Using geospatial mapping to design HIV elimination strategies for sub-Saharan Africa

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Treatment as prevention (TasP) has been proposed by the World Health Organization and the Joint United Nations Programme on HIV/AIDS (UNAIDS) as a global strategy for eliminating HIV. The rationale is that treating individuals reduces their infectivity. We present a geostatistical framework for designing TasP-based HIV elimination strategies in sub-Saharan Africa. We focused on Lesotho, where ~25% of the population is infected. We constructed a density of infection map by gridding high-resolution demographic data and spatially smoothing georeferenced HIV testing data. The map revealed the countrywide geographic dispersion pattern of HIV-infected individuals. We found that ~20% of the HIV-infected population lives in urban areas and that almost all rural communities have at least one HIV-infected individual. We used the map to design an optimal elimination strategy and identified which communities should use TasP. This strategy minimized the area that needed to be covered to find and treat HIV-infected individuals. We show that UNAIDS’s elimination strategy would not be feasible in Lesotho because it would require deploying treatment in areas where there are ~4 infected individuals/km². Our results show that the spatial dispersion of Lesotho’s population hinders, and may even prevent, the elimination of HIV.

INTRODUCTION

The World Health Organization (WHO) (1) and the Joint United Nations Programme on HIV/AIDS (UNAIDS) (2) propose using “treatment as prevention” (TasP) for the global elimination of HIV. The vast majority, ~25 million, of individuals living with HIV are in sub-Saharan Africa (3). The rationale behind TasP is straightforward: Treatment decreases viral load, reducing the infectiousness of HIV-infected individuals (4). Therefore, a high coverage of treatment could potentially prevent a substantial number of new HIV infections (5–7). The elimination plan proposed by UNAIDS is described as the 90-90-90 strategy: to diagnose 90% of HIV-infected individuals, treat 90% of the diagnosed, and achieve viral suppression in 90% of those patients (8). The aim is to achieve these goals by 2020. TasP is now being used in many resource-rich countries where HIV epidemics are concentrated in “high-risk groups” and the 90-90-90 goals appear attainable (7, 9). However, TasP has not yet been introduced into resource-constrained countries in sub-Saharan Africa where HIV epidemics are severe, transmission is predominantly heterosexual, and a high proportion of the population is infected. As a consequence, to eliminate HIV, TasP will need to be used throughout entire countries. Notably, the majority (~60%) of the population in sub-Saharan Africa lives in rural areas (10), where settlements are often widely dispersed and population density is low (11). The potential effect of these spatial demographics on hindering or perhaps even preventing the TasP-based elimination of HIV in sub-Saharan Africa has not been considered by either UNAIDS or WHO. Here, we present a geostatistical framework for designing TasP-based elimination strategies in sub-Saharan Africa. The strategies take into account the characteristic spatial demographics of populations in sub-Saharan Africa, the countrywide spatial diffusion of HIV epidemics, and resource constraints. The framework is based on the construction of a map that reveals the geographic dispersion pattern of all HIV-infected individuals in an entire country. Here, we focus on Lesotho, where ~70% of the population lives in rural areas (10). We also use our framework to evaluate the feasibility, and potential success, of the 90-90-90 elimination strategy.

UNAIDS has identified the HIV epidemic in Lesotho as a priority for elimination (8). The epidemic is one of the most severe worldwide, with a prevalence in the general population of ~25% (12). Health care is decentralized and the country is divided into 10 health care districts (Fig. 1A). In each district, there is one major urban center; in two health care districts, Maseru and Leribe, there are several large towns. Currently, only 36% of HIV-infected individuals in Lesotho are receiving treatment (13); this is dispensed at ~200 clinics throughout the country (Fig. 1B).

We designed a TasP-based elimination strategy for Lesotho by estimating and mapping the geographic location of all (diagnosed and undiagnosed) HIV-infected individuals (15 to 49 years old). The resultant map shows the density of infection (DOI), that is, the number of HIV-infected individuals per square kilometer. We used three “types” of data to construct the map: gridded high-resolution demographic data from the WorldPop project (14), age structure data from the 2010 census in Lesotho, and georeferenced HIV testing data from ~7000 individuals (15 to 49 years old) who participated in the 2010 Lesotho Demographic Health Survey (15). This survey is a nationally representative population-level survey (see Materials and Methods and fig. S1). We used the DOI map to design a TasP-based HIV elimination strategy that optimizes the efficiency of resource utilization. Efficiency was optimized by allocating treatment to minimize the geographic area that needed to be covered to find and treat HIV-infected individuals. We also determined how to implement the optimal elimination strategy in a decentralized health care system. Specifically, we identified the optimal allocation of a limited supply of treatment among Lesotho’s 10 health care districts. We compared this optimal treatment allocation strategy to the current treatment allocation strategy. Notably, we did not predict the epidemiological outcomes of either treatment allocation strategy. This would require developing a complex spatially explicit transmission model based on the DOI map and taking population mobility and all major forms of migration into account.

RESULTS

Spatial demographics

The gridded WorldPop data show the settlement dispersion patterns in Lesotho and the geographic variation in population density at a resolution...
of 0.01 km² (Fig. 2A); the total population size of Lesotho is ~2 million. The settlements were identified by using satellite data on surface imagery of land cover patterns to reallocate population census data (11). About 27% of the population lives in 1 of the 12 urban centers in Lesotho (10); the population density is highest (~4000 individuals/km²) in the capital city, Maseru (Fig. 2, A and B). The majority live in small, dispersed, rural settlements where (on average) there are ≤100 individuals/km² (Fig. 2B); this includes individuals of all ages. We found relatively little variation in age structure among health care districts, but an urban–rural difference was apparent (fig. S2): ~60% of the population in urban centers was 15 to 49 years old versus ~50% in rural areas.

The epidemic surface prevalence map

The epidemic surface prevalence (ESP) map (Fig. 2C) provides a spatial visualization of the HIV epidemic throughout Lesotho. Specifically, it shows the percentage of the population (15 to 49 years old) that is infected with HIV. The map was constructed using spatial interpolation techniques (16) and the georeferenced HIV testing data from the Lesotho Demographic Health Survey (see Materials and Methods). We found relatively little variation in HIV prevalence among the health care districts, except in Butha-Buthe in the north where the prevalence was lower (16%) than in the rest of the country. Notably, an individual’s probability of HIV infection was higher in urban centers than in rural areas; HIV prevalence (on average) was 27% in urban centers versus 21% in rural settlements.

The DOI map

The DOI map (Fig. 3A) is a reflection of the spatial diffusion of the epidemic in the general population, the dispersion patterns (and size) of rural and urban settlements, and geographic variation in population density. We constructed the map by combining the three maps shown in Fig. 2 (A and C) and fig. S2 (see Materials and Methods). The DOI map provides a high-resolution visualization of Lesotho’s HIV epidemic in terms of the number of HIV-infected individuals (15 to 49 years old) per square kilometer. It reveals the geographic dispersion pattern of all HIV-infected individuals (both diagnosed and undiagnosed) and shows that the epidemic has spread to almost every community in the country (Fig. 3A). Subsequently, all numbers we report for HIV-infected individuals refer only to those between 15 and 49 years old.

Our results show that the geographic dispersion pattern of HIV-infected individuals directly reflects the spatial demographics of the population. The DOI in the 12 urban areas in Lesotho ranges from 100 to 450 infected individuals/km²; the DOI is one to two orders of magnitude lower in rural settlements (Fig. 3, A and B). Notably, the vast majority of infected individuals live in rural areas, many where the DOI was extremely low. Almost a third live in rural settlements, where there are less than 6 infected individuals/km² (Fig. 3, A and B). The HIV prevalence is high (~20%), even when the DOI is extremely low (Fig. 3C). Most HIV-infected individuals in rural settlements live close (within 1 km) to ~2 to 20 uninfected individuals of the opposite sex, whereas (on average) most HIV-infected individuals in urban centers live in close proximity to ~350 to 500 uninfected adults of the opposite sex (Fig. 3C). The DOI varies substantially within, as well as among, the 10 health care districts (Fig. 4).

Using the DOI map, we estimated that there were 223,500 HIV-infected individuals (15 to 49 years old) living in Lesotho; this includes both diagnosed and undiagnosed individuals. This estimate lies within the 95% confidence interval (CI) obtained when estimating the number of HIV-infected individuals (15 to 49 years old) without spatially smoothing the prevalence data (CI, 213,540 to 243,229).
An epidemic concentration curve for the HIV epidemic in Lesotho

An epidemic concentration curve (ECC) plot provides a quantitative estimate of both the degree of urbanization of an HIV epidemic (the percentage of the epidemic that is concentrated in urban areas) and the degree of dispersion of HIV-infected individuals in rural areas. The national ECC plot for Lesotho (Fig. 5A) shows that the epidemic is predominantly rural: Only ~20% of infected 15- to 49-year-old individuals live in urban areas (red data). Outside the urban areas, the DOI drops precipitously and then slowly decreases (Fig. 5A). The shape of the curve in the ECC plot shows that finding a high percentage of HIV-infected individuals, and then treating these individuals, will become progressively more challenging as the treatment coverage goal increases.

Designing an optimal TasP-based elimination strategy for Lesotho

We used the national ECC plot (Fig. 5A) to design a TasP-based elimination strategy that optimized the efficiency of resource utilization. The strategy minimized the geographic area that needs to be covered to find, diagnose, and treat HIV-infected individuals; this spatial optimization was accomplished by concentrating treatment in communities with the highest DOI.

We used the national ECC plot (Fig. 5A) to identify which communities should use TasP if only ~70% of HIV-infected individuals could be treated. According to UNAIDS, this is the minimum treatment coverage needed for elimination (see Materials and Methods). The dotted black line in the ECC plot (Fig. 5A) shows that TasP should only be used in communities where there were at least 5 infected individuals/km². The DOI map (Fig. 3A) shows the geographic location of these communities. TasP should first be used in urban communities in the red areas of the DOI map (where there were 100 to 450 infected individuals/km²), then in rural communities in the yellow areas (where there were 10 to 100 infected individuals/km²), and finally in rural communities in green areas (where there were 5 to 10 infected individuals/km²) (Fig. 3A). This strategy would ensure universal coverage in all urban areas in all 10 health care districts and in the largest rural communities in the country. Under this strategy, TasP would not be used in the gray and white areas of the DOI map.

Implementing the optimal TasP-based elimination strategy in a decentralized health care system

Lesotho has, as do many other countries in sub-Saharan Africa, a decentralized health care system. When using TasP for elimination, decisions will need to be made regarding how to divide the available treatment supply among the health care districts. To design an optimal treatment allocation strategy for Lesotho, we constructed an ECC plot for each of the 10 districts. The ECC plot for the most urbanized district, Maseru, is shown in Fig. 5B; the ECC plot for one of the most rural districts, Mokhotlong, is shown in Fig. 5C. The ECC plots for the eight other districts are shown in fig. S3. The variation in the shape of the 10 curves (Fig. 5, B and C, and fig. S3) reflects differences among the districts in the urbanization of their epidemic (shown by the red data) and the degree of geographic dispersion of HIV-infected individuals in their rural areas (shown by the blue data). These differences reflect the variation, among the districts, in spatial demographics (that is, in the dispersion pattern and size of rural and urban settlements), as well as in the geographic variation in population density.

To implement the optimal TasP-based elimination strategy (that is, to optimize the efficiency of resource utilization), the treatment supply
should be divided among districts on the basis of the geographic dispersion pattern of HIV-infected individuals throughout the country. Because of the substantial differences among districts in their spatial demographics, optimizing efficiency would result in considerable variation in district-specific coverage. This is shown by the dotted black lines in the 10 ECC plots (Fig. 5, B and C, and fig. S3); these results are based on using UNAIDS's minimum elimination coverage of ~70%. District-specific coverage would vary from a minimum of 4% in the most rural district, Thaba-Tseka (fig. S3H), to a maximum of 94% in the most urbanized district, Maseru (Fig. 5B). Coverage would be low in Thaba-Tseka because very few individuals live in urban areas and rural settlements are small and widely dispersed. Coverage would be high in Maseru because ~40% of the population in this district lives in urban areas and rural settlements are relatively large and clustered.

Comparing the optimal and current treatment allocation strategies

The current strategy for allocating treatment among health care districts has the objective of achieving treatment equity. Under this strategy, spatial demographics are not considered. The treatment supply is divided among the districts in proportion to the burden of disease, that is, in proportion to the number of HIV-infected individuals in each district. Under this strategy, the treatment coverage in every district would be the same as the national coverage. This is shown by the dotted green lines in the 10 ECC plots (Fig. 5, B and C, and fig. S3); these results are based on using UNAIDS's minimum elimination coverage of ~70%.

The amount of treatment that each district would receive would depend on which allocation strategy was used to implement the TasP-based elimination strategy. The six most rural districts would receive more treatment under the current allocation strategy (shown by the dotted green lines in Fig. 5C and fig. S3, D to H) than under the optimal allocation strategy (shown by the dotted black lines in Fig. 5C and fig. S3, D to H). Conversely, the four most urbanized districts would receive more treatment under the optimal allocation strategy (shown by the dotted black lines in Fig. 5B and fig. S3, A to C) than under the current allocation strategy (shown by the dotted green lines in Fig. 5B and fig. S3, A to C).

Evaluating the feasibility of the UNAIDS 90-90-90 elimination strategy

The national ECC plot (Fig. 5A), coupled with the DOI map (Fig. 3A), shows that achieving UNAIDS goals may not be possible in Lesotho, even if the optimal treatment allocation strategy was used. To reach the 90% diagnosis goal would require finding many HIV-infected individuals who are living in widely dispersed rural settlements, where there may be only 2 infected individuals/km² (Figs. 3A and 5A). To treat 90% of these diagnosed individuals would require treating many who are living in fairly inaccessible rural areas, where there may be as few as 4 infected individuals/km² (Figs. 3A and 5A). Even reaching a treatment coverage of ~70% (the minimum, according to UNAIDS, needed for elimination) may not be feasible (Fig. 5A). Notably, to achieve universal access to treatment, as proposed by WHO (1), would require treating many individuals in areas where there is likely to be only 1 infected individual/km² (Figs. 3A and 5A).

Fig. 3. Results showing the geographic dispersion of HIV-infected individuals throughout Lesotho. (A) DOI map shows the dispersion pattern and the geographic variation in the number of HIV-infected individuals (15 to 49 years old) per square kilometer: white (≤1), gray (1 to 5), green (5 to 10), yellow (10 to 100), and red (>100). (B) Histogram shows the distribution of the HIV epidemic (number of HIV-infected 15- to 49-year-old individuals) as a function of the DOI. The color code is the same as in (A). (C) Histogram shows the distribution of the population (15 to 49 years old) and the prevalence of HIV as a function of the DOI: purple data represent HIV-infected individuals, gray data represent uninfected individuals, and red dots represent HIV prevalence.
Evaluating the potential success of the UNAIDS 90-90-90 elimination strategy

The success of any TasP-based elimination strategy will depend, in part, on migration rates and population mobility. TasP will not be an effective elimination tool if individuals “import” HIV into or “export” HIV out of their home communities. We assessed the potential for individuals to have sex partners outside their home communities by constructing two nationwide connectivity maps and a mobility map (see Materials and Methods for a description of how the maps were constructed). Both the connectivity maps (Fig. 6, A and B) and the mobility map (Fig. 6C) show the potential for people to have sex partners from outside their home community. The connectivity maps show that many families are geographically separated on a temporary basis: ~40% had a household member living part time in another region of Lesotho (Fig. 6A), and ~30% had a household member living part time in South Africa (Fig. 6B). The two maps show distinct geographic patterns that differ based on where the household member (who was away from their home community) was living. The mobility map shows that the population is very mobile (Fig. 6C): Overall, ~50% of 15- to 49-year-old individuals had made one or more overnight trips in the past 12 months. Notably, travel was extremely high along the border with South Africa.

DISCUSSION

By viewing the HIV epidemic in Lesotho within a demographic context, we have gained a greater understanding of one of the most severe HIV epidemics in sub-Saharan Africa. Although there is relatively little geographic variation in HIV prevalence throughout the country, the DOI varies over two orders of magnitude. The geographic dispersion pattern of HIV-infected individuals reflects the spatial demographics of the country and highlights the importance of the urban-rural divide. Only ~20% of the epidemic is concentrated in the urban centers. The vast majority of HIV-infected individuals live in small, widely dispersed, rural settlements. Notably, most rural settlements appear to contain at least one infected individual, even those in the most remote mountainous regions.

The spatial diffusion of the epidemic reflects the high mobility of the population and the high levels of circular and cross-border migration. Temporary migration in Lesotho is related to employment; there is circular migration within the country to work in agriculture or the textile industry and cross-border migration to work in the mines in South Africa. Previous studies of Lesotho have shown that (on average) residents who travel have higher numbers of sex partners than those who do not and that men who travel frequently have an increased risk of HIV infection (17). Permanent migration may also have facilitated the spatial diffusion of HIV. In Lesotho, between 2001 and 2011, ~45% of the population changed their permanent residency (18), moving from rural areas to urban centers, or within urbanized regions. The high mobility of the population and high migration rates are likely to be important in driving ongoing transmission. These factors and the high degree of connectivity with South Africa will increase the difficulty of eliminating HIV in Lesotho.

To date, TasP has only been shown to be effective in preventing HIV infections in one clinical trial (5) and in a few real-world settings (6, 7).

Fig. 4. Geographic dispersion pattern of HIV-infected individuals in each health care district. Histograms show the distribution of the population (15 to 49 years old) in Lesotho health care districts as a function of the DOI: purple data represent HIV-infected individuals, and gray data represent uninfected individuals. (A) Maseru, (B) Leribe, (C) Berea, (D) Mafeteng, (E) Mohale’s Hoek, (F) Mokhotlong, (G) Butha-Buthe, (H) Quthing, (I) Qacha’s Nek, and (J) Thaba-Tseka health care districts.

Four clinical trials in South Africa and Zambia are studying the effectiveness of TasP in decreasing the incidence of HIV (19). One study has reported preliminary results: TasP was not found to be effective in reducing incidence, but treatment coverage only reached 40% (20). There are many reasons that TasP may not be effective in controlling HIV epidemics in sub-Saharan Africa: Resource constraints may limit the treatment supply (and hence the achievable coverage levels), viral suppression rates may not be great enough, and mobility/migration may result in the continuous importation/exportation of HIV into/out of communities within a country or between countries. However, the decision to use TasP has already been made (1, 2), and TasP will soon be rolled out in sub-Saharan Africa (21). As a consequence, our study focuses on the design and evaluation of potential elimination strategies and the feasibility of the UNAIDS 90-90-90 elimination program.

Even if TasP is ineffective in reducing the incidence of HIV in sub-Saharan Africa, rolling out TasP will be extremely beneficial for those who receive treatment in that they will gain a substantial increase in life expectancy (22). The number of individuals who will directly benefit from the rollout will be determined by the level of resource constraints, but not by the treatment allocation strategy. Both our treatment allocation strategy and the current allocation strategy will cause the same overall reduction in the AIDS mortality rate at the national level. However, using our strategy rather than the current strategy would result in lower AIDS mortality rates in the more urbanized health care districts and higher rates in the most rural health care districts. This would exacerbate the already significant urban-rural disparities in health care. Notably, the optimal strategy that we have identified is likely to be more cost-effective (in terms of costs per life-year saved) than the current strategy because it would make it easier to find, diagnose, and treat individuals and would require an overall smaller catchment area for treatment programs. In addition, if TasP is effective, implementing the rollout using our strategy may be more likely to succeed in eliminating HIV than using the current allocation strategy, because TasP may be more effective at a high DOI than at a low DOI.

Our geostatistical framework can be used to design implementation strategies for other types of interventions for controlling HIV epidemics in sub-Saharan Africa, for example, circumcision (23–25) and pre-exposure prophylaxis (26). It could be used to evaluate their feasibility, as well as improve their efficiency and cost-effectiveness. Additionally, it could be used for increasing the efficiency and cost-effectiveness of large-scale HIV testing campaigns. Our approach identifies both the geographic dispersion pattern of HIV-infected individuals and the number of uninfected individuals living in close proximity to them. Consequently, it could be used to decide which of the available prevention modalities (including TasP) are most appropriate for each community. The DOI map that we have developed for Lesotho highlights the necessity of developing new prevention tools for uninfected individuals living in inaccessible areas of the country, or where the DOI is low and mobility/migration rates are high.

Many other countries in sub-Saharan Africa have severe HIV epidemics, similar spatial demographics to Lesotho, and a significant percentage of their population living in rural areas (table S1); many also have highly mobile populations and high rates of circular migration (27–29). The data that are necessary to construct DOI maps and ECC plots for 24 of these countries are publicly available (30). The geographic dispersion pattern of HIV-infected individuals in each country is likely to vary because of country-specific differences in epidemiology and spatial demographics. However, the dispersion patterns may be
qualitatively similar (in terms of the urban-rural divide) to the pattern in Lesotho. The DOI maps and ECC plots for the 24 countries could be used in the same manner as we have shown for Lesotho. By analyzing the specific patterns, it could be determined in which, if any, of these countries TasP could succeed in eliminating HIV. Additionally, our approach could be used to develop achievable country-specific diagnosis and treatment coverage goals.

As with all studies, ours has limitations. It is not possible to obtain a quantitative assessment of the accuracy of the ESP map (16), that is, to generate a map of standard errors. Methods to generate such maps are under development (31). The ESP map is based on spatially smoothing prevalence data; therefore, the degree to which the data are smoothed is important. The map is likely to be imprecise if prevalence is low. In the case of Lesotho, the ESP map is likely to be fairly accurate because the data are smoothed on the basis of a sample size of 200 individuals (see Materials and Methods), and prevalence is very high throughout the country. The ESP map that we have generated, to construct our DOI map, shows the prevalence of HIV infection in adults (that is, in both women and men) who are between 15 and 49 years old. Elsewhere, we have shown that gender-based HIV ESP maps of Lesotho differ both quantitatively and qualitatively (32). Their spatial patterns differ, and HIV prevalence is always substantially higher in women than in men. Consequently, the associated gender-specific DOI maps would also be considerably different. This demonstrates that it would be essential to construct gender-specific DOI maps if the objective is to develop health policies for gender-based prevention tools, for example, vaginal microbicides. Notably, we have analyzed the most up-to-date data sets that were available: spatial demographic and HIV testing data from 2010. However, more recent demographic data will soon become available. The Bureau of Statistics in Lesotho has just completed the 2016 census; data from this census will be used to update the spatial demographic estimates in the WorldPop database. In addition, HIV testing data from the 2014 Lesotho Demographic Health Survey will soon become available. HIV prevalence is unlikely to have changed significantly over 4 years, but some small settlements in remote areas have been reported to have been abandoned in the past few years. Any demographic changes would need to be included in a DOI map before using it to make detailed health policy decisions.

Our results have implications for global health policies. UNAIDS did not consider the spatial demographics of populations in sub-Saharan Africa when they designed their TasP-based HIV elimination strategy and set their 90-90-90 treatment goals. We have evaluated the feasibility of implementing their plan in Lesotho, where one of four adults is infected with HIV. We have shown that the feasibility directly depends on the geographic dispersion pattern of HIV-infected individuals and that the pattern reflects the spatial demographics of the population. In Lesotho, infected individuals are widely dispersed, and many live in rural settlements in areas where there is a very low DOI. These conditions will make it extremely challenging to reach the diagnosis and treatment coverage goals of the 90-90-90 strategy. Resource constraints will limit the availability of treatment for TasP. However, our results show that the spatial dispersion pattern of Lesotho’s population hinders, and may even prevent, the elimination of their HIV epidemic. This may also be the case for other countries in sub-Saharan Africa that have predominantly rural populations.

MATERIALS AND METHODS

Study design

This study presents a geostatistical framework for designing and evaluating TasP-based elimination strategies in Lesotho in sub-Saharan Africa. Our framework includes two components: a country-level DOI map and ECC plots. The DOI map shows, throughout the country, the number of HIV-infected individuals per square kilometer: both diagnosed and undiagnosed individuals. An ECC is a theoretical construct that we have introduced for the study of infectious diseases; it is a semi-logarithmic plot that enables an epidemic to be characterized within a spatial demographic context. We constructed a national ECC plot for Lesotho and ECC plots for each of the 10 health care districts in Lesotho. The data from the DOI map were used to construct the ECC plots.

UNAIDS’s minimum treatment coverage goal needed for elimination

The elimination strategy proposed by UNAIDS requires diagnosing 90% of infected individuals, treating 90% of the diagnosed, and achieving viral suppression in 90% of the treated individuals. Treating ~70% of HIV-infected individuals and achieving viral suppression in essentially all of them would result in the same overall impact. Therefore, on the basis of the UNAIDS strategy, we considered ~70% as the minimum treatment coverage needed for elimination.
The WorldPop project data set

The WorldPop database contains estimates for the geographic distribution of the population in terms of population density and settlement patterns for 126 countries in Africa, America, and Asia (33). Fifty African countries, including Lesotho, are represented in the database. For our analyses, we used the alpha version of the WorldPop data set for Lesotho; this version contains 2010 estimates of the number of people/0.01 km².

The WorldPop data set for Lesotho is in the form of a raster image; that is, it is a data set of population estimates presented in a set of discrete uniform cells (pixels) that are based on a gridded surface, where each pixel on the grid represents a defined area in a specific geographic location. The WorldPop data set for Lesotho has a resolution of 100 m × 100 m.

The WorldPop database was constructed by using satellite data on surface imagery, specifically imagery on land cover patterns, to map the settlement patterns. The surface imagery data were used to reallocate the population census data to settlements; settlements in Lesotho vary from cities to small rural homesteads. Satellite data were taken from NASA’s Landsat spacecraft, which uses Enhanced Thematic Mapper imagery to monitor Earth’s land cover. The details of the methodologies used by Linard et al. (11) to construct the database are described on the WorldPop website (14). These data are available online (33).

Lesotho 2010 Demographic and Health Survey data set

The Lesotho Demographic and Health Survey (15) is a nationally representative population-level survey that was conducted between 2009 and 2010. The survey used a two-stage cluster sample design. The number and location of clusters were determined on the basis of a list of 33 enumeration areas so that the population sample was geographically proportional to the most recent census estimate. Four hundred clusters were sampled: 94 urban and 306 rural. Geographic coordinates that specify the location of each cluster were collected in the field using handheld Global Positioning System receivers; cluster locations are shown in fig. S1. Geographic coordinates were measured during the survey sample listing process or during the administration of the survey itself; further methodological details are provided online (30). Five clusters did not have geographic coordinates, so they were not used in our analyses.

After the locations for the 400 clusters had been chosen, a complete listing of households was created for each cluster. Households were then randomly selected for participation in the survey; the response rate was 94% (9391 households participated). Three types of questionnaires were used to collect data in the Lesotho Demographic Health Survey: the Household Questionnaire, the Women’s Questionnaire, and the Men’s Questionnaire.

One representative from each of the participating households completed the Household Questionnaire, where they provided data for themselves, all of the individuals who were regular members of their household, and any visitors who were staying at their house. The representative specified (for each individual) their age, gender, and relationship to the head of the household. Data were collected on 44,546 individuals (from the 9391 households), infants to 96-year-old adults; identifiers linked the data for each individual to the household (and the cluster location) where the Household Questionnaire was completed.

The Lesotho Demographic Health Survey considered an individual to be a household member if they had slept in the house the night before the survey. On the basis of this definition, 33,719 individuals (newborns to 96 year olds) were considered to be household members: 18,233 women and 15,486 men.

All of the women (between 15 and 49 years old) in the 9391 households were eligible to participate in the individual-level survey, that is, to complete the Women’s Questionnaire. This survey collected data on demographics, economics, behavior, and health; 98% of the 7786 eligible women participated. Then, ~50% of the 9391 households were randomly selected. All of the men in the selected households (between 15 and 59 years old) were eligible to participate in the individual-level survey, that is, to complete the Men’s Questionnaire. Ninety-five percent of the 3493 eligible men participated in the individual-level survey.

In the households where men were interviewed, all 15- to 59-year-old men and all 15- to 49-year-old women were eligible for HIV testing; 94% of the eligible women and 88% of the eligible men were tested. This resulted in a total of 7099 HIV test results: 3928 from women and 3171 from men. For each individual, their HIV test result was linked to their data collected in the individual- and household-level surveys. The testing data were georeferenced by using the geographic coordinates for the cluster location. A more detailed description of the Lesotho Demographic Health Survey data sets and HIV testing data can be found elsewhere (12). These data are also available online (15).

Estimating the number of HIV-infected individuals

We estimated the number of individuals aged 15 to 49 years old and then multiplying this number by the average HIV prevalence level in Lesotho. We calculated the number of 15- to 49-year-old individuals by multiplying the total number of individuals of all ages living in Lesotho (from the WorldPop database) with the proportion of individuals who are aged 15 to 49 years (from the 2010 census data). We estimated the average HIV prevalence in Lesotho from the HIV testing data collected in the 2010 Lesotho Demographic Health Survey. Using this procedure, we estimate there were 228,384 (mean; 95% CI, 213,540 to 243,229) HIV-infected individuals (15 to 49 years old) living in Lesotho. This includes both diagnosed and undiagnosed individuals.

Notably, it has been shown using Heckman-type selection models (34) that HIV prevalence estimates that are determined using data from the 2010 Lesotho Demographic Health Survey are not susceptible to selection bias. They do not need adjusting to account for nonparticipation in testing; this is due to the extremely high response rate (94% of eligible women and 88% of eligible men were tested for HIV).

Constructing the DOI map

We first constructed a high-resolution demographic map of Lesotho by plotting gridded data from the WorldPop project (33). Next, we constructed a second map by plotting age structure data from the 2010 census; data were stratified at the level of the health care district and subsequently between urban and rural areas. Then, we constructed the ESP map; we used the HIV testing data from the Lesotho Demographic Health Survey and spatial interpolation techniques (16). All three maps were saved as raster images. To construct the DOI map, we used raster multiplication to combine the three maps; this procedure was performed in ArcGIS (using the ArcMap Advanced 10.1 software) (35) and R (36).

Constructing the ESP map

We generated the ESP map by using an adaptive bandwidth kernel density (ABKD) estimation method (16) to smooth spatially and interpolate georeferenced HIV testing data from 7099 individuals (15 to 49 years old) who participated in the 2010 Lesotho Demographic Health Survey; the bandwidth specifies the degree of smoothing. Each individual is linked by an identifier to one of the households in one of the
clusters in the data set. The ABKD estimation method was used to smooth the localized HIV prevalence around each cluster (16).

The ESP map is defined, when using the ABKD estimation method, as a density surface. The ABKD method prevents undersmoothing in areas with sparse observations and oversmoothing in areas with many observations. We used the R programming package preVR for implementation (36). This software package was first used to construct an intensity surface for the infected population and an intensity surface for the total population (that is, infected and uninfected individuals). It was then used to generate the ESP map by dividing the intensity surface for the infected population by the intensity surface for the total population. The intensity \( \hat{s}(x, y) \) (that is, the number of individuals per unit area) at spatial location \((x, y)\) is determined by the following equation:

\[
\hat{s}(x, y) = \sum_{i=1}^{N} \frac{1}{h_i^2} K\left( \frac{d_i}{h_i} \right)
\]

where \(N\) is the number of individuals included in the smoothing circle, \(d_i\) is the geometric distance between cluster \(i\) and the geographic location point \((x, y)\), \(K\) is the kernel density function, and \(h_i\) is the smoothing bandwidth used at cluster \(i\). A two-dimensional Gaussian function is used for the kernel density function. The smoothing bandwidth \(h_i\) used at cluster \(i\) is proportional to the radius \(r\) of the smoothing circle that is drawn around cluster \(i\) to encompass \(N\) individuals. We used an \(N\) of 200. The size of the smoothing circles reflects population density. With an \(N\) of 200, the smoothing circle around each cluster encompasses at least four clusters and, even when prevalence is low (~10%), encompasses at least 20 infected individuals.

### Constructing the national-level ECC plot

We used the DOI map to obtain estimates \(\phi_k\) for the number of 15- to 49-year-old HIV-infected individuals in each square kilometer of the country. These were ordered from low to high as \(\phi(1), \phi(2), \ldots, \phi(n)\). The ECC was then constructed by plotting \(c_j\) for \(j = [0, \phi(n)]\) on a semi-logarithmic scale, where

\[
c_j = 100 \left( \frac{1}{l} \right) \sum_{k=1}^{n} \phi(k)
\]

and

\[
l = \sum_{k=1}^{n} \phi(k)
\]

### Constructing the connectivity and mobility maps

To construct the connectivity maps, we used data from the 2010 Lesotho Demographic Health Survey and spatial interpolation techniques (16) to map the percentage of individuals (15 to 49 years old) who had made one or more overnight trips in the past 12 months.

### Supplementary Materials

[Online content](http://stm.sciencemag.org/cgi/content/full/9/383/eaag0019/DC1)


17. L. Palk, S. Blower, Mobility and circular migration in Lesotho: Implications for trends of HIV prevalence from Demographic and Health Surveys (DHS).

18. L. Palk, S. Blower, Mapping divided households and residency changes: The effect of couple separation on sexual behavior and risk of HIV infection.

Using geospatial mapping to design HIV elimination strategies for sub-Saharan Africa
Brian J. Coburn, Justin T. Okano and Sally Blower

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Mapping a path to HIV elimination
About ~25 million individuals in sub-Saharan Africa are living with HIV. In new work, Coburn et al. design HIV elimination strategies for this region. The authors focused on Lesotho, where ~25% of the population is infected with HIV. They combined several large data sets and constructed a map that revealed the countrywide geographic dispersion pattern of HIV-infected individuals. They estimated that ~20% of the population lives in urban areas, and almost all rural communities have at least one HIV-infected individual. Their analyses showed that the spatial dispersion of Lesotho’s population hinders, and may even prevent, the elimination of HIV. This may hold true for other predominantly rural countries in sub-Saharan Africa.