dynamics were consistent with observed population deficits. A model that has shown considerable validity to the Uganda epidemic[4] was used. The model defines an HIV infection curve, by time, as a gamma function similar to WHO's Epimodel[18] ($t^{(p-1)}e^{-t}/(p-1)!$, where t is time and p is a constant) for a period of growth in HIV incidence, and an age distribution as a Pearson function $([1 + (a + a_1 - a_2)/(a_2 - a_1)]^m [1 - (a + a_1 - a_2)/(a_3 - a_1)]^n$, where a is age and a_1, a_2, a_3, m, n are constants). This is applied to a population, $N(a,t)$, defined for $t = 0$, and with non-AIDS mortality from the relevant Coale-Demeney West life table[19] for mortality $Q(0) = 0.104$–0.108. Age-specific fertility rates, $f(a)$, are from the 1991 Uganda census, with the number of HIV-positive newborns, $Y(0,t) = \sum_{a=0}^{\infty}(f(a)\,Y(a,t)(1-\varepsilon)$, where ε is the fraction of children born to HIV-positive mothers who remain uninfected, and $(1-\varepsilon) = 0.3$ (ref. 20). HIV-positive children are estimated to survive 2 years in Uganda. Intervals from HIV infection to AIDS mortality are modeled as a Weibull distribution, in this example concentrated around a median 7 years ($\alpha = 3.5$, $\beta = 7.75$).

The parameters of the model that determine peak HIV prevalence, date of onset and period of HIV incidence growth were varied and compared with the estimated population deficits (Fig. 5). Parameters most consistent with estimated deficits from the 1991 Uganda census above were as follows: parish level 35% peak HIV prevalence within 5 years from 1980; district level 15% peak HIV prevalence within 7 years; national level 10% peak HIV prevalence within 11 years. The model does not simulate dynamics of sexual mixing, but defines an HIV infection curve by time and age, varied until consistent with observed data, and is described elsewhere in detail and validated to Ugandan data[4].

Population deficits were calculated from the model as the difference between simulations with and without AIDS for identical non-AIDS parameters. The percentage population deficits in ages 0–4 by year due to direct pediatric HIV mortality, and fertility loss from mortality in women of childbearing age, were calculated to investigate the determinants of population deficits (Fig. 6). Population growth rates by year were also calculated for simulations at the national level, Rakai district, and parishes severely affected by HIV in Rakai.

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