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

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Abstract

Generalized HIV epidemics in sub-Saharan Africa (SSA) show substantial geographic variation in prevalence. This variation is taken into account when designing epidemic control strategies. Here, we hypothesize that the migratory behavior of the "general population" of countries in SSA could have a significant impact on HIV epidemics, and challenge the elimination effort. To test this hypothesis we use census data (from 2017) to identify, construct, and visualize the migration network of the population of Botswana. Botswana has one of the most severe HIV epidemics worldwide. We found that, over twelve months, ~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 substantial geographic 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 significant impact on the HIV epidemic: 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 significant challenge to eliminating HIV in Botswana and other countries in SSA; these networks should be considered when designing epidemic control strategies.

Keywords

Epidemic control; Migration; Network; sub-Saharan Africa

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Authors' contributions

JTO, LB, and SB designed the project and interpreted the results. EV and KS contributed to interpreting the results. JTO performed all statistical analysis of BAIS IV data. EV estimated migration rates and performed 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 co-authors contributed to writing subsequent drafts. JTO, LB, KS, EV, and SB have all read and approved the final manuscript.

Competing interests

JTO, LB, KS, EV, and SB declare that they have no conflicts of interest.

Introduction:

Numerous studies of generalized HIV epidemics in sub-Saharan Africa (SSA) have shown that geographic variation in prevalence is common.[1–5] As a consequence, this variation is taken into account when designing epidemic control strategies; e.g., by using geographic targeting strategies. Here, we hypothesize that the migratory behavior of the "general population" of countries in SSA could have a significant impact on HIV epidemics, and present a challenge to the elimination effort. Migration is defined as a change in residency from one area to another, that involves moving across an administrative boundary, during a specified time interval. We show how individual-level census data can be used to construct, identify, and visualize a large-scale migration network of the entire population of a country in SSA: Botswana. Botswana has one of the most severe HIV epidemics worldwide. We define migration networks in terms of migratory flows between geographic areas (i.e., 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. This is the first analysis that focuses on evaluating the potential impact of large-scale population-level migration networks on HIV epidemics; previous studies, in contrast, have focused on small-scale networks (i.e., cohort studies, or networks of specialized groups).[6–8] Notably, many of these studies have shown that these small-scale networks have a substantial impact on the transmission dynamics of HIV in SSA. Here 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 geographic areas of the country, and to reveal recent changes in the geographic distribution of the population. We then discuss the potential impact of these large-scale migration networks on HIV epidemics, and how they may be undermining HIV epidemic control strategies in SSA.

Botswana: demography and epidemiology

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

HIV prevalence has remained fairly stable since 2013 when the last Botswana AIDS Impact Survey, BAIS IV, was conducted. The survey was based on a large representative sample of the population; 10,140 participants were tested for HIV, and demographic and behavioral data were collected.[10] Botswana has 28 healthcare districts (HCDs); all were included in BAIS IV except for the Okavango Delta and the Central Kalahari Game Reserve. These two HCDs were not sampled due to logistical issues. Both consist of large wildlife reserves, and contain less than one percent of Botswana's population. Of the remaining 26 HCDs, two are the cities (Gaborone and Francistown), five are the towns (Lobatse, Selebi-Phikwe, Orapa, Jwaneng, and Sowa Town), and the remaining 19 HCDs 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 HCD, for individuals aged 15–69 years old (figure 1C). The average prevalence was 23%; however, there was considerable geographic variation in prevalence amongst the HCDs ranging from 12% to 32%. Six of the 28 HCDs contained 58% (CI: 55%–61%) of all people living with HIV. This concentration reflected, in large part, the distribution of the population: 53% of 15–69 year olds were living in the six HCDs. Two of these HCDs are the cities, one HCD (Kweneng East) contains most of the urban villages that are satellites of Gaborone, one HCD (Central-Tutume) contains most of the urban villages that are satellites of Francistown, one HCD (Central-Serowe) contains the largest urban village in Botswana, and one HCD (Central-Mahalapye) contains the main road linking the two cities.

Botswana: epidemic control

HIV testing, prevention interventions, and treatment programs are widely available throughout Botswana. HIV testing services can be accessed through health facilities, targeted outreaches, voluntary counselling and testing centers, workplace, mobile clinics and drop-in centers; there is an ongoing roll-out of self-testing.[11] Individuals who test negative are linked to prevention services which include the provision of pre-exposure prophylaxis, and voluntary medical male circumcision, etc. 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,[12] and in 2016 adopted a 'test-and-treat' policy for citizens; anyone testing positive for HIV can initiate treatment immediately.[13] Botswana extended free HIV treatment to non-citizens in 2019. This is likely to have had, and continue to have, a significant impact on helping reduce transmission in Botswana. UNAIDS, using mathematical modeling, estimated that treatment coverage was 67% by 2018.[14]

Using census data to construct, identify, and visualize, large-scale migration networks

The Government of Botswana defines internal migration as a change in residency between two HCDs. Here we conceptualize the large-scale migration network of the general population as an origin-destination (OD) matrix that shows the magnitude of the migratory flows amongst the 26 HCDs that were included in BAIS IV. Each entry in the OD matrix contains the number of individuals (migrants) who moved their residency from one HCD (the origin HCD) to another HCD (the destination HCD); i.e., the migratory flow between an origin-destination pair of HCDs. A plot of all of the migratory flows in the OD matrix reveals the pattern of the network: i.e., the strength of the connectivity amongst all 26 HCDs. Migration networks depend upon the migration interval; the commonly used intervals are one year, five years, or lifetime. Here we use a migration interval of one year.

To construct the large-scale migration network for the general population we calculated the migratory flow between each pair of HCDs, over a 12-month time period, using the most recent data on migration: individual-level data collected in the 2017 Botswana Demographic Survey (BDS).[15] The 2017 BDS was the fourth intercensal survey that has been conducted 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 taken into consideration in the 2017 BDS: specifically, (i) nationals of Botswana who were temporarily living outside Botswana at the time of the census were included by collecting data from family members, and (ii) nationals of Botswana who had permanently left Botswana prior to the census were not included in the survey. We calculated migratory flows for the 12 months prior to October 2017, the date when the intercensal survey data were collected. To visualize the migration network, we plotted the OD matrix in the form of a chord diagram, a standard method for displaying a network.

Calculating migration metrics

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

The 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 geographic areas of the country (represented by HCDs), and to reveal recent changes in the geographic distribution of the population.

We found that internal migration was extremely high. Approximately 14% of the population of Botswana moved from one HCD to another between 2016 and 2017. By examining the OD matrix we found that four types of migration occurred: urban-to-urban, rural-to-urban, urban-to-rural, and rural-to-rural. Figure 2A shows a visualization of the large-scale migration network of the population of Botswana in the form of a chord diagram. The diagram shows migratory flows between pairs of HCDs, in the previous twelve months; HCDs represent nodes in the network. Each HCD is represent by a different color on the outer part of the circle. The thickness of the line connecting two HCDs represents the net-migration between them; the thicker the line, the greater the number of migrants. The color of the line represents the HCD where the net-migration was negative. The angular width of each HCD is proportional to the total number of migrants who moved from, or moved into, that specific HCD. Taken together the results in the chord diagram show the magnitude of the migratory flow between each pair of HCDs, the overall directionality of the migratory flow, and the geographic pattern of the migration network (in terms of connections between pairs of HCDs). Figure 2A shows that the population moved throughout Botswana in a complex pattern: migratory flows connected HCDs in many different parts of the country. Markedly, migration between the two cities was fairly low: only 3·4% of Gaborone migrants moved to Francistown, and 9·6% of Francistown migrants moved to Gaborone.

The high overall level of migration and the specific migration pattern resulted in a substantial geographic redistribution of the population; the net-migration in some HCDs was positive, whereas the net-migration in other HCDs was negative (figure 2B). Not surprisingly, HCDs 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 living in urban areas grew between 2016 and 2017. This occurred because the urban villages substantially increased in size; the HCD which included the largest urban villages (Kweneng East) increased 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 HCDs the high level of internal migration led to very high rates of population-level churn; geographically, the rates ranged from 13% to 34% (figure 2C). The highest rates of churn were in the towns.

The 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 impact on HIV transmission. Internal migration is high; each year, many individuals change their residency over fairly large distances, moving from one HCD to another. All HCDs are connected to each other to some degree, because of urban-to-urban, urban-to-rural, rural-to-urban, and rural-to-rural migration. The high mobility and connectivity, coupled with the substantial geographic variation in HIV prevalence, suggests that there may be important transmission corridors (i.e., risk flows)[17] between HCDs that are tightly coupled by mobility. Additionally, mobility-linkages may be resulting in source-sink transmission dynamics:[18] HCDs where HIV prevalence is high may be maintaining transmission in HCD where transmission is too low to be self-sustaining. The changing geographic distribution of the population, driven by internal migration, may be changing the transmission, and spatial epidemiology, of HIV. For example, the increasing size of urban villages may enable them to begin to act as "sources" and maintain micro-epidemics in surrounding rural villages, which may be becoming "sinks" as they decrease in size.[18] The changing demographics may also be changing the geographic location of high-transmission areas; currently these are in the cities.[14] The large urban villages may soon become the most important high-transmission areas due 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 significant implications for epidemic control strategies. Large-scale population-level migration networks have not previously been evaluated in the context of HIV epidemics; it has been implicitly assumed that internal migration is very low. However, here we have shown, that in Botswana, there is a very high rate of internal migration and a complex migration network. These factors, likely driven by urbanization, are generating a substantial turnover (over a fairly short timespan) in residents in many areas of the country, and causing a large-scale geographic redistribution of the population. Increased urbanization is to be expected, therefore high levels of turnover and changes in the geographic redistribution of the population are likely to continue. The high annual turnover of the population in some HCDs may be reducing the effectiveness of epidemic control strategies. It may explain why treatment coverage in Botswana has still not achieved very high levels (although treatment has been available for almost two decades),[12,22] and why "treatment as prevention" has only reduced the incidence rate in Botswana by ~30%.[23,24] The migration network is leading to an increased concentration of Botswana's epidemic in only a few HCDs: the HCDs that contain the largest urban villages. This suggests that current treatment programs may need to be relocated, and that there will be a substantial increase in the need for interventions and treatment programs 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-centered with the capacity to move with the individual.

The potential impact of large-scale migration networks on HIV epidemics in SSA and HIV control strategies have not been considered previously. Here we have shown that the large-scale migration network in Botswana could be having a substantial impact on its 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 in order to design effective control strategies. Many other countries in SSA with generalized HIV epidemics are becoming increasingly urbanized.[26] Therefore, internal migration in these countries is likely to be high. We suggest that similar studies to the one that we have presented for Botswana be conducted in these countries. All of these countries have census data that can be used to construct, identify, and visualize 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 geographic areas of the country, and to reveal recent changes in the geographic distribution of the population. If large-scale migration networks exist in other countries, as well as in Botswana, they will present a significant challenge to eliminating HIV in SSA.

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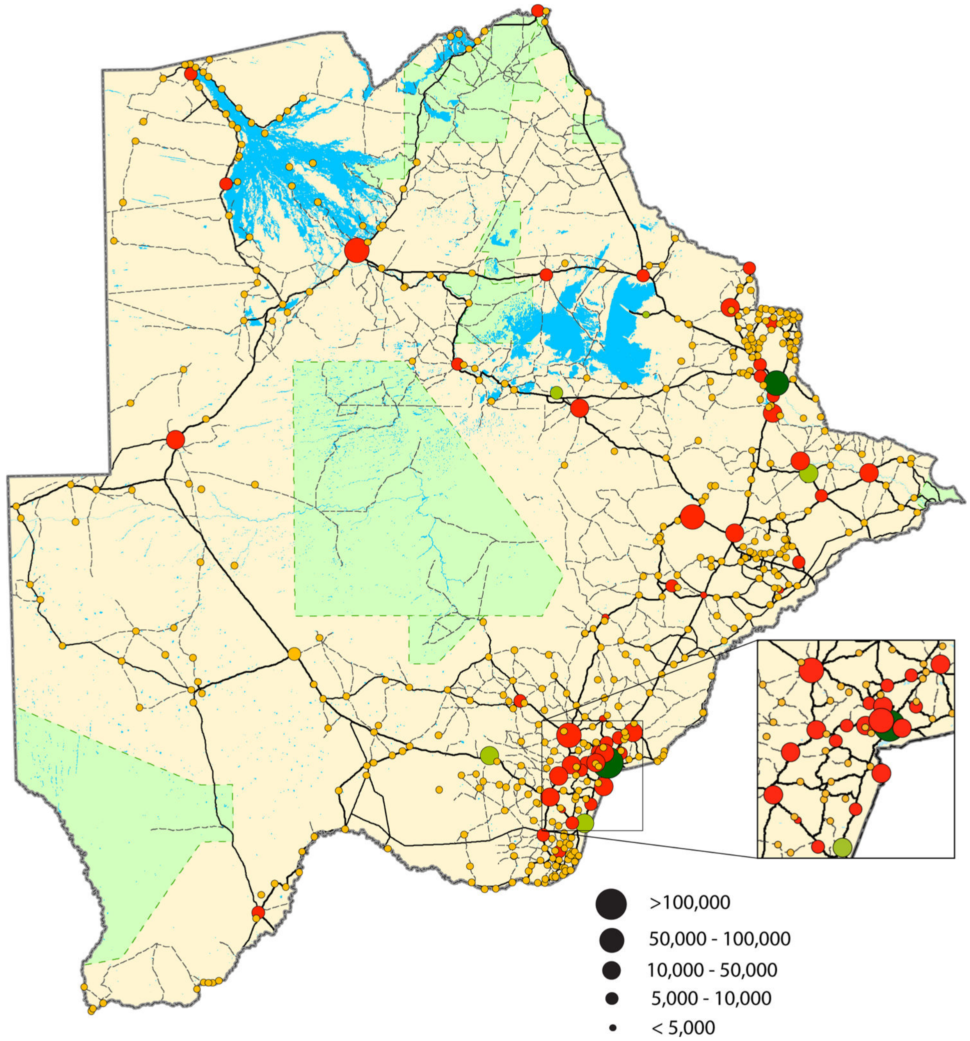
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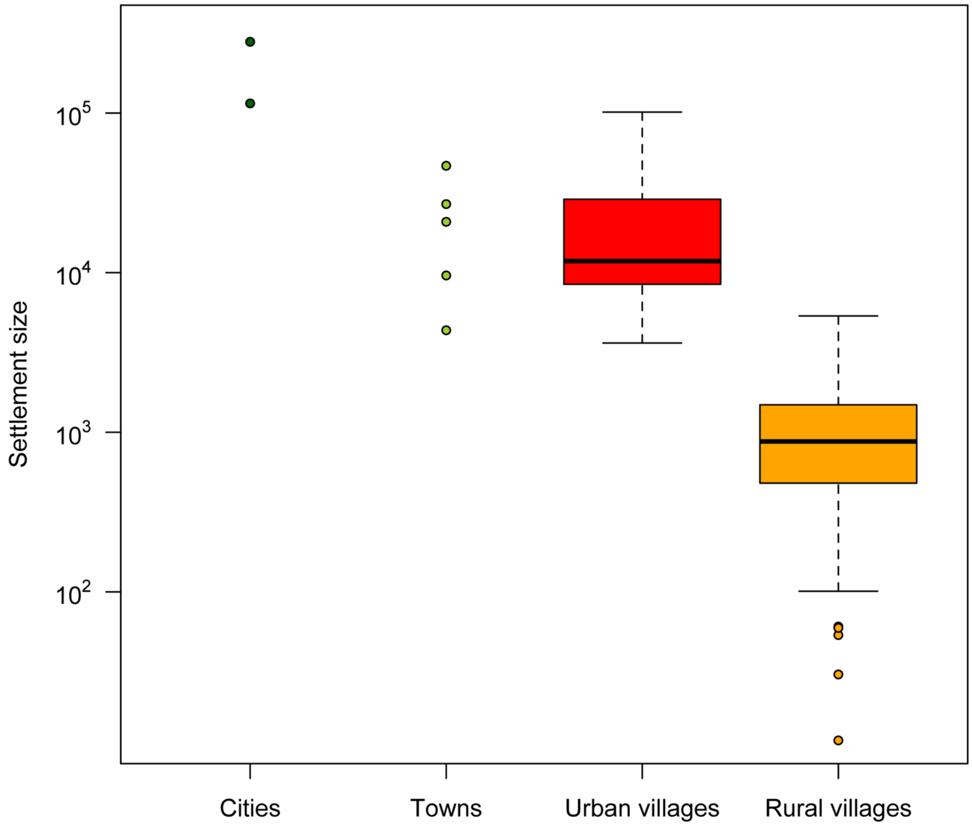
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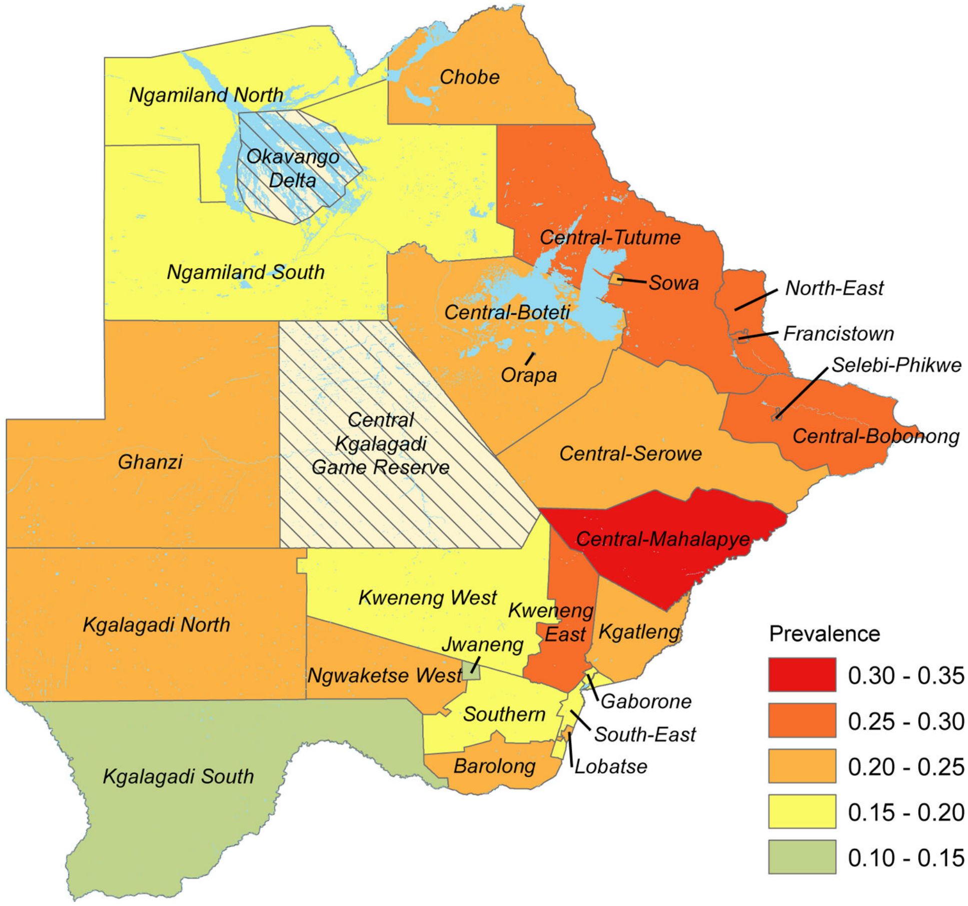
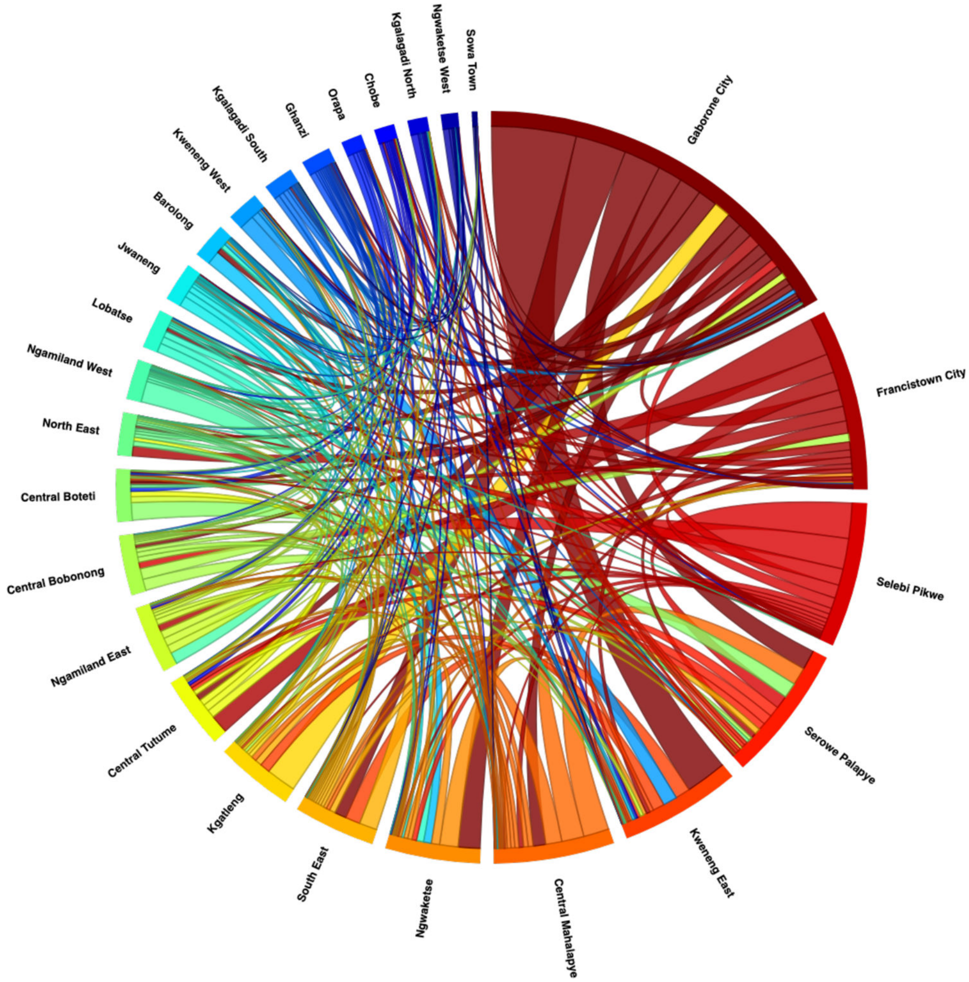


Figure 1: The geographic distribution of the population of Botswana and the spatial epidemiology of HIV.

(A) Map showing the number of settlements, and their projected size in 2020; a settlement is either a city, town, urban village, or rural village. Projections were made by Statistics Botswana.[9] The number of individuals living in each settlement is represented by circle size. 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 (orange circles). The road network consists of: primary roads (thick black lines), secondary roads (thin black lines), and tertiary roads (dotted 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. **(C)** Map of HIV prevalence in each HCD. The color code shows the prevalence level for individuals aged 15–69; map and estimates are based on HIV-testing data collected in BAIS IV, in 2013.[10]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Orapa
Ghanzi
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Ngamiland West
North East
Central Boteti
Central Bobonong
Ngamiland East
Central Tutume
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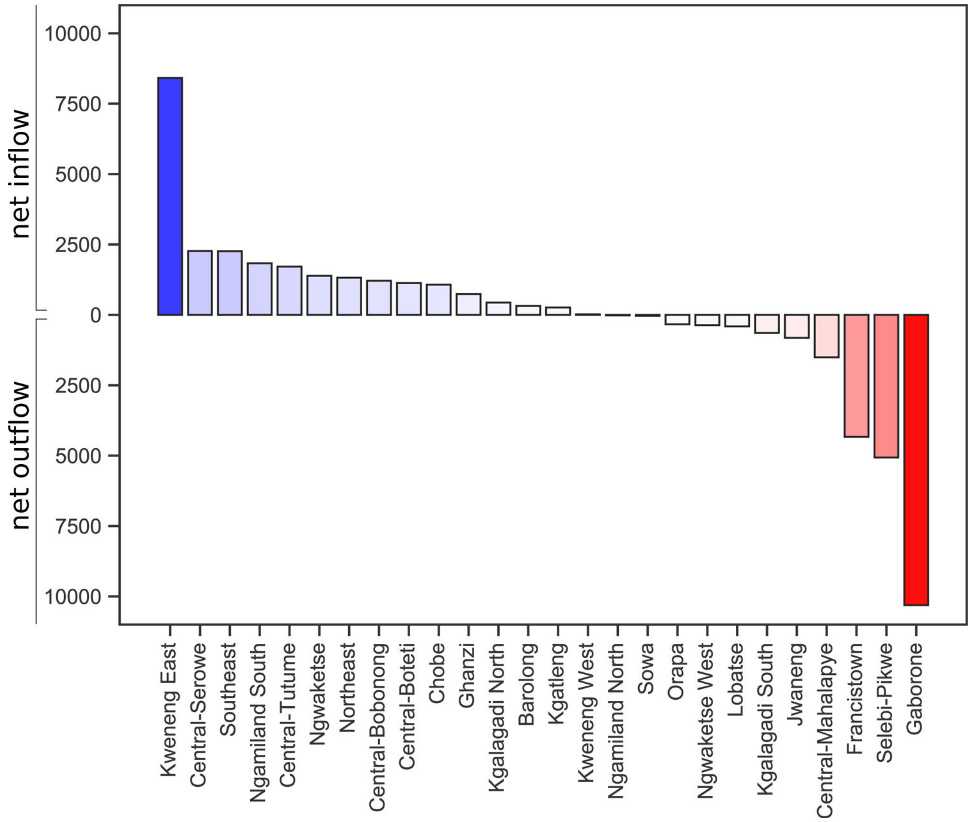
Ngwaketse
Central Mahalapye
Kweneng East
Serowe Palapye
Selebi Pikwe
Francistown City
Gaborone City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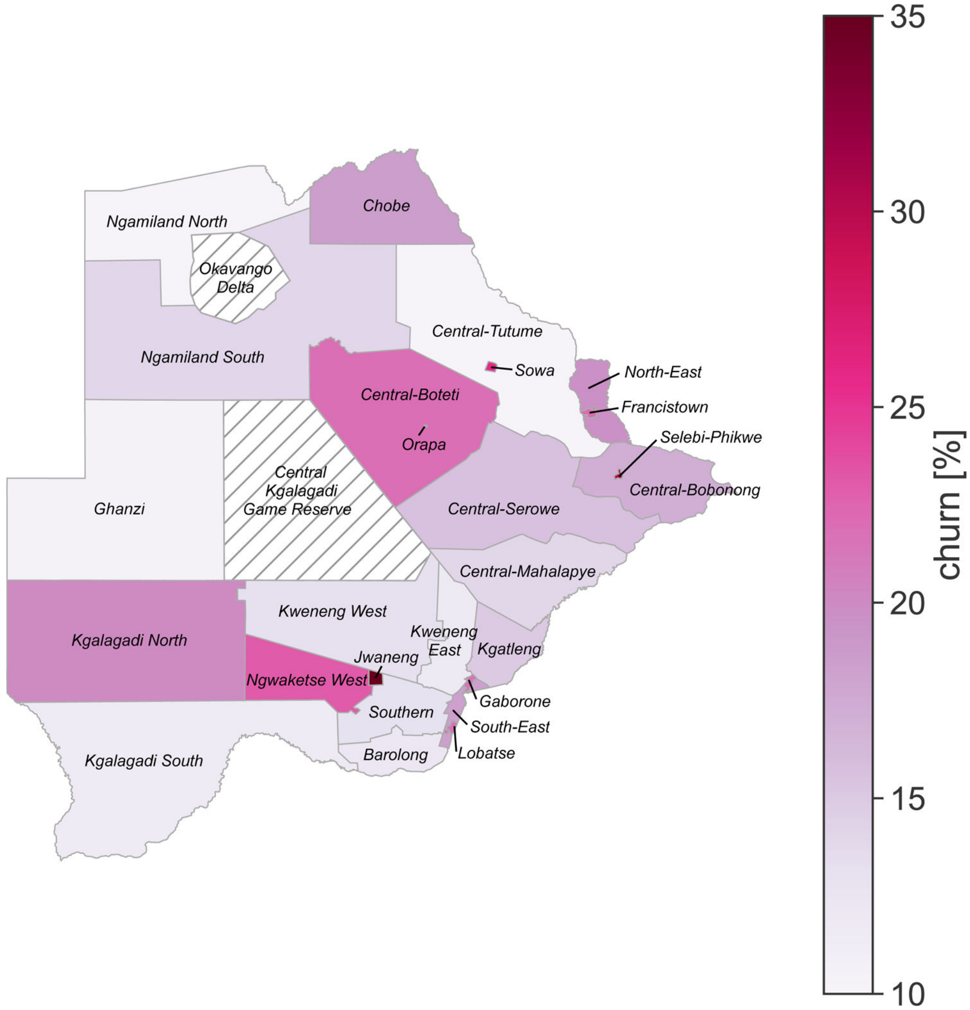

Figure 2: The large-scale migration network of the population of Botswana.

Data shown in this figure were collected in the BDS in 2017. **(A)** Chord diagram showing the migration network of the general population between 2016 and 2017. Each color represents a different HCD. The thickness of a line is proportional to the net number of migrants that moved between the two connected HCDs; the color of the line represents the HCD where the net-migration was negative. **(B)** Histogram showing net-migration for each HCD between 2016 and 2017. **(C)** Map showing population-level churn in each HCD. ArcGIS was used for mapping.[16]