The potential impact of country-level migration networks on HIV epidemics in sub-Saharan Africa: the case of Botswana

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Generalised HIV epidemics in sub-Saharan Africa show substantial geographical variation in prevalence, which is considered when designing epidemic control strategies. We hypothesise that the migratory behaviour of the general population of countries in sub-Saharan Africa could have a substantial effect on HIV epidemics and challenge the elimination effort. To test this hypothesis, we used census data from 2017 to identify, construct, and visualise the migration network of the population of Botswana, which has one of the most severe HIV epidemics worldwide. We found that, over 12 months, approximately 14% of the population moved their residency from one district to another. Four types of migration occurred: urban-to-urban, rural-to-urban, urban-to-rural, and rural-to-rural. Migration is leading to a marked geographical redistribution of the population, causing high rates of population turnover in some areas, and further concentrating the population in urban areas. The migration network could potentially be having a substantial effect on the HIV epidemic of Botswana: changing the location of high-transmission areas, generating cross-country transmission corridors, creating source–sink dynamics, and undermining control strategies. Large-scale migration networks could present a considerable challenge to eliminating HIV in Botswana and in other countries in sub-Saharan Africa, and should be considered when designing epidemic control strategies.

Lancet HIV 2021; 8: e787–92

Published Online November 10, 2021 https://doi.org/10.1016/S2352-3018(21)00267-8

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Introduction

Numerous studies of generalised HIV epidemics in sub-Saharan Africa have shown that geographical variation in prevalence is common.[1–5] As a consequence, this variation is considered when designing epidemic control strategies, for example with geographical targeting strategies. In this Viewpoint, we hypothesise that the migratory behaviour of the general population of countries in sub-Saharan Africa could have a substantial effect on HIV epidemics and challenge the elimination effort. Migration is defined as a change in residency from one area to another, which involves moving across an administrative boundary during a specified time interval. Using Botswana, which has one of the most severe HIV epidemics in the world, as an example, we show how individual-level census data can be used to construct, identify, and visualise a large-scale migration network of the entire population of a country in sub-Saharan Africa. We define migration networks in terms of migratory flows between geographical areas (ie, the number of migrants who move between areas), migratory patterns (areas that are connected by migratory flows), and a time interval over which migration occurs. To our knowledge, this is the first analysis that focuses on evaluating the potential impact of large-scale population-level migration networks on HIV epidemics; by contrast, previous studies have focused on small-scale networks (eg, cohort studies, or networks of specialised groups).[6–8] Notably, many of these studies have shown that these small-scale networks have an impact on the transmission dynamics of HIV in sub-Saharan Africa. We use the census-derived migration network and associated metrics to quantify the overall mobility of the population of Botswana, to identify connections between different geographical areas of the country, and to reveal recent changes in the geographical distribution of the population. We then discuss the potential impact of these large-scale migration networks on HIV epidemics, and how they might be undermining HIV epidemic control strategies in sub-Saharan Africa.

Demography and epidemiology in Botswana

Botswana has a small population: at the time of the last census, which was done in 2011, the population was estimated to be about 2·02 million, and was projected to be around 2·37 million by 2020.[9] Botswana has only 500 settlements; around 90% of these are rural villages that are sparsely distributed throughout the country (figure 1A). There are three types of urban settlement: cities, towns, and urban villages. The size of each settlement in 2020 (figure 1B) was projected by Statistics Botswana[9] using the Government of Botswana's demographic model; the model takes fertility, mortality, and migration into account. More than 60% of the population was projected to be living in urban areas by 2020: around 280 000 in the capital city (Gaborone), around 115 000 in Francistown (the only other city in Botswana), and the rest either in one of the five towns or in an urban village. The largest urban villages are very close to the two cities: six are satellites of Gaborone and three are satellites of Francistown. The largest urban village was projected to have almost as many residents as Francistown by 2020. However, about 40% of the population was projected to still be living in small, widely dispersed, rural villages, with the average village having fewer than 1000 residents, and some villages having fewer than 100.

The prevalence of HIV has remained fairly stable since 2013, when the last Botswana AIDS Impact Survey (BAIS IV) was done. The survey involved a large representative sample of the population: 10 140 participants were tested for HIV, and demographic and behavioural data

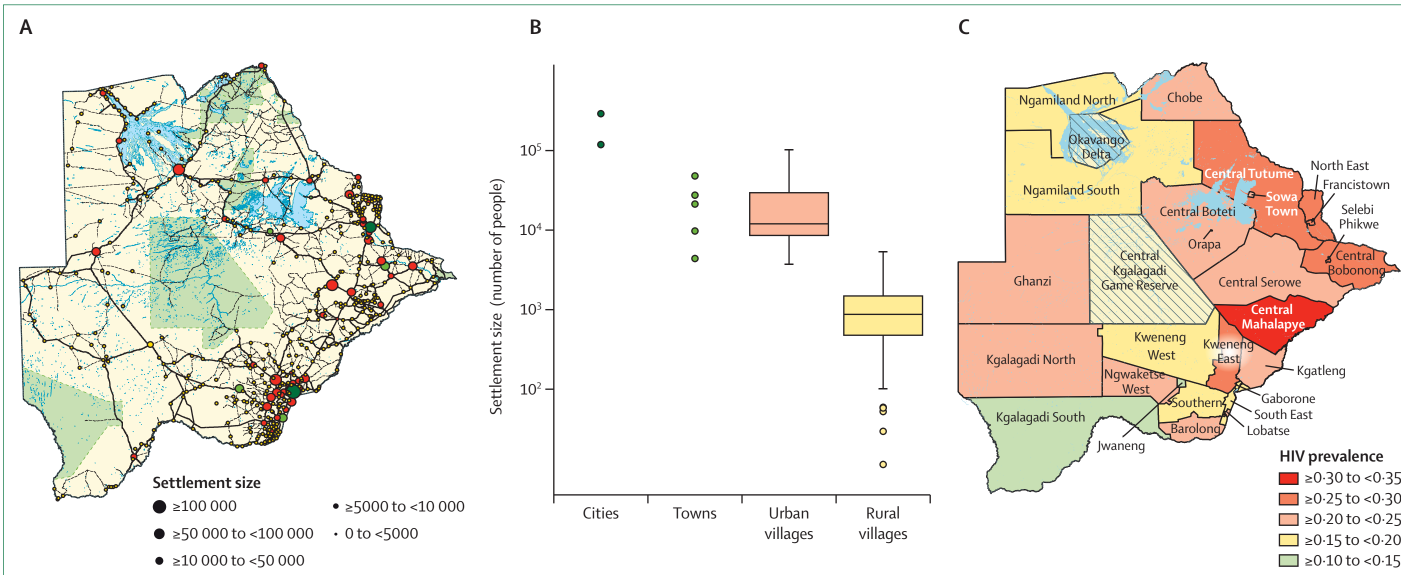

***Figure 1:* The geographical distribution of the population of Botswana and the spatial epidemiology of HIV**

(A) Map showing the number of settlements (city, town, urban village, or rural village) and their projected size in 2020. Projections were made by Statistics Botswana.[9] There are 500 settlements in total: two cities (dark green circles), five towns (light green circles), 51 urban villages (red circles), and 442 rural villages (yellow circles). The road network consists of primary roads (thick black lines), secondary roads (thin black lines), and tertiary roads (dashed black lines). Lakes and rivers are shown in light blue and national parks are shown in light green. (B) Boxplot showing the frequency distribution of the projected sizes of all cities, towns, urban villages, and rural villages in 2020.[9] The centre line gives the median settlement size, the box boundaries provide the interquartile range, and the whiskers extend from the minimum to the maximum excluding outliers (shown as dots). (C) Map of HIV prevalence in each health-care district. The colour code shows the prevalence for individuals aged 15–69 years; map and estimates are based on HIV-testing data collected in the Botswana AIDS Impact Survey IV in 2013.[10] Throughout this Viewpoint, health-care districts take on the naming conventions and geographical delineations of the 2011 census.[11] ArcGIS 10.1 was used for mapping.

were collected.[10] Botswana has 28 health-care districts, all of which were included in BAIS IV except for the Okavango Delta and the Central Kgalagadi Game Reserve, which were not sampled owing to logistical issues. Both of these health-care districts consist of large wildlife reserves and contain less than 1% of Botswana's population. Of the remaining 26 health-care districts, two are the cities (Gaborone and Francistown), five are the towns (Lobatse, Selebi Phikwe, Orapa, Jwaneng, and Sowa), and 19 health-care districts contain a mixture of urban and rural villages. The results from BAIS IV are shown as an HIV prevalence map, at the level of the health-care district, for individuals aged 15–69 years (figure 1C). The average prevalence was 23%; however, there was considerable geographical variation in prevalence among the health-care districts, ranging from 12% to 32%. Six of the 28 health-care districts contained 58% (95% CI 55–61%) of all people living with HIV. This concentration reflected, in large part, the distribution of the population: 53% of people aged 15–69 years were living in these six health-care districts. Two of these health-care districts are the cities, one health-care district (Kweneng East) contains most of the urban villages that are satellites of Gaborone, one health-care district (Central Tutume) contains most of the urban villages that are satellites of Francistown, one health-care district (Central Serowe) contains the largest urban village in Botswana, and one health-care district (Central Mahalapye) contains the main road that links the two cities.

Epidemic control in Botswana

HIV testing, prevention interventions, and treatment programmes are widely available throughout Botswana. HIV-testing services can be accessed through health facilities, targeted outreaches, voluntary counselling and testing centres, workplaces, mobile clinics, drop-in centres, and ongoing roll-out of self-testing.[12] Individuals who test negative are linked to prevention services that include, for example, the provision of pre-exposure prophylaxis and voluntary medical male circumcision. Condoms and HIV-prevention messages are also distributed as part of the HIV-prevention package. Individuals who test positive for HIV are linked to treatment and care, and treatment is widely available. In 2002, Botswana was the first country in sub-Saharan Africa to roll out free HIV treatment,[13] and in 2016 the country adopted a test-and-treat policy for citizens; anyone testing positive for HIV can initiate treatment immediately.[14] Botswana extended free HIV treatment to non-citizens in 2019. This policy is likely to have had, and to continue to have, a substantial effect on helping to reduce transmission in Botswana. Using mathematical modelling, PEPFAR estimated a treatment coverage of 67% of people living with HIV in Botswana by 2018.[15]

Use of census data to construct, identify, and visualise large-scale migration networks

The Government of Botswana defines internal migration as a change in residency between two health-care districts.

In this Viewpoint, we conceptualise the large-scale migration network of the general population as an origin–destination matrix that shows the magnitude of the migratory flows among the 26 health-care districts that were included in BAIS IV. Each entry in the origin–destination matrix contains the number of individuals (migrants) who moved their residency from one health-care district (the origin health-care district) to another health-care district (the destination health-care district), therefore, representing the migratory flow between an origin–destination pair of health-care districts. A plot of all the migratory flows in the origin–destination matrix reveals the pattern of the network (ie, the strength of the connectivity among all 26 health-care districts). Migration networks depend on the migration interval; the commonly used intervals are 1 year, 5 years, or lifetime. In this Viewpoint, we use a migration interval of 1 year.

To construct the large-scale migration network for the general population, we calculated the migratory flow between each pair of health-care districts over a 12 month time period, using the most recent data on migration: individual-level data collected in the 2017 Botswana Demographic Survey (BDS).[16] The 2017 BDS was the fourth intercensal survey done in Botswana, and was designed to collect information on population demographics, mortality, migration, household characteristics (such as access to water and sanitation), and non-communicable diseases. External migration was considered in the 2017 BDS; specifically, nationals of Botswana who were temporarily living outside the country at the time of the census were included by collecting data from family members, and nationals of Botswana who had permanently left the country before the census were not included in the survey. We calculated migratory flows for the 12 months before October, 2017, the month in which data collection for the intercensal survey was completed. To visualise the migration network, we plotted the origin–destination matrix in the form of a chord diagram (a standard method for showing a network).

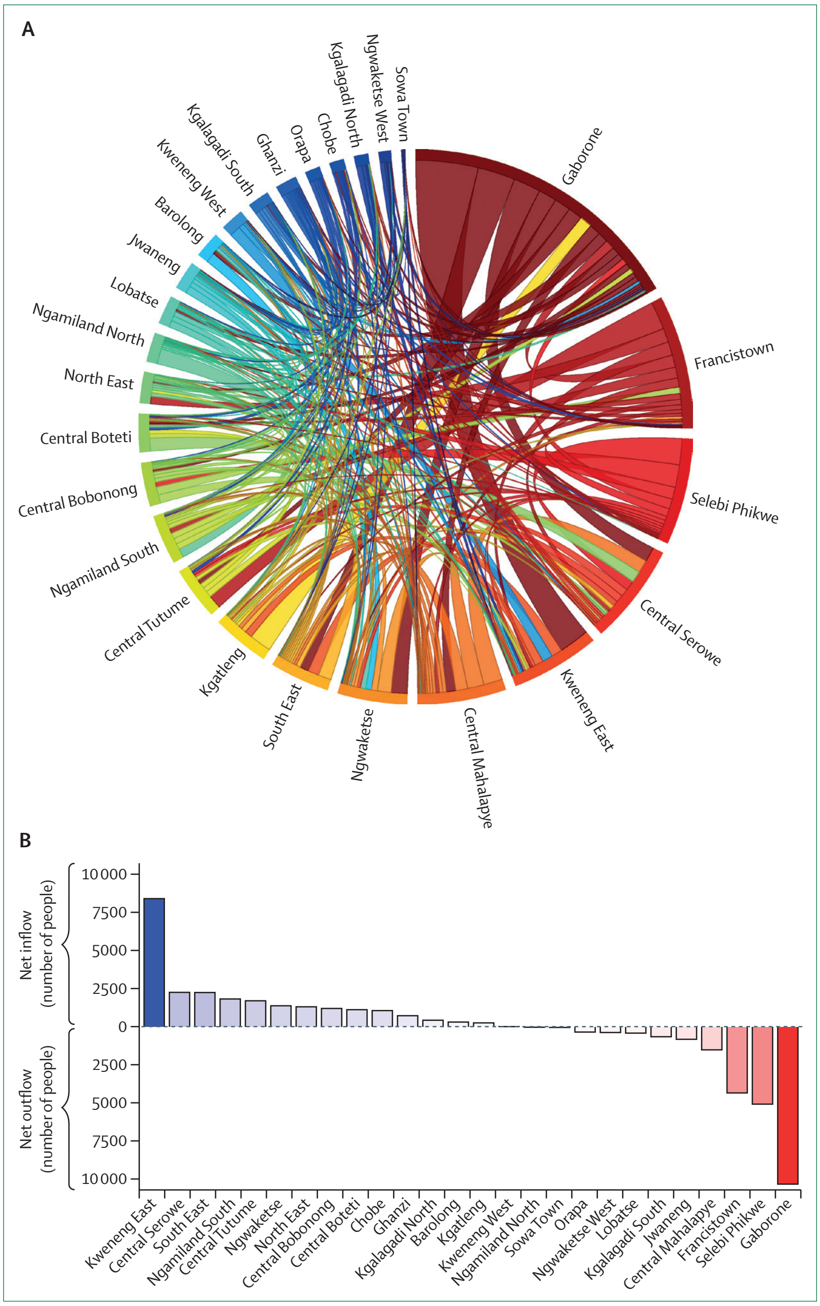

Figure 2: **The large-scale migration network of the population of Botswana**
Data shown were collected in the BDS[16] in 2017. (A) Chord diagram showing the migration network of the general population in the 12 months before the BDS. Each colour on the outer part of the circle represents a different health-care district. The thickness of a line is proportional to the net number of migrants that moved between the two connected health-care districts; the thicker the line, the greater the number of migrants. The colour of the line represents the health-care district in which the net migration was negative. The angular width of each health-care district is proportional to the total number of migrants who moved from, or moved into, that specific health-care district. (B) Histogram showing net migration for each health-care district in the 12 months before the 2017 BDS. BDS=Botswana Demographic Survey.

Calculating migration metrics

We also used data from the 2017 BDS to calculate two metrics of internal migration for each health-care district (net migration and population-level churn) in the previous 12 months. Net migration is defined as the difference between in-migration and out-migration. An in-migrant to a specific health-care district is a person who moves into that health-care district; an out-migrant from a specific health-care district is a person who moves out of that health-care district. Consequently, net migration can be either positive or negative. Positive net migration means that the population size of the health-care district is increasing; negative net migration means that the health-care district is decreasing in population size. We define population-level churn, for each health-care district, as the number of individuals who moved into the health-care district (in-migrants) during the previous 12 months plus the number who moved out of the health-care district (out-migrants) during the previous 12 months, divided by the number of residents of the health-care district at the beginning of the 12 month period. The number of

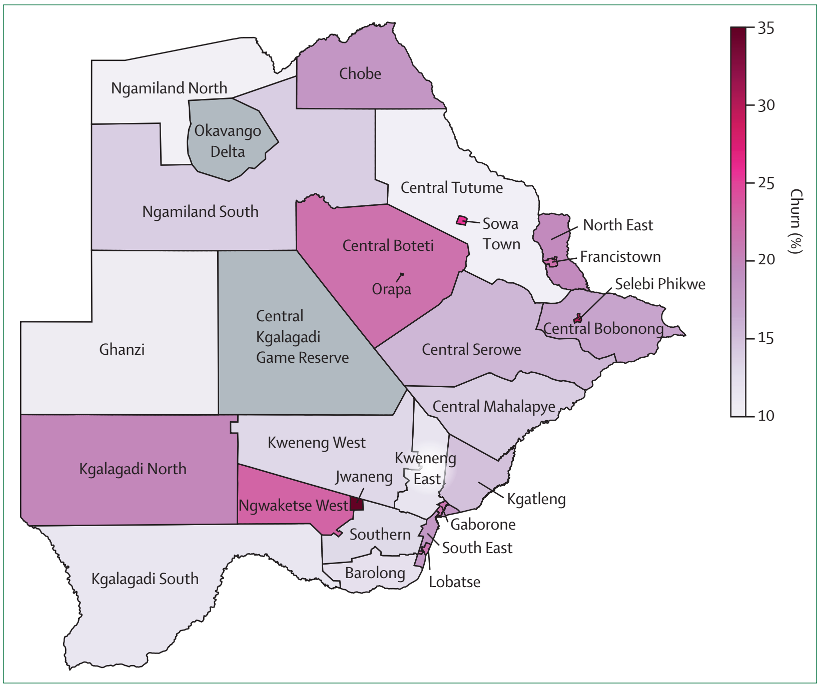

Figure 3: **Map showing population-level churn in each health-care district**
ArcGIS 10.1 was used for mapping.

residents at the beginning of the 12 month period includes the number of individuals who subsequently out-migrated in the next 12 months, but not the number of individuals who moved into that health-care district.

Utility of census-derived migration networks and migration metrics

We used the migration networks and migration metrics to quantify the overall mobility of the population of Botswana, to identify connections between different geographical areas of the country (represented by health-care districts), and to reveal recent changes in the geographical distribution of the population.

We found that internal migration was extremely high. Over the 12 months before the 2017 BDS, approximately 14% of the population of Botswana moved from one health-care district to another. By examining the origin–destination matrix, we found that four types of migration occurred: urban-to-urban, rural-to-urban, urban-to-rural, and rural-to-rural. The large-scale migration network of the population of Botswana can be visualised using a chord diagram (figure 2A). The diagram shows migratory flows between pairs of health-care districts in the previous 12 months; health-care districts represent nodes in the network. The data in the chord diagram show the magnitude of the migratory flow between each pair of health-care districts, the overall directionality of the migratory flow, and the geographical pattern of the migration network (in terms of connections between pairs of health-care districts). The population moved throughout Botswana in a complex pattern, as migratory flows connected health-care districts in many different parts of the country. Markedly, migration between the two cities was fairly low: only 3·4% of migrants from Gaborone moved to Francistown, and 9·6% of migrants from Francistown moved to Gaborone.

High overall migration and the specific migration pattern resulted in a substantial geographical redistribution of the population: the net migration in some health-care districts was positive, whereas in other health-care districts the net migration was negative (figure 2B). Health-care districts that were predominantly rural decreased in size. Notably, some individuals moved to the cities (Gaborone and Francistown), but others left the cities; overall, the net migration for both cities was negative, and they both decreased in size. However, the overall percentage of the population that was living in urban areas increased in the 12 months before the 2017 BDS. This growth occurred because the urban villages substantially increased in size; the health-care district that included the largest urban villages (Kweneng East) increased in size the most. The migration network (figure 2A) shows that people from the cities, towns, and rural villages moved into the urban villages. Notably, in some health-care districts the large amount of internal migration led to very high rates of population-level churn; geographically, the rates ranged from 13% to 34% (figure 3). The highest rates of churn were in the towns.

Potential impact of large-scale migration networks on HIV epidemics and control strategies

The large-scale migration network in Botswana has the potential to have a substantial effect on HIV transmission. Internal migration is high; each year, many individuals change their residency over fairly large distances, moving from one health-care district to another. All health-care districts are connected to each other to some degree, because of urban-to-urban, rural-to-urban, urban-to-rural, and rural-to-rural migration. The high mobility and connectivity, coupled with the substantial geographical variation in HIV prevalence, suggests that there could be important transmission corridors (ie, risk flows)[17] between health-care districts that are tightly coupled by mobility. Additionally, mobility linkages could be resulting in source–sink transmission dynamics:[18] health-care districts in which HIV prevalence is high could be maintaining transmission in health-care districts in which transmission is too low to be self-sustaining. The changing geographical distribution of the population, driven by internal migration, might be changing the transmission, and the spatial epidemiology, of HIV. For example, the increasing size of urban villages might enable them to begin to act as sources and maintain microepidemics in surrounding rural villages, which in turn might become sinks as they decrease in size.[18] The changing demographics might also be changing the geographical location of high-transmission areas; currently these are in the cities.[15] The large urban villages could soon become the most important high-transmission areas owing to their increasing numbers of in-migrants; results from multiple studies[19–21] show that migrants have a high risk of acquiring HIV.

The migration network of the general population in Botswana has important implications for epidemic control strategies. Large-scale, population-level migration networks have not previously been evaluated in the context of HIV epidemics; internal migration is implicitly assumed to be very low. However, in this Viewpoint, we have shown a very high rate of internal migration and a complex migration network in Botswana. These factors, which are probably driven by urbanisation, are generating a substantial turnover (over a fairly short timespan) of residents in many areas of the country and are causing a large-scale geographical redistribution of the population. Increased urbanisation is to be expected in the future; therefore, high turnover and changes in the geographical redistribution of the population are likely to continue. The high annual turnover of the population in some health-care districts could be reducing the effectiveness of epidemic control strategies. High population turnover might explain why Botswana has still not achieved very high treatment coverage (although treatment has been available for almost two decades),[13,22] and why treatment as prevention has reduced the incidence of HIV in Botswana by only around 30%.[23,24] The migration network is leading to an increased concentration of Botswana's epidemic in only a few health-care districts: the health-care districts that contain the largest urban villages. Therefore, current treatment programmes might need to be relocated, and there will be a substantial increase in the need for interventions and treatment programmes in urban villages. Additionally, our results highlight the need for innovative HIV care and prevention services. Specifically, service delivery should not only be geographically targeted and facility-based, but should also be person-centred, with the capacity to move with the individual.

To our knowledge, the potential impact of large-scale migration networks on HIV epidemics in sub-Saharan Africa and on HIV control strategies has not been considered previously. We have shown that the large-scale migration network in Botswana could be having a substantial effect on the country's HIV epidemic and undermining control strategies. UNAIDS has designated Botswana as one of its highest-priority countries for eliminating HIV by 2030;[25] we suggest that the migration network needs to be taken into consideration to design effective control strategies. Many other countries in sub-Saharan Africa with generalised HIV epidemics are becoming increasingly urbanised.[26] Therefore, internal migration in these countries is likely to be high. We suggest that studies similar to the one we have presented for Botswana be done in these countries. They all have census data that can be used to construct, identify, and visualise large-scale population-level migration networks. These networks can then be used, as we have shown here, to quantify the overall mobility of the general population, to identify connections between different geographical areas of the country, and to reveal recent changes in the geographical distribution of the population. If large-scale migration networks exist in other countries, they will present a substantial challenge to eliminating HIV in sub-Saharan Africa.

Contributors

JTO, LB, and SB designed the project and interpreted the results. EV and KS contributed to the interpretation of the results. JTO did all statistical analyses of the Botswana AIDS Impact Survey IV data. EV estimated migration rates and did a network analysis using the 2017 Botswana Demographic Survey. JTO and EV verified the underlying data. SB wrote the first draft of the manuscript; all authors contributed to writing subsequent drafts. All authors read and approved the final manuscript.

Declaration of interests

We declare no competing interests.

Acknowledgments

JTO, EV, and SB acknowledge financial support from the National Institute of Allergy and Infectious Diseases, National Institutes of Health (grant numbers R01 AI116493 and R56 AI152759). We acknowledge Statistics Botswana for making available all data used.

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