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Geospatial and Temporal Analysis of HIV Prevalence and Progress Towards the UNAIDS 95–95–95 Targets in Six sub-Saharan African Countries

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Tables 1 to 3 are available in the Supplementary Files section.

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Abstract

Background: HIV/AIDS remains a major public health challenge worldwide, and sub-Saharan Africa (SSA) continues to bear the greatest burden. In 2020, UNAIDS set treatment continuum targets for HIV status awareness, receipt of antiretroviral therapy (ART), and viral load suppression (VLS) (95–95–95). However, comparable multi-country evidence of subnational geographic variation over time remains limited. Our study aimed to: (1) demonstrate the spatial distribution and temporal changes in HIV prevalence and progress toward the UNAIDS 95–95–95 targets across six SSA countries; and (2) identify geographic clusters of HIV prevalence and gaps in UNAIDS 95–95–95 indicators using spatial autocorrelation and hotspot analyses.

Methods: We analyzed data from Population-based HIV Impact Assessment (PHIA) surveys conducted in Eswatini, Lesotho, Malawi, Tanzania, Uganda, and Zimbabwe. Data from two survey rounds were included: PHIA1 (2015–2019) and PHIA2 (2020–2023). Gaussian kernel smoothing was used to map the spatial distribution of HIV prevalence and UNAIDS 95–95–95 indicators. Global Moran's I and Local Indicators of Spatial Association (LISA) were used to assess spatial autocorrelation and identify spatial clusters (hotspots and coldspots) and outliers.

Results: Aggregate HIV prevalence across the six countries decreased from 7.6% in PHIA1 to 6.9% in PHIA2. Eswatini had the highest HIV prevalence, followed by Lesotho. Progress was observed across all three UNAIDS indicators at the national level; however, spatial heterogeneity persisted within countries. The spatial distribution of UNAIDS 95–95–95 indicators became more uniform over time in most countries, whereas subnational variation in HIV prevalence persisted. In contrast, Uganda showed marked regional variation. Hotspot analyses showed that

HIV prevalence clusters remained relatively stable, whereas spatial clusters and outliers for gaps in the HIV care continuum shifted geographically between survey rounds.

Conclusions: The two PHIA survey rounds, conducted about five years apart, showed geographical and temporal heterogeneity in HIV prevalence and progress toward the UNAIDS targets. Across all countries, our analysis identified persistent and shifting gaps in HIV diagnosis, treatment, and VLS, highlighting the need for targeted interventions and subnational monitoring to accelerate progress toward ending HIV.

Keywords: HIV, sub-Saharan Africa, UNAIDS 95–95–95, Geospatial, Antiretroviral therapy, Viral load suppression, Hotspot analysis

Background

HIV (Human Immunodeficiency Virus) or AIDS (Acquired Immunodeficiency Syndrome) remains a major public health challenge, affecting millions of people worldwide [1,2,3,4]. Globally, an estimated 40.8 million people were living with HIV in 2024, with 1.3 million people newly infected with HIV in that year [1,2,3]. Africa remains the most affected, with 26.3 million people living with HIV (PLWH), and 650,000 new infections in 2024 [1,2,3]. Notably, sub-Saharan Africa (SSA) bears a disproportionate burden, accounting for two-thirds of all PLWH and about half of new infections worldwide [1,4,5]. Globally, HIV prevalence rate among individuals aged 15 years and older was estimated at 0.7%, with particularly higher levels in eastern and southern Africa (6.0%) and western and central Africa (1.2%) [1,2,5]. To address this ongoing epidemic, the Joint United Nations Programme on HIV/AIDS (UNAIDS) established the ambitious 95–95–95 targets for 2025, which aimed for at least 95% of PLWH to know their status, at least 95% of those diagnosed to receive sustained antiretroviral therapy (ART), and at least 95% of those on treatment to achieve viral load suppression (VLS) [1,5]. Achieving these targets for UNAIDS indicators is considered a key milestone for ending AIDS as a public health threat by 2030 [1]. By 2024, global progress toward these targets reached approximately 87–89–94 across testing, treatment, and VLS [1,5]. Countries in eastern and southern Africa have made substantial progress (93–91–95), but countries in western and central Africa are far from achieving those targets (81–94–92) [1,2,3,5].

Although several countries in SSA have made substantial progress in achieving these targets, high-burden settings are particularly vulnerable to gaps in the HIV care continuum (pathway from HIV diagnosis to treatment and VLS) [1,6,7,8]. National-level estimates can obscure substantial variation within countries, masking localized differences in HIV prevalence

and UNAIDS targets [9,10,11,12]. These disparities often vary widely across geographic areas and are influenced by a combination of structural, socioeconomic, and health system factors, such as unequal access to healthcare, stigma, poverty, and differences in program implementation [10,13,14,15]. As a result, certain subnational areas may experience disproportionately high HIV prevalence or lower engagement in care, limiting overall progress toward epidemic control [9,10,11]. Hence, understanding the spatial distribution of HIV burden and the UNAIDS indicators is essential for guiding more targeted public health responses [10,16]. Geospatial analytical methods have therefore become increasingly used to uncover localized patterns of disease burden and service coverage that are not apparent in aggregated data [10,16,17,18,19].

Geospatial analysis refers to techniques used to collect, visualize, and explore data that have a geographic or location-based component [17,20]. In public health research, these methods are used to examine how health outcomes are distributed across space, explore potential drivers of disease patterns, and inform the design of targeted interventions [17,21]. Mapping the spatial distribution of HIV prevalence and the UNAIDS indicators has become increasingly important for identifying populations and locations with unmet needs, improving allocation of limited health resources, and understanding spatial heterogeneity in both disease burden and service coverage [18,19,21,22]. In the context of SSA, applying geospatial approaches to identify spatial distribution patterns of HIV prevalence and UNAIDS indicators is particularly valuable for identifying areas with higher or lower burden and for highlighting geographic outliers that may require focused interventions, and also could help prevent new HIV infections by scaling up resources to high-burden areas [9,18,19,22]. Despite its importance, the spatial distribution of HIV and related service coverage in SSA is not yet fully understood [16,18,19,23,24].

Previous studies have shown substantial spatial heterogeneity in HIV prevalence and UNAIDS indicators [10,19,21,22,23,24,25]. However, most of this evidence is based on single-country analyses, which limits the ability to compare patterns across different settings [10,21,22,23,24,25]. While those studies have identified localized hotspots (a geographic area with a high rate surrounded by areas of high rates) and spatial clustering, broader multi-country patterns in HIV burden and UNAIDS indicators remain insufficiently explored [10,19,22,23,25]. To address this gap, our study uses geospatial analytical approaches to examine changes in HIV prevalence and UNAIDS indicators across multiple countries in SSA. This approach is particularly relevant given population mobility and the complex social and transmission networks that shape the HIV epidemic [18,19]. Our study aimed to: (1) demonstrate the geospatial distribution of HIV prevalence and progress toward the UNAIDS 95–95–95 indicators across six SSA countries; and (2) to identify geographic clusters of HIV prevalence and gaps in UNAIDS indicators using spatial autocorrelation and hotspot analyses and evaluate changes over time.

Material and Methods

Study design

We used data from the Population-based HIV Impact Assessment (PHIA) survey conducted in high-HIV burden countries in SSA [26]. The PHIA surveys are nationally representative and funded by the U.S. President's Emergency Plan for AIDS Relief and technically supported by the International Center for AIDS Care and Treatment Programs (ICAP) at Columbia University through the U.S. Centers for Disease Control and Prevention (CDC) in collaboration with ministries of health in each country [26]. The surveys are conducted in two phases, with phase 1 (PHIA1) carried out between 2015 and 2019 and phase 2 (PHIA2) carried out between 2020 and

2023 [26]. We used data from six SSA countries: Lesotho, Malawi, Eswatini, Tanzania, Uganda, and Zimbabwe. Our analysis included participants aged 15 years and older. Each phase has an independent population sample. Each survey used a two-stage stratified cluster sampling design to produce estimates representative of PLWH at national and subnational levels [26]. In the first stage, enumeration areas (EAs) were selected using probability proportional to population size. In the second stage, a sample of households was randomly selected within each EA [26]. All eligible individuals (aged 15 years and older) who spent the night before the survey in a selected household were invited to participate. The geospatial dataset for each PHIA survey contains a unique cluster identifier, latitude, and longitude information [27]. The geographic coordinates for each cluster centroid have been geomasked using a spatially adaptive random perturbation method [27].

Survey questionnaire

The PHIA surveys used standardized and structured questionnaires to collect nationally representative data across participating countries. In each selected household, a household questionnaire was first completed by the head of the household or a designated representative to gather data on household residents, assets, socio-economic characteristics, and mortality [26]. Eligible individuals were then invited to participate in individual interviews, which included a questionnaire on sociodemographic characteristics, HIV-related knowledge and behaviors, history of HIV testing, marital status, alcohol use, access to HIV care, and treatment [26]. All survey materials, including questionnaires, were translated from English into local languages [26].

Study outcome and covariates

The study outcomes were HIV prevalence and progress toward the UNAIDS 95–95–95 targets. HIV prevalence was defined as the proportion of adults who tested positive for HIV among all participants who were interviewed and tested. The first 95 of the UNAIDS indicators was the proportion of PLWH who were aware of their HIV-positive status, based on self-reported HIV-positive status, the presence of antiretroviral drugs in their blood sample, or both. The second 95 was the proportion of PLWH who were aware of their status and were receiving ART, as determined by self-report, the presence of antiretroviral drugs in their blood sample, or both. The third 95 was the proportion of those on ART who had VLS, defined as less than 1,000 HIV RNA copies per milliliter of blood. The covariates considered were socio-demographic variables (age, gender, and urban/rural residence) and socioeconomic factors (highest level of education, socioeconomic status [SES], employment status, and marital status).

Statistical analysis

We summarized the data using descriptive statistics. Continuous variables were reported as medians with interquartile ranges (IQRs), while categorical variables were presented as frequencies and percentages. All estimates accounted for the complex survey design using sampling weights and jackknife variance estimation. Statistical analyses were conducted in R (4.5.3) [28]. Interactive visualizations were developed using the Shiny package in R [29] to facilitate exploration of spatial patterns across countries, indicators, and survey rounds (https://rajasanjeevkumar.shinyapps.io/Geospatial/). In this manuscript, we present Uganda as an example to demonstrate how to interpret the findings for all the countries on the dashboard.

Geospatial analysis

Geospatial analyses were conducted using EA coordinates (latitude and longitude) provided in the PHIA datasets. Spatial analyses focused on HIV prevalence and the three UNAIDS 95–95–95 indicators. To visualize the geographic distribution of these indicators, Gaussian kernel smoothing with an adaptive bandwidth was applied to generate continuous surface maps [30].

Spatial autocorrelation for HIV prevalence and gaps (HIV status unawareness among PLWH, lack of ART coverage among those aware of their HIV status, and viral non-suppression among participants on ART) in the HIV care continuum was assessed using Global Moran's I, and Local Indicators of Spatial Association (LISA) [31,32,33]. Global Moran's I was first calculated to determine whether the spatial distribution of each indicator was clustered, dispersed, or randomly distributed across each country. A first-order Queen contiguity matrix was used to define neighboring administrative units, where districts sharing either a common boundary or vertex were considered neighbors [31,32]. The significance of spatial autocorrelation was evaluated using 999 Monte Carlo permutations under the null hypothesis of complete spatial randomness [32]. For each indicator, Global Moran's I was calculated, and the value ranged from −1 to +1. A positive spatial autocorrelation indicates that neighboring areas have similar values (spatial clustering), whereas a negative spatial autocorrelation indicates that neighboring areas have dissimilar values (spatial dispersion), and values close to zero indicate a random spatial pattern [32]. Statistical significance was assessed using Moran's I test, with $p < 0.05$ considered statistically significant [32]. The Global Moran's I is expressed by the formula:

$$I = \frac{N}{\left(\sum_i \sum_j w_{ij}\right)} * \frac{\sum_i \sum_j w_{ij} \left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{\sum_i \left(X_i - \bar{X}\right)^2}$$

Where N is the number of spatial units indexed by i and j; X is the variable of interest, $\bar{X}$ is the mean of the sample means computed within each spatial unit; and w_{ij} represents the coefficient of the spatial weight matrix with index (i,j) [32].

We then used LISA to measure local spatial autocorrelation and locate clusters of neighborhoods with relatively high or low rates at the second administrative level within each country [33]. LISA statistics classified each neighborhood with a significant local LISA statistic at the $p<0.01$, $p<0.05$ and $p<0.10$ levels into four categories: high–high cluster (hotspot which is a geographic area with a high rate surrounded by areas of high rates), low–low cluster (coldspot which is a geographic area with a low rate surrounded by areas of low rates), low–high (geographic area with a low rate surrounded by areas of high rates) and high-low (geographic area with a high rate surrounded by areas of low rates) outliers [33]. A separate LISA analysis was performed for each survey round. It is expressed as

$$I_i = z_i \sum_j w_{ij} z_j$$

Where z_i is the value of the variable x_i in standardized form, and w_{ij} is the spatial weight.

Separate hotspot analyses were conducted for HIV prevalence and gaps in the HIV care continuum. The results were displayed as cluster maps to identify regions with high HIV burden and gaps across the HIV care continuum. All spatial analyses were performed using the R packages sf, spatstat, spdep, and geobounds [34,35,36,37].

Results

Our analysis included a total of 250,794 participants from six SSA countries across the two PHIA survey rounds, with 122,907 from PHIA1 and 127,887 from PHIA2. The median age of

participants was similar across the two survey rounds (PHIA1: 29 years [IQR: 21–41]; PHIA2: 30 years [IQR: 21–43]). In both rounds, more than half of the participants were female (PHIA1: 51.85% (n=71,084); PHIA2: 52.47% (n=74,827)). About one-third of participants lived in urban areas (PHIA1: 32.23% (n=38,245); PHIA2: 33.09% (n=36,112). More than half were married or cohabiting (PHIA1: 55.91% (n=68,400); PHIA2: 55.22% (n=70,499)). Over half of the participants had at least a primary level of education in both survey rounds (PHIA1:53.96% (n=60,735); PHIA2:52.52% (n=63,158)). SES was divided into five categories (from lowest to highest), with participants distributed evenly, approximately 20% in each category, in both rounds. More than half of the participants were unemployed in the 12 months before the survey (PHIA1: 56.56% (n=73,910); PHIA2: 51.39% (n=72,232)). HIV prevalence decreased slightly between the two rounds, at 7.61% (n=15,539) in PHIA1 and 6.90% (n=15,344) in PHIA2. The participants' baseline socio-demographic characteristics across all six countries and both survey rounds are summarized in Table 1.

Spatial distribution of enumeration areas

A total of 4,964 EAs were included across the six countries, with 2,749 EAs in PHIA1 and 2,215 EAs in PHIA2. Except for Tanzania, the number of sampled EAs for the remaining countries was lower in PHIA2 than in PHIA1. Figure 1 shows the distribution of EAs in Uganda, for both survey rounds. The number of sampled EAs decreased from 520 in PHIA1 to 313 in PHIA2, despite providing broad geographic coverage. The distribution of EAs for other countries can be explored through the dashboard.

National-level HIV prevalence and progress of UNAIDS 95–95–95 targets

The aggregate HIV prevalence across the six countries decreased slightly between the two survey rounds, from 7.61% (n=15,539) in PHIA1 and 6.90% (n=15,344) in PHIA2. In both rounds, the highest HIV prevalence was observed in Eswatini (26.98% in PHIA1 and 24.8% in PHIA2), followed by Lesotho (25.56% PHIA1 and 22.71% in PHIA2). In most countries, HIV prevalence either declined slightly or remained relatively stable between the two survey rounds. Female participants had higher HIV prevalence across all countries and survey rounds. Progress towards the UNAIDS 95–95–95 targets improved across all six countries in PHIA2 compared with PHIA1. However, the first 95 (awareness of HIV status among PLWH) remained below 95% in most countries despite noticeable improvements between survey rounds, and it was higher among female participants. The second 95 (ART coverage) reached or exceeded 95% in most countries during PHIA2 and showed improvement compared with PHIA1; it was similar between male and female participants overall, although slightly higher among female participants in some countries. Progress toward the third 95 (VLS) improved between survey rounds; Eswatini and Malawi achieved viral suppression above 95%. This was also similar between male and female participants across both survey rounds. Country-specific estimates for HIV prevalence and the three UNAIDS 95–95–95 targets are summarized in Table 2.

Spatial heterogeneity and temporal trends in HIV prevalence and UNAIDS targets

The spatial distribution of HIV prevalence and the UNAIDS 95–95–95 targets showed heterogeneity across subnational areas in all six SSA countries across both PHIA survey rounds. Figure 2 presents Uganda as an example, showing the geospatial distribution of HIV prevalence in PHIA1 (left panel) and PHIA2 (right panel); the highest prevalence was observed in the island areas of the Central region: above 35% in both survey rounds, although a small decline was seen

in PHIA2. In Eswatini, the highest prevalence was observed in the Lubombo and Shiselweni regions. In Lesotho, the southern districts as well as some northern areas showed high prevalence above 25% in both surveys. Tanzania showed relatively low and spatially stable prevalence across regions, usually below 20%. In Zimbabwe, higher prevalence was mainly observed in the southern provinces, while a similar pattern was observed in southern Malawi. Overall, national HIV prevalence changed only slightly between PHIA1 and PHIA2, but clear subnational differences persisted within and across countries.

For the UNAIDS first 95, the geospatial analysis showed improvement over time across all countries, although important regional differences remained. Eswatini and Lesotho showed the highest proportions of awareness, with most parts of the country above 90% in both PHIA1 and PHIA2. The largest improvements between survey rounds were observed in Tanzania, where several regions with lower awareness in PHIA1 showed substantial improvement in PHIA2, particularly in the northern, western, and southern parts of the country. Similar patterns were also observed in Zimbabwe and Malawi. In Malawi, lower awareness levels were concentrated in the Southern region during PHIA1, but these regional differences became less pronounced in PHIA2. Likewise, Zimbabwe moved from having uneven and fragmented provinces of moderate awareness in PHIA1 to high awareness in PHIA2. Whereas in Uganda, the lowest proportions of awareness were observed in the Eastern, Western, and Central regions, although improvements were still observed in PHIA2 compared with PHIA1 (Figure 3).

For the second 95, geospatial analysis showed improvements across all six countries between PHIA1 and PHIA2. By PHIA2, ART coverage exceeded 90% across most geographic areas. Compared with PHIA1, areas with low ART coverage were reduced to smaller, localized pockets in PHIA2. Despite these overall improvements, some sub-national disparities in ART

coverage remained. Low ART coverage was observed in parts of the southern part and lake-zone Tanzania, Central and Northern regions of Malawi, borders along the northern and southern parts of Zimbabwe, and in Northern, Eastern, and Central regions of Uganda (Figure 4).

For the third 95, Eswatini and Malawi achieved VLS levels above 95% across nearly all parts of the country in PHIA2. This improvement was especially noticeable in Malawi, where VLS patterns changed from uneven regional coverage in PHIA1 to a more uniform distribution in PHIA2. The other countries also showed high levels of VLS, with most areas reaching above 90%. However, some geographic disparities remained, particularly in remote and border regions. In Uganda, lower VLS persisted in the borders of the Northern and Eastern regions (Figure 5). Similar gaps were observed in the northern and eastern provinces of Zimbabwe. In Tanzania, lower VLS remained in regions bordering Lake Victoria and western regions. In Lesotho, lower VLS was mainly concentrated in the southeastern highland district of Qacha's Nek.

Spatial autocorrelation

Spatial autocorrelation of HIV prevalence and gaps in HIV care (status unawareness, not receiving ART, and lack of VLS) was assessed using Global Moran's I, and the results are presented in Table 3. In both PHIA1 and PHIA2, all indicators showed significant positive spatial autocorrelation ($p < 0.05$). A notable temporal change was observed in Malawi, where viral non-suppression did not show significant spatial clustering (Moran's $I = 0.049$, $p = 0.236$) during PHIA1, suggesting random geographic distribution. However, in PHIA2, viral non-suppression became significantly clustered (Moran's $I = 0.190$, $p = 0.039$). Overall, these results confirm the presence of spatial clustering and justify further subnational analysis to identify hotspots, cold spots, and spatial outliers.

Distribution of spatial clusters and outliers for HIV prevalence

Local spatial clustering analysis identified hotspots, coldspots, and spatial outliers across all six countries in both PHIA survey rounds. In Uganda, HIV prevalence hotspots during PHIA1 were observed in the Central and Western regions, while coldspots were observed in the Northern and Eastern regions (Figure 6). By PHIA2, hotspots expanded within the Central region, whereas coldspots became more prominent in the Eastern region. In Eswatini, HIV prevalence hotspots persisted in the eastern Lubombo region across both survey rounds, while new hotspots emerged near the border of Shiselweni and Lubombo. In Lesotho, the spatial distribution of HIV prevalence shifted over time from the eastern highlands toward the northwestern lowlands. In Tanzania, HIV prevalence hotspots consistently occurred in the southern highland regions and in the Kagera region in both survey rounds. In Zimbabwe, hotspot clusters decreased substantially in PHIA 2 compared with PHIA 1, while coldspots were observed in the northern and eastern parts of the country.

Distribution of spatial clusters and outliers for gaps in the HIV care continuum

Hotspot analyses of HIV status unawareness showed notable geographic changes between survey rounds across countries. In Uganda, areas with high levels of HIV status unawareness became more widespread over time. During PHIA1, hotspots were observed in the Eastern and Central regions, whereas by PHIA2 these clusters had expanded northward (Figure 7). Many of these hotspot districts coincided with cold spots of HIV prevalence. In Eswatini, hotspots of HIV status unawareness were observed in the northern Hhohho region during PHIA1 but were no longer present in PHIA2. Conversely, the southern and eastern regions changed from coldspots in PHIA1 to hotspots in PHIA2. In Lesotho, the hotspots persisted in the southern districts across both survey rounds. In Malawi, hotspots expanded during PHIA2, particularly across

neighboring districts in the Central region. Similar to Uganda, these hotspots were largely located in regions that were coldspots of HIV prevalence. In Tanzania, the spatial distribution of HIV status unawareness shifted substantially between surveys. Hotspots that were concentrated in the western region during PHIA1 moved toward the central and northern regions in PHIA2. The Zanzibar islands remained persistent hotspots across both survey rounds, while the southern highlands transitioned to coldspots despite being hotspots for HIV prevalence. In Zimbabwe, hotspots of HIV status unawareness were observed in the northern and eastern provinces. By PHIA2, these clusters had diminished considerably, with only a few isolated hotspots remaining.

For gaps in ART coverage, Uganda showed persistent geographic clustering across survey rounds. In PHIA1, hotspots of individuals not receiving ART were observed across the Northern, Central, and Western regions (Figure 8). By PHIA2, most of these hotspots remained unchanged. New coldspots emerged along the borders of the Northern and Eastern regions. Despite some improvement, areas with low ART coverage remained concentrated in a corridor extending from the Northern to the Central regions in Uganda. In Eswatini, districts in the Hhohho region consistently appeared as outliers with low ART coverage in both survey rounds. Hotspots identified in the Lubombo and Manzini regions during PHIA1 transitioned to coldspots or outliers by PHIA2. In contrast, districts that were coldspots in Shiselweni during PHIA1 became hotspots in PHIA2. Lesotho also showed evidence of improvement in ART coverage. Mokhotlong, identified as a hotspot for low ART coverage in PHIA1, became a coldspot by PHIA2. However, new hotspots emerged in the northwestern districts. In Malawi, substantial improvements were observed between survey rounds. Distinct hotspot clusters were observed across Central and Southern regions during PHIA1. In Tanzania, geographic disparities in ART coverage became more pronounced over time. During PHIA1, hotspots were primarily located in

Arusha, Kigoma, and Tabora. By PHIA2, the hotspot in Arusha had shifted to a coldspot, while hotspots in Kigoma and Tabora expanded into neighboring Katavi, forming a larger cluster of low ART coverage in western Tanzania. In Zimbabwe, spatial clustering of low ART coverage became more evident in PHIA2. While little significant clustering was observed during PHIA1, PHIA2 revealed new spatial outliers and hotspot clusters.

In Uganda, hotspots of viral load non-suppression during PHIA1 were observed in the Western, Northern, and Eastern regions, while coldspots were located in the Western and Central regions (Figure 9). By PHIA2, coldspots expanded from the Western border through the Central regions. At the same time, hotspots became less extensive and were largely confined to the Northern and Eastern regions. A notable change was the transition of some districts in the Eastern region from coldspots in PHIA1 to hotspots in PHIA2. In Eswatini, hotspots of viral load non-suppression expanded during PHIA2. In Lesotho, hotspot clusters shifted toward the northwestern regions. In Malawi, hotspot clusters were not identified in either survey round, although coldspots and low-high outliers were observed. A low-high outlier in the Northern region in PHIA1 became a cold spot in PHIA2. In Tanzania, hotspots of viral load non-suppression became more widespread in PHIA2 compared with PHIA1. In PHIA1, these areas were relatively small and localized, but in PHIA2, larger hotspot clusters appeared in southern and northern regions. In Zimbabwe, patterns of viral load non-suppression also changed between survey rounds. During PHIA1, hotspots were observed in Mashonaland Central and Manicaland, with a high-low outlier in the Matabeleland North surrounded by cold spots. However, in PHIA2, hotspots appeared along the northern border, with high-low outliers in Masvingo and Matabeleland South.

The hotspot analyses revealed substantial spatial heterogeneity in HIV prevalence and gaps in the HIV care continuum between PHIA1 and PHIA2 across the six countries. HIV prevalence hotspots were observed in historically high-burden areas and remained relatively stable over time, although the extent and location of some clusters changed between survey rounds. In contrast, hotspot and coldspot clusters for gaps in the HIV care continuum showed greater geographic variability, like the disappearance of existing clusters and the emergence of new clusters in different regions.

Discussion

Our study used data from two rounds of the PHIA surveys to evaluate changes in HIV prevalence and progress toward the UNAIDS 95–95–95 targets across six SSA countries. The six countries showed substantial progress toward controlling the HIV epidemic. Aggregate HIV prevalence across all six countries decreased slightly from 7.6% in PHIA1 to 6.9% in PHIA2. Eswatini, followed by Lesotho, had the highest HIV prevalence in both survey rounds, with prevalence exceeding 20% in each country. This was consistent with findings from previous studies across the regions [5,38,39,40]. The high HIV burden in Eswatini and Lesotho may be influenced by a combination of behavioral, social, and structural factors, such as multiple sexual partners, inconsistent condom use, age-disparate relationships, population mobility, transactional sex, early sexual debut, gender inequality, sexual violence, low male circumcision coverage, and alcohol or substance use [38,41,42,43,44,45]. HIV prevalence was higher among female participants across all countries and both survey rounds, consistent with other studies [5,38]. This disparity could be due to gender inequalities, including biological susceptibility, differences in economic opportunities, and barriers to accessing prevention services [5,38].

Although progress was observed between PHIA1 and PHIA2 at the national level, the geospatial analyses provided additional insights beyond national estimates. The spatial heterogeneity observed for HIV burden across the six SSA countries in our study was comparable with other recent studies that used different spatial interpolation methods [9,46,47]. In most countries, high HIV prevalence was observed in southern or southeastern regions of Lubombo and Shiselweni in Eswatini; the Southern region in Malawi; and the southern highlands (Mbeya, Njombe, Iringa, Ruvuma and Kagera) in Tanzania. This was consistent with the findings from other studies across SSA [25,47,48]. Historical labor migration, cross-border population movement, transport corridors, and mining-related economies have been linked to the prevalence and persistence of HIV in these regions [46,49,50,51,52]. In contrast, in Uganda, high HIV prevalence was observed in island communities within the Central region. This could be due to the fishing communities in this region, who were vulnerable to HIV because of high population mobility, transactional sex, limited healthcare access, and economic instability, as noted in previous studies in Uganda [53,54,55].

Substantial progress was observed in the first 95 between the two survey rounds, reflecting continued expansion of HIV testing and diagnosis services in SSA. Although none of the countries achieved the 95% target at the national level, substantial improvements were observed, particularly in Tanzania, while Eswatini and Lesotho reached above 90% during PHIA2. These findings are consistent with previous studies reporting increased awareness of HIV-positive status due to the scale-up of facility-based testing, community outreach programs, HIV self-testing, home-based testing approaches, decentralization of testing services, mobile and outreach testing programs, and the integration of HIV testing into routine healthcare services, including prevention of mother-to-child transmission (PMTCT) services [56,57,58,59,60,61,62].

In most countries, the spatial distribution of HIV-positive status awareness became more uniform over time, with many regions that previously had lower levels of awareness showing considerable improvement by PHIA2. This suggests that HIV testing services have expanded beyond traditional high-coverage areas and reached populations that were previously underserved. However, some geographic disparities remained. Uganda and Tanzania continued to exhibit sub-national differences, with some regions having a lower proportion of awareness across both survey rounds. Previous studies have reported that barriers such as limited access to testing services, stigma, socioeconomic challenges, and differences in healthcare utilization continue to affect progress toward HIV-positive status awareness [13,14,15].

Considerable progress was also observed for the second 95 of the UNAIDS target between PHIA1 and PHIA2. At the national level, ART coverage exceeded 95% in all six countries by PHIA2. The geospatial analyses also showed that ART coverage improved across most regions between survey rounds. This finding is consistent with previous studies from SSA, which reported substantial improvements in ART uptake, influenced by the expansion of the WHO “treat all” strategy, decentralization of HIV services, wider implementation of differentiated service delivery models, and continued investment in national HIV programs across SSA [6,60,61,62,63,64]. Despite these improvements, some localized gaps in ART coverage remained. These disparities may be related to barriers such as long travel distances to health facilities, shortages of healthcare workers, transportation challenges, population mobility, poverty, stigma, and interruptions in HIV care services [15,65,66]. Studies from Uganda and other countries in SSA have shown that financial, logistical, and social barriers can also limit access to treatment and affect long-term retention in care [15,65]. Food insecurity and economic hardship may also reduce the ability of PLWH to initiate and maintain treatment [15]. As a result,

individuals living in remote or underserved areas often experience greater difficulties accessing and remaining engaged in HIV care, which may contribute to lower ART coverage [15,65,66]. The COVID-19 pandemic may also have contributed to treatment gaps between 2020 and 2022, lockdowns and disruptions to health services affected HIV testing, delayed ART initiation, and reduced access to routine viral load monitoring in several countries across SSA [6].

Similar progress was observed for the third 95 of the UNAIDS target. By PHIA2, Eswatini and Malawi had achieved nation-level progress above 95%, and geospatial analyses also showed many subnational areas having high levels of viral suppression. The shift from fragmented spatial patterns in PHIA1 to more uniform geographic coverage in PHIA2, particularly in Tanzania, Uganda, and Zimbabwe, could be influenced by improvements in treatment effectiveness, retention in care, and continuity of HIV services [7,64,66,67,68]. These improvements were associated with the expansion of ART programs, improvements in patient monitoring, differentiated service delivery models, and strengthened HIV care systems across the region [6,60,61,62,63]. Nevertheless, geographic disparities persisted in some remote, border, and hard-to-reach regions, including northern and eastern parts of Zimbabwe and Uganda, communities surrounding Lake Victoria, western and southern parts of Tanzania, and southeastern parts of Lesotho. Similar geographic inequalities have been reported in previous studies and may reflect barriers such as long travel distances to health facilities, shortages of healthcare workers, interruptions in treatment access, population mobility, and challenges with long-term adherence to ART [13,14,52,53,54,55,66].

Our hotspot analyses also showed that important subnational disparities remained across the HIV prevalence and gaps in the HIV care continuum. Notably, some clusters of coldspots for HIV prevalence became hotspots for HIV status unawareness during PHIA2, including the

Central region in Malawi, northeastern parts of Tanzania, and Northern and Eastern regions in Uganda. Similar findings have been reported in previous studies, which highlighted that HIV testing programs are often concentrated in high-burden areas, while some lower-prevalence regions continue to experience gaps in HIV diagnosis and testing services [56,57,59,67]. In contrast, sub-national parts in Eswatini and Lesotho showed overlap between hotspots of HIV prevalence and HIV-positive status unawareness, indicating that some high-burden regions still face challenges [67]. In Uganda, hotspots of HIV status unawareness overlapped with hotspots of no ART coverage and viral load non-suppression. This was consistent with previous studies in the region that highlighted multiple barriers to accessing HIV care [54,55,61]. On the other hand, some high-prevalence regions, such as the southern highlands of Tanzania, showed fewer hotspot clusters for no ART coverage, which may reflect the successful expansion of HIV treatment services [13]. These differences suggest that barriers to HIV care were not uniform and may be influenced by factors such as healthcare access, service availability, treatment adherence, and program implementation [14,15,58]. Importantly, the geospatial analyses demonstrated that national-level improvements did not always translate into equitable progress across all regions.

Practical and policy implications

Our study identified substantial spatial heterogeneity for both HIV burden and progress along the 95–95–95 targets across the six SSA countries. Our findings suggest that national-level indicators alone can hinder substantial local gaps in HIV testing, treatment, and viral suppression. In some regions with high HIV prevalence, gaps in the care continuum were still present, while some low-prevalence regions also showed high unawareness and low ART coverage. These indicate that HIV programs should be tailored to the sub-national level rather than using the same approach everywhere. The clusters of hotspots for HIV-positive status

unawareness, low ART coverage, and viral non-suppression can help guide more targeted public health responses. These regions may benefit from stronger community-based HIV testing, better linkage to care, and improved support for people on treatment to stay in care and maintain VLS. In addition, some of the hotspots were located near borders and major migration routes, suggesting the importance of cross-border and mobile population interventions. Comparing the two PHIA survey rounds, conducted about five years apart, showed heterogeneity in HIV prevalence and progress toward the 95–95–95 targets at the sub-national level across geography and time. Our findings highlight the need for regular subnational monitoring to track where progress is being made and where additional efforts are still required. Such information can help policymakers focus resources more effectively and ensure that all regions benefit equally from HIV programs.

Strengths and limitations

Our study has several strengths. First, we used large population-based data from six SSA countries, including two rounds of surveys conducted about five years apart. This allowed us to assess changes in HIV burden and progress across the HIV care continuum over time at both national and subnational levels. Second, HIV status, ART coverage, and VLS were primarily based on biomarker measurements rather than self-reported information, reducing the risk of reporting bias. Third, the use of geospatial methods allowed us to identify important subnational differences in HIV burden and progress across the HIV care continuum that would not have been evident from national estimates alone. Hotspot analyses further showed temporal shifts in clusters (hotspots, coldspots) and identified persistent spatial outliers. Certain limitations should also be considered when interpreting the findings. First, the PHIA surveys are cross-sectional; therefore, causal relationships cannot be established. The two survey rounds represent different

samples from the population rather than the same individuals followed over time. Second, our analysis was restricted to participants aged 15 years and older, which may limit generalizability to younger populations. Third, ART coverage was based on the detection of first- and second-line regimens and may not have identified all individuals receiving treatment, which could have led to underestimation of both awareness and ART coverage. Fourth, our spatial analyses were conducted at the second administrative level and may not capture smaller geographic differences within districts. Furthermore, PHIA geographic coordinates were intentionally displaced to protect participant confidentiality. Although this displacement is generally small, it may affect the precise location of some spatial clusters and outliers. Finally, while the PHIA surveys provide population-based estimates, they were not specifically designed for small-area estimation. As a result, some local estimates may be less precise, particularly in areas with small sample sizes.

Conclusion

Our study analyzed the geospatial distribution of HIV prevalence and progress toward the UNAIDS 95–95–95 targets across six SSA countries using data from two PHIA survey rounds. Although all countries showed improvements in HIV status awareness, ART coverage, and VLS over time, important geographic disparities remained. Our findings revealed that HIV burden and gaps in the HIV care continuum were not evenly distributed across regions, and areas with high HIV prevalence did not always correspond to areas with the greatest gaps in the HIV care continuum. The geospatial analyses provided valuable insights beyond national-level estimates by identifying spatial clusters and spatial outliers of HIV burden and gaps in the HIV care continuum. These findings highlight the importance of using subnational data to guide HIV programs and allocate resources more effectively. Targeted interventions are needed to improve HIV status awareness, access to treatment, and VLS in underserved areas while addressing local

barriers to care. Overall, our study demonstrates the use of geospatial approaches for monitoring HIV epidemics and identifying communities that require additional support. Continued subnational monitoring and geographically targeted HIV interventions will be essential for accelerating progress toward achieving the UNAIDS 95–95–95 targets and ending HIV as a public health threat by 2030.

Abbreviations

HIV: Human Immunodeficiency Virus; AIDS: Acquired Immunodeficiency Syndrome; PLWH: people living with HIV; SSA: sub-Saharan Africa; UNAIDS: Joint United Nations Programme on HIV/AIDS; ART: antiretroviral therapy; VLS: viral load suppression; PHIA: Population-based HIV Impact Assessment; ICAP: International Center for AIDS Care and Treatment Programs; CDC: Centers for Disease Control and Prevention; EA: Enumeration area; SES: socioeconomic status; IQR: Interquartile range; LISA: Local Indicators of Spatial Association; PMTCT: Prevention of mother-to-child transmission

Declarations

Ethics approval and consent to participate

All PHIA survey protocols, consent documents, and data collection instruments were reviewed and approved by relevant national ethics and regulatory authorities as well as by the institutional review boards of Columbia University Medical Center, Westat, and the U.S. Centers for Disease Control and Prevention. Each survey included external monitoring visits conducted twice during implementation. Survey management teams conducted continuous surveillance to identify any protocol deviations and adverse events, which were reported to the institutional review boards. Written informed consent was obtained at every stage of the survey. Our secondary analysis used

publicly available, anonymized PHIA data. All analyses were conducted in accordance with ethical standards to protect participant privacy and confidentiality.

Consent for publication

Not applicable

Availability of data and materials

The datasets used in the manuscript are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Author's Contributions

Sindhuri Gandla analyzed data and wrote/reviewed the manuscript. Raja Nakka analyzed data and reviewed the manuscript. Musie Ghebremichael conceived the study, wrote/reviewed the manuscript, and provided guidance on manuscript writing, data analyses, and interpretation of the findings.

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Figure legends

Figure 1: Spatial distribution of survey enumeration areas (EAs) in Uganda for PHIA1 (left panel) and PHIA2 (right panel).

Figure 2: Spatial distribution of HIV prevalence in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 3: Spatial distribution of the first UNAIDS 95, the awareness of HIV status among people living with HIV in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 4: Spatial distribution of the second UNAIDS 95, ART coverage among people aware of their HIV-positive status in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 5: Spatial distribution of the third UNAIDS 95, viral load suppression among people receiving antiretroviral therapy (ART) in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 6: Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of HIV prevalence in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 7: Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of HIV status unawareness among people living with HIV in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 8: Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of no antiretroviral therapy (ART) coverage among participants aware of their HIV-positive status in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figure 9: Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) for viral non-suppression among participants on ART in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Figures

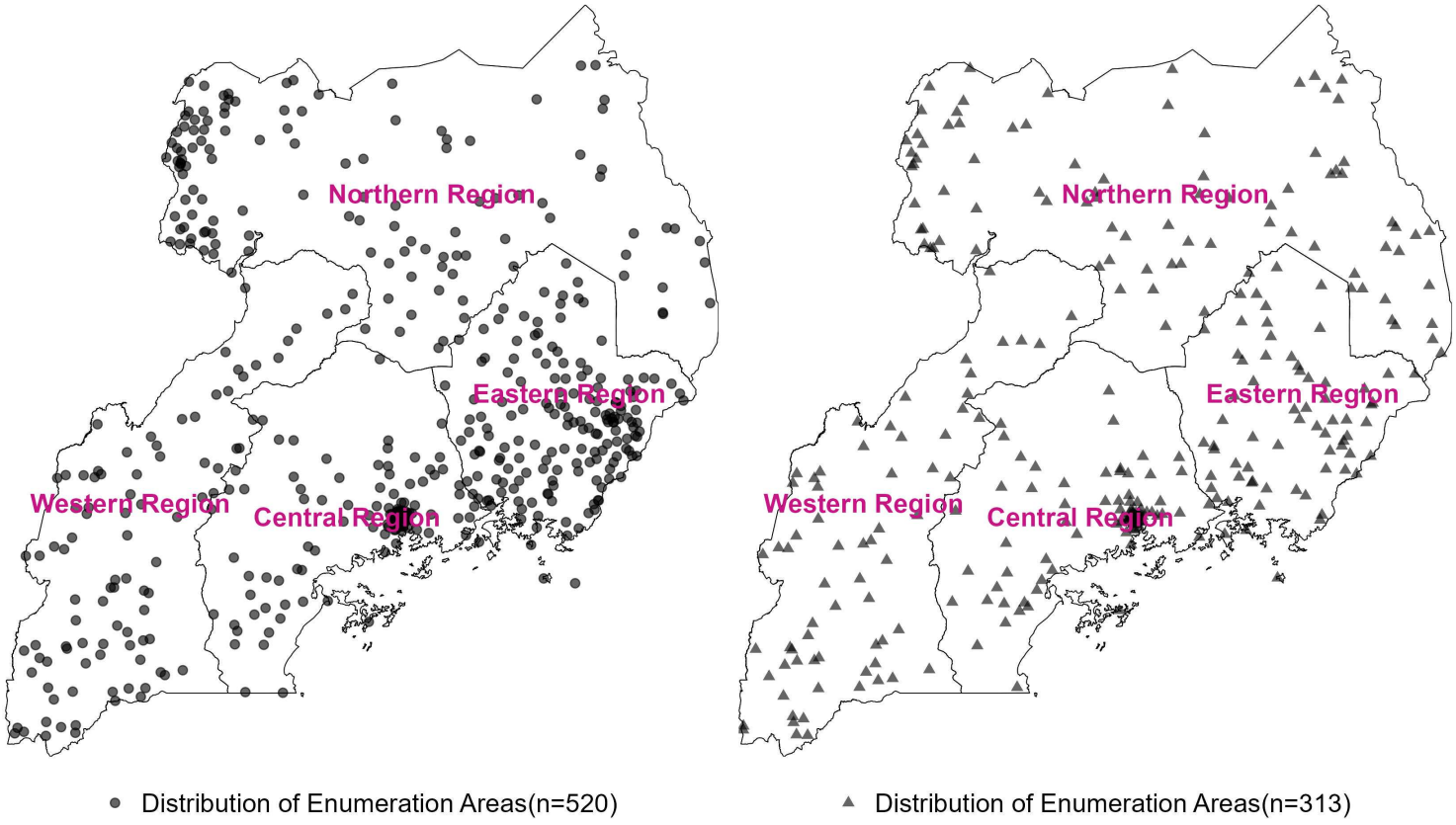


Figure 1

Spatial distribution of survey enumeration areas (EAs) in Uganda for PHIA1 (left panel) and PHIA2 (right panel).

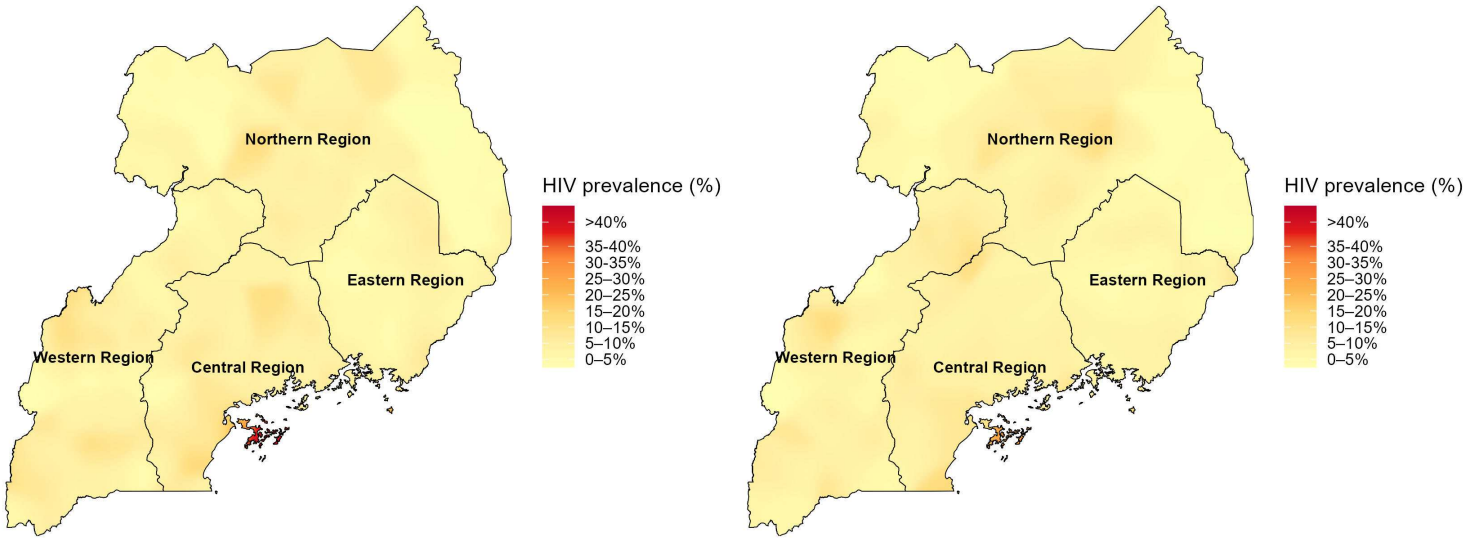


Figure 2

Spatial distribution of HIV prevalence in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

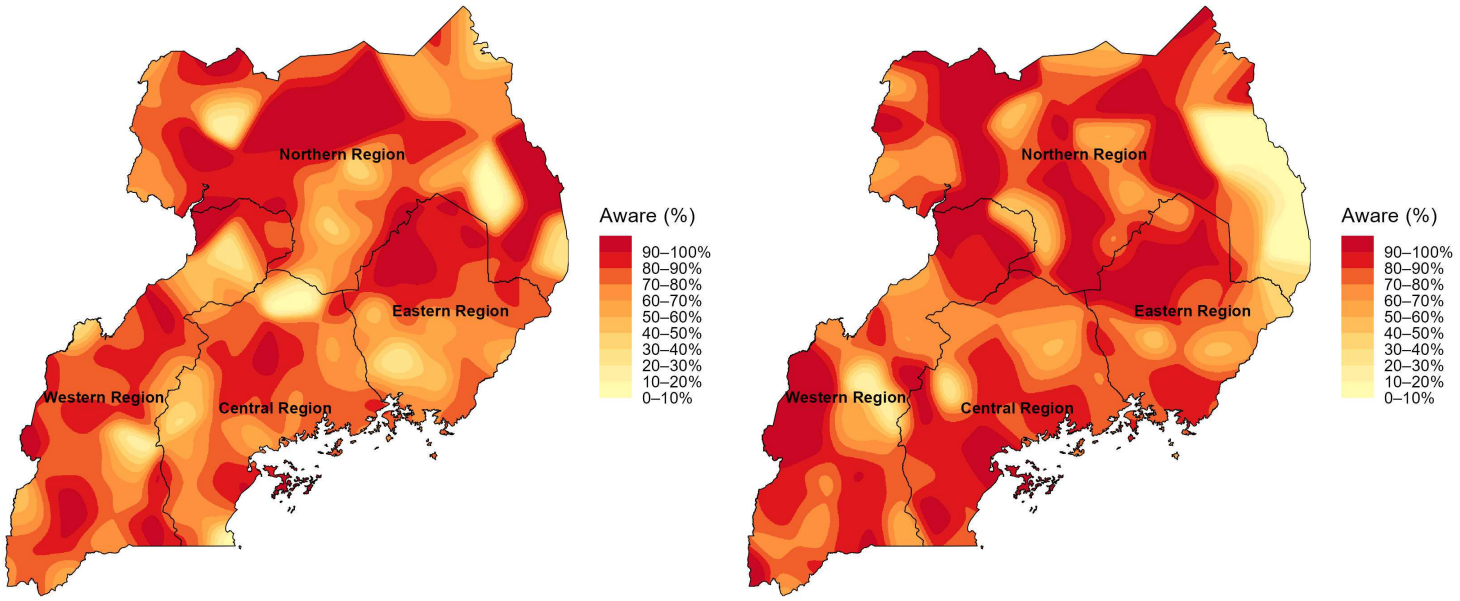


Figure 3

Spatial distribution of the first UNAIDS 95, the awareness of HIV status among people living with HIV in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

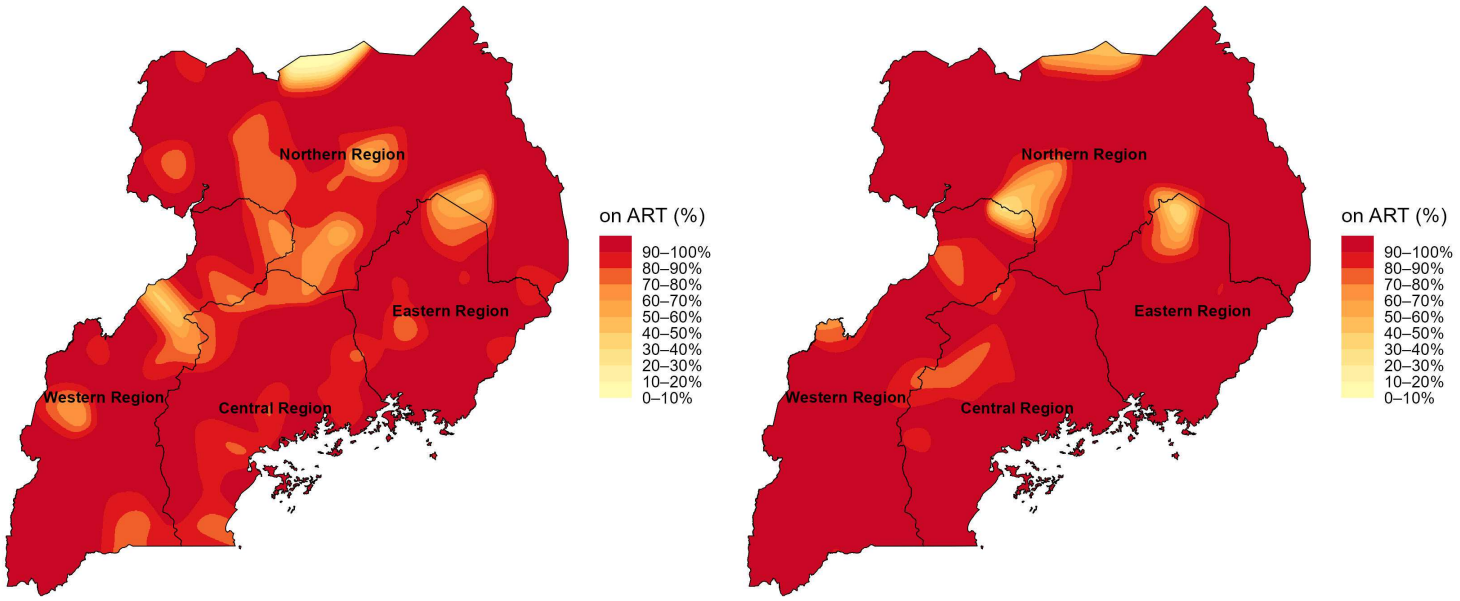


Figure 4

Spatial distribution of the second UNAIDS 95, ART coverage among people aware of their HIV-positive status in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

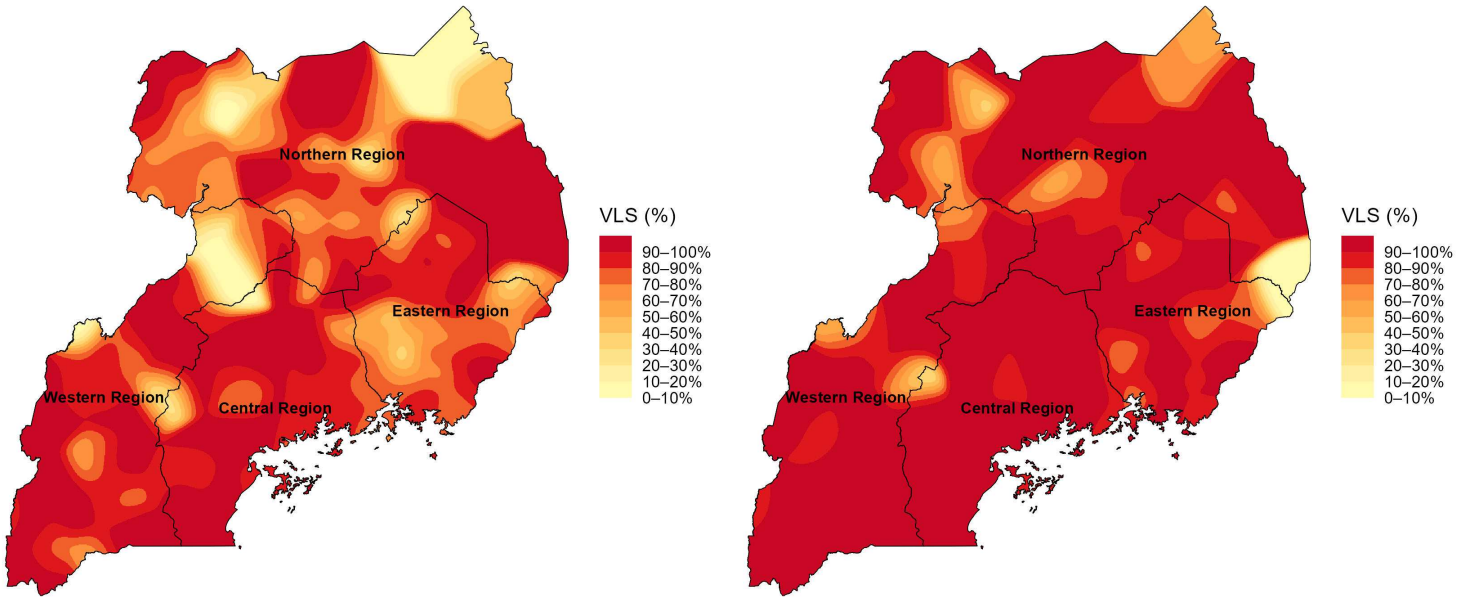


Figure 5

Spatial distribution of the third UNAIDS 95, viral load suppression among people receiving antiretroviral therapy (ART) in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

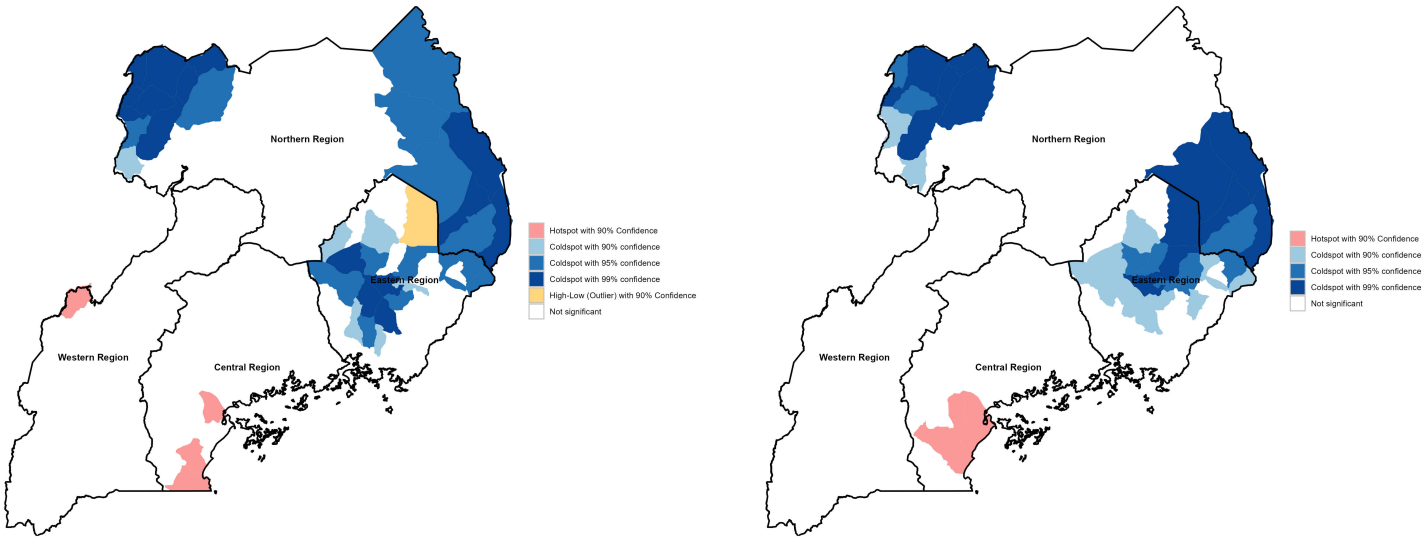


Figure 6

Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of HIV prevalence in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

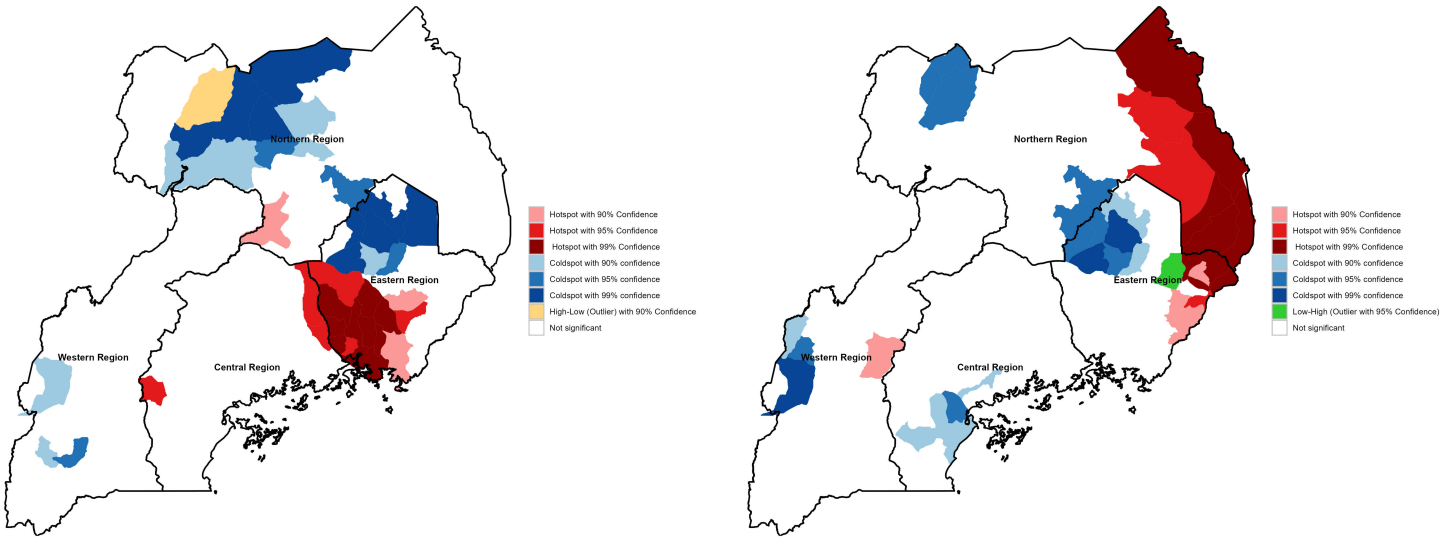


Figure 7

Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of HIV status unawareness among people living with HIV in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

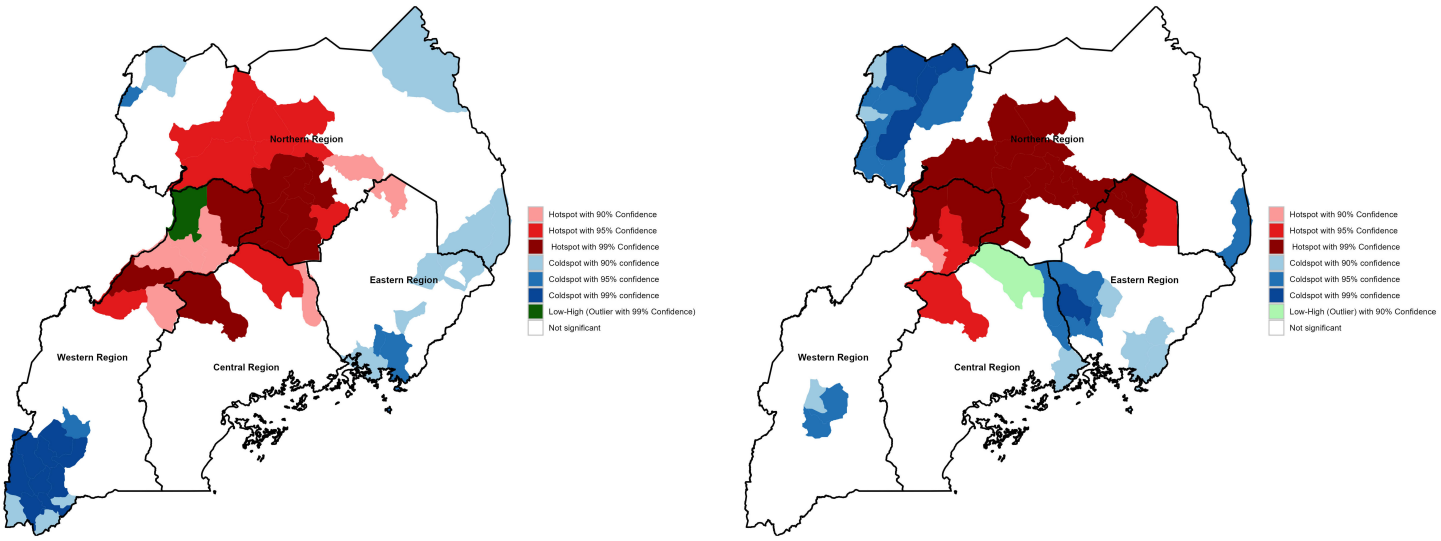


Figure 8

Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) of no antiretroviral therapy (ART) coverage among participants aware of their HIV-positive status in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

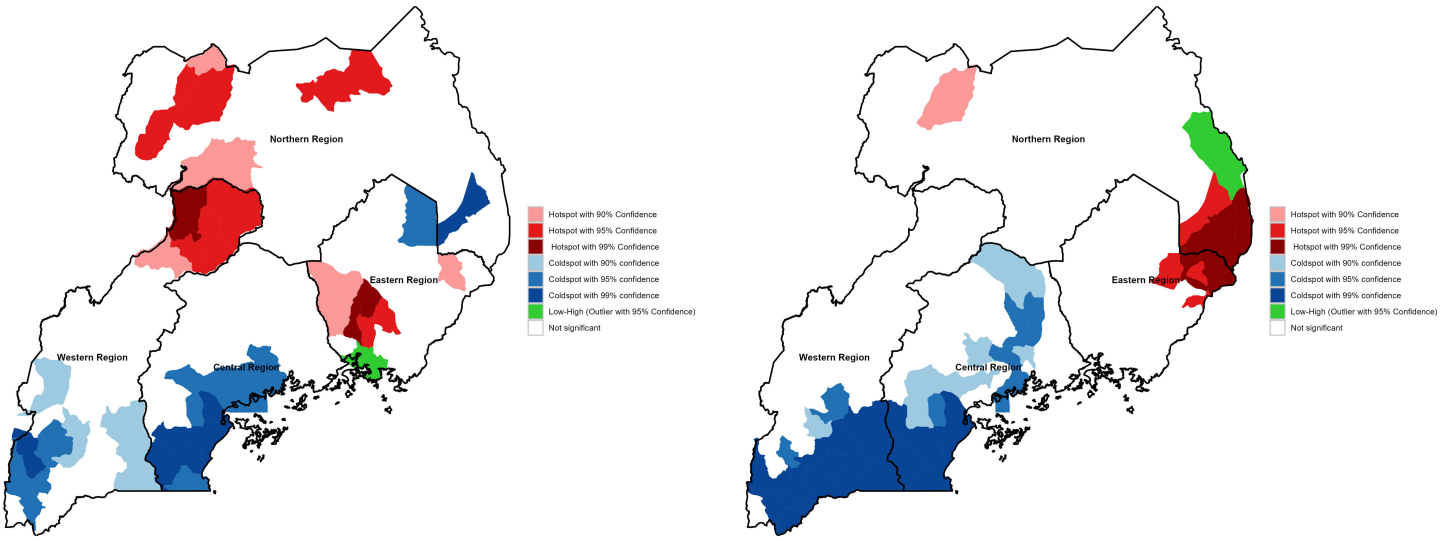


Figure 9

Distribution of spatial clusters (hotspots, coldspots) and outliers (high-low, low-high) for viral non-suppression among participants on ART in Uganda during PHIA1 (left panel) and PHIA2 (right panel).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx