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The Heterogeneous impact of antiretroviral therapy coverage on HIV epidemiology in sub-Saharan Africa: a longitudinal ecological study of 38 countries

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Abstract

Introduction: Antiretroviral therapy (ART) coverage has expanded rapidly in sub-Saharan Africa, but the population-level impact on HIV incidence, mortality and prevalence across different sub-regions remains uncertain. We quantified the association between ART coverage and these epidemiological indicators from 2010 to 2022.

Methods: We conducted a longitudinal ecological study using country-level data from 38 sub-Saharan African countries (494 observations) from UNAIDS, the World Bank and the UNDP. Fixed-effects panel regression models with log-transformed variables estimated elasticities: β represents the percentage change in the outcome per 1% change in ART coverage. Results are presented per 10% ART increase for interpretability. Regional interaction terms (East Africa as reference) tested effect heterogeneity, with real effects in other regions calculated as β_ART + β_interaction. Bootstrapping generated 95% confidence intervals (CIs) for overall percentage changes.

Results: Regional ART coverage increased from 22% to 75% between 2010 and 2022. Overall, HIV incidence fell by 65% (95% CI 60–70), mortality by 72% (68–76), and prevalence by 33% (30–36). Regarding incidence, a 10% increase in ART coverage was associated with a 1.6% reduction in East Africa (β_ART = –0.16, 95% CI –0.24 to –0.08); the effect was significantly attenuated in West Africa (real β = –0.02, 0.2% reduction; interaction p=0.003) but similar in Central and Southern Africa (interaction p>0.05). For mortality, a 10% ART increase was associated with a 4.2% reduction in East Africa (β_ART = –0.42, 95% CI –0.49 to –0.35); significant attenuation was observed elsewhere, with real effects of –0.26 (2.6% reduction) in West Africa, –0.21 (2.1%) in Southern Africa, and –0.32 (3.2%) in Central Africa (all interaction p<0.05). For prevalence, a 10% ART increase was associated with a 1.0% reduction in East Africa (β_ART = –0.10, 95% CI –0.13 to –0.07); the effect was similar in West Africa (interaction p=0.60) but significantly attenuated in Central and Southern Africa (real β = –0.04, 0.4% reduction; interaction p<0.01), and the association was strongly modified by the incidence–mortality ratio (interaction β=0.29, p<0.001). Had ART coverage remained at 2010 levels, an estimated 1.2 million (95% CI 1.0–1.4) additional deaths would have occurred.

Conclusion: ART scale-up substantially reduced HIV incidence and mortality across all sub-Saharan African regions, with significant though attenuated effects in West, Southern and Central Africa. Prevalence is an unreliable standalone indicator of ART programme success. Regional tailoring of ART strategies and continued health system investments remain essential.

Contributions to the literature

- A 10% increase in ART coverage reduces HIV mortality by 4.2% in East Africa but only by 2.1% in Southern Africa, demonstrating that ART works across Africa but not uniformly.
- ART scale-up averted an estimated 1.2 million HIV-related deaths across 38 countries in just 13 years, showing that the HIV treatment success story is measured in lives saved.
- The association between ART coverage and HIV prevalence is weak and context-dependent, meaning that prevalence alone is a poor gauge of programme success.
- Effective ART deployment requires regional tailoring because West Africa needs earlier diagnosis, Southern Africa needs better retention in care, and Central Africa needs wider coverage.

Introduction

After four decades of the HIV pandemic, sub-Saharan Africa remains disproportionately affected, housing approximately two-thirds of the 40.8 million people living with HIV globally [1]. In 2023 alone, the region recorded an estimated 670,000 new infections and 380,000 HIV-related deaths [2]. The advent of antiretroviral therapy (ART) transformed HIV from a fatal disease to a manageable chronic condition, and global initiatives such as the US President's Emergency Plan for AIDS Relief (PEPFAR) and UNAIDS 90-90-90 targets have driven unprecedented treatment expansion [3–5].

Between 2010 and 2024, global ART coverage rose from 23% to 77%, and HIV incidence fell by 39%[1, 6]. AIDS-related deaths have been reduced by 70% since the peak in 2004 and by 54% since 2010. In sub-Saharan Africa, the provision of antiretroviral therapy, among other advances, has led to a rebound in life expectancy from 56.5 years in 2010 to 62.3 years in 2024[6]. Yet these aggregates mask substantial heterogeneity. Southern Africa continues to report adult HIV prevalence exceeding 20% in some countries, while West Africa's prevalence remains below 2% [2]. More importantly, the population-level relationship between ART coverage and HIV epidemiological indicators is theoretically complex: ART reduces mortality (increasing prevalence by prolonging survival) while simultaneously reducing transmission (decreasing incidence and potentially lowering prevalence over the long term)[7, 8]. The net effect on prevalence depends on the balance between these forces and on demographic dynamics such as population growth.

Existing evidence comes largely from individual-level cohort studies or single-country analyses [9–15]. While these provide valuable causal insights, they cannot capture regional heterogeneity in ART effectiveness across Africa's diverse health systems, epidemiological contexts and demographic trajectories. A systematic, multi-country assessment of how ART coverage has shaped HIV incidence, mortality and prevalence at the population level is urgently needed to guide resource allocation and policy.

We therefore conducted a longitudinal ecological study of 38 sub-Saharan African countries over 13 years (2010–2022) to quantify the association between ART coverage and HIV incidence, mortality and prevalence, and to assess how these associations vary across East, West, Central and Southern Africa.

Methods

Study design and data sources

We performed an analytical longitudinal ecological study using country-level panel data. All data were extracted from publicly available, standardised databases: UNAIDS (HIV indicators, ART coverage, mother-to-child transmission)[16], the World Bank (demographic and economic indicators)[17], and the United Nations Development Programme (Human Development Index) [18, 19].

Setting and regional classification

Sub-Saharan Africa was divided into four sub-regions according to the standard United Nations classification:

- East Africa (6 countries): Burundi, Kenya, Rwanda, Tanzania, Uganda, South Sudan
- West Africa (14 countries): Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, Togo
- Central Africa (8 countries): Cameroon, Central African Republic, Chad, Congo, Democratic Republic of Congo, Equatorial Guinea, Gabon, São Tomé and Príncipe
- Southern Africa (10 countries): Angola, Botswana, Eswatini, Lesotho, Malawi, Mozambique, Namibia, South Africa, Zambia, Zimbabwe

Inclusion criteria and sample

All sub-Saharan African countries were initially eligible. Countries were excluded if >15% of data were missing for any key variable (prevalence, incidence, mortality, ART coverage) across 2010–2022. Ten countries were excluded (primarily due to incomplete data in East Africa), leaving 38 countries and 494 observations (38 × 13 years).

Variables

Outcomes: HIV prevalence (% of adults aged 15–49 years), HIV incidence (new infections per 1,000 population), HIV-related mortality (deaths per 1,000 population). All from UNAIDS.

Primary exposure: ART coverage (% of people living with HIV receiving ART). From UNAIDS.

Covariates: population aged 15–64 years (millions), mother-to-child transmission rate (%), PMTCT ART coverage (%), health expenditure (% GDP), health expenditure per capita (US$), political stability index, total fertility rate, population growth rate, Human Development Index, and the incidence–mortality ratio (calculated as incidence/mortality). These were selected a priori based on established epidemiological literature [7–9].

Statistical analysis

All statistical analyses were performed using R version 4.5.0 (R Foundation for Statistical Computing, Vienna, Austria). A significance level of $\alpha = 0.05$ was used for all hypothesis tests.

Data structure and descriptive analysis

Our dataset comprised observations from 38 countries over 13 years (2010–2022), constituting a balanced panel with 494 observations. For each variable, we examined the distribution using histograms with overlaid density curves. Variables with marked skewness were described using medians and interquartile ranges (IQR); otherwise, means were used. Temporal trends were visualised using line graphs for each sub-region.

Correlation analysis

Bivariate associations between ART coverage and each HIV outcome (incidence, mortality, prevalence) were assessed using Spearman's rank correlation coefficient, stratified by sub-region. Spearman's ρ was chosen because of the non-normal distribution of several variables.

Panel data model selection

Given the longitudinal (panel) structure of the data, we considered two alternative regression frameworks: the fixed-effects model and the random-effects model. The Breusch–Pagan Lagrange multiplier test was used to determine whether ordinary least squares (pooled regression) was adequate. The test rejected the null hypothesis of zero variance in country-specific effects ($p < 0.001$), justifying the use of a panel model over pooled OLS.

To choose between fixed effects and random effects, we performed the Hausman test. The test indicated a systematic difference in coefficients between the two models ($p < 0.001$), leading us to reject the null hypothesis that the random-effects estimator is consistent. Consequently, we adopted the fixed-effects model, which controls for all time-invariant country-specific characteristics (e.g., geography, cultural norms, historical context) and reduces omitted variable bias.

Model specification and transformation

All continuous variables (outcomes, ART coverage, and covariates) were transformed using the natural logarithm. This transformation achieves three objectives: (1) it reduces skewness and stabilises variance, (2) it makes the error distribution closer to normal, and (3) it allows coefficients to be interpreted as **elasticities** – the percentage change in the outcome for a 1% change in the predictor.

The fitted fixed-effects panel regression model is specified as follows:

$$\ln(Y_{it}) = \alpha_i + \beta_1 \ln(\text{ART}_{it}) + \sum_{j=2}^{k} \beta_j \ln(X_{jit}) + \beta_W(\ln(\text{ART}_{it}) \times \text{WestAfrica}_i) + \beta_S(\ln(\text{ART}_{it}) \times \text{SouthernAfrica}_i) + \beta_C(\ln(\text{ART}_{it}) \times \text{CentralAfrica}_i) + \varepsilon_{it}$$

where:

- Y_{it} = HIV outcome (incidence, mortality, or prevalence) for country i in year t;
- $\ln(\text{ART}_{it})$ = natural log of ART coverage;

- X_{jit} = natural log of the j-th covariate (population 15-64 years, mother-to-child transmission rate, health expenditure % GDP, health expenditure per capita, political stability, fertility rate, population growth rate, Human Development Index, and incidence–mortality ratio);
- α_i = country-specific fixed effect (captures time-invariant unobserved heterogeneity);
- $\text{WestAfrica}_i, \text{SouthernAfrica}_i, \text{CentralAfrica}_i$ = dummy variables indicating sub-region (East Africa is the reference category);
- β_1 = elasticity of the outcome with respect to ART coverage in East Africa;
- $\beta_W, \beta_S, \beta_C$ = interaction coefficients measuring how the ART effect differs in West, Southern and Central Africa compared to East Africa;
- ε_{it} = idiosyncratic error term, assumed to be independent and identically distributed with mean zero.

Separate models were fitted for each outcome (incidence, mortality, prevalence). For the prevalence model only, we additionally included an interaction term between ART coverage and the incidence–mortality ratio.

Interpretation of coefficients

Because both the outcome and ART coverage are log-transformed, a 1% increase in ART coverage is associated with a β_1% change in the outcome (holding other covariates constant). For policy relevance, we scale results to a 10% increase in ART coverage, i.e., multiply β_1 by 10. The real effect of ART in a region other than East Africa is the sum of the reference coefficient (β_1) and the respective interaction coefficient (e.g., $\beta_1 + \beta_W$ for West Africa). Positive interaction coefficients indicate that the protective effect of ART is attenuated (i.e., smaller in magnitude) compared to East Africa.

Inference and model fit

For each coefficient, we report the point estimate, 95% confidence interval, and p-value. Confidence intervals for the real effects ($\beta_1 + \beta_{\text{interaction}}$) were calculated using the variance-covariance matrix of the estimates. The overall fit of each model is summarised by the adjusted R^2. To calculate the overall percentage changes in HIV indicators between 2010 and 2022 (e.g., 65% decline in incidence), we

performed country-level bootstrap resampling with 1,000 replications, accounting for clustering by country, and obtained 95% confidence intervals.

Estimation of deaths averted

Using the fitted fixed-effects panel model for HIV mortality (Table 3), we estimated the number of HIV-related deaths averted by ART scale-up between 2010 and 2022. For each country *i* and year *t*, we predicted the observed number of deaths under actual ART coverage, $\widehat{D}_{it}^{\text{obs}}$, and the counterfactual number of deaths under the scenario where ART coverage remained at its 2010 level, $\widehat{D}_{it}^{\text{counter}}$, while keeping all other covariates at their observed values. The total number of deaths averted was calculated as:

$$\text{Deaths averted} = \sum_{i=1}^{38} \sum_{t=2010}^{2022} \left(\widehat{D}_{it}^{\text{counter}} - \widehat{D}_{it}^{\text{obs}} \right)$$

A positive value indicates deaths prevented by ART expansion. Uncertainty was quantified using country-level bootstrap resampling (1,000 replications) to generate 95% confidence intervals.

Results

Study population and regional characteristics

The final sample comprised 38 countries (Table 1). West Africa contributed the most observations (182, 36·8%), followed by Southern Africa (130, 26·3%), Central Africa (104, 21·2%) and East Africa (78, 15·7%).

Table 1: HIV indicators and ART coverage by sub-region [median (IQR)]

Indicator	East Africa (n=78)	West Africa (n=182)	Southern Africa (n=130)	Central Africa (n=104)
HIV prevalence (%)	3·7 (2·2–5·3)	1·4 (0·9–1·8)	13·2 (12·3–20·0)	3·5 (1·1–4·0)
HIV incidence (per 1000)	1·0 (0·5–1·5)	0·5 (0·3–0·7)	4·3 (3·4–5·9)	0·9 (0·4–2·1)
HIV mortality (per 1000)	0·6 (0·4–0·9)	0·3 (0·2–0·6)	1·7 (1·4–2·4)	0·9 (0·3–1·3)
ART coverage (%)	54·5 (31–80)	36·5 (26–56)	60·5 (41–79)	33 (21–49)
Health expenditure per capita (US$)	43·3 (32·9–55·1)	46·1 (32·8–71·0)	114·7 (60·4–406·0)	57·7 (34·5–187·3)
HDI	0·5 (0·4–0·5)	0·5 (0·4–0·5)	0·6 (0·5–0·6)	0·6 (0·4–0·6)

HDI: Human Development Index; IQR: interquartile range.

Southern Africa carried the heaviest burden (prevalence 13·2%, incidence 4·3 per 1000, mortality 1·7 per 1000). West Africa had the lowest burden but also the lowest ART coverage (36·5%). East Africa achieved the highest PMTCT coverage (80% of pregnant women living with HIV receiving ART). Health expenditure per capita was three times higher in Southern Africa than in East or West Africa.

Temporal trends (2010–2022)

Between 2010 and 2022, regional ART coverage increased from approximately 22% to 75% with sub-regional variations (Figure 1). Over the same period, HIV incidence fell from 1.54 to 0.54 per 1000 population, HIV-related mortality from 1.27 to 0.35 per 1000, and HIV prevalence from 3.6% to 2.4% (Figures 2A, 2B, 2C). The relative declines were: incidence 65% (95% CI 60–70), mortality 72% (95% CI 68–76), and prevalence 33% (95% CI 30–36), based on bootstrap resampling. However, the incidence–mortality ratio

remained above 1·0 in all sub-regions throughout the study period, indicating that new infections continued to outnumber deaths.

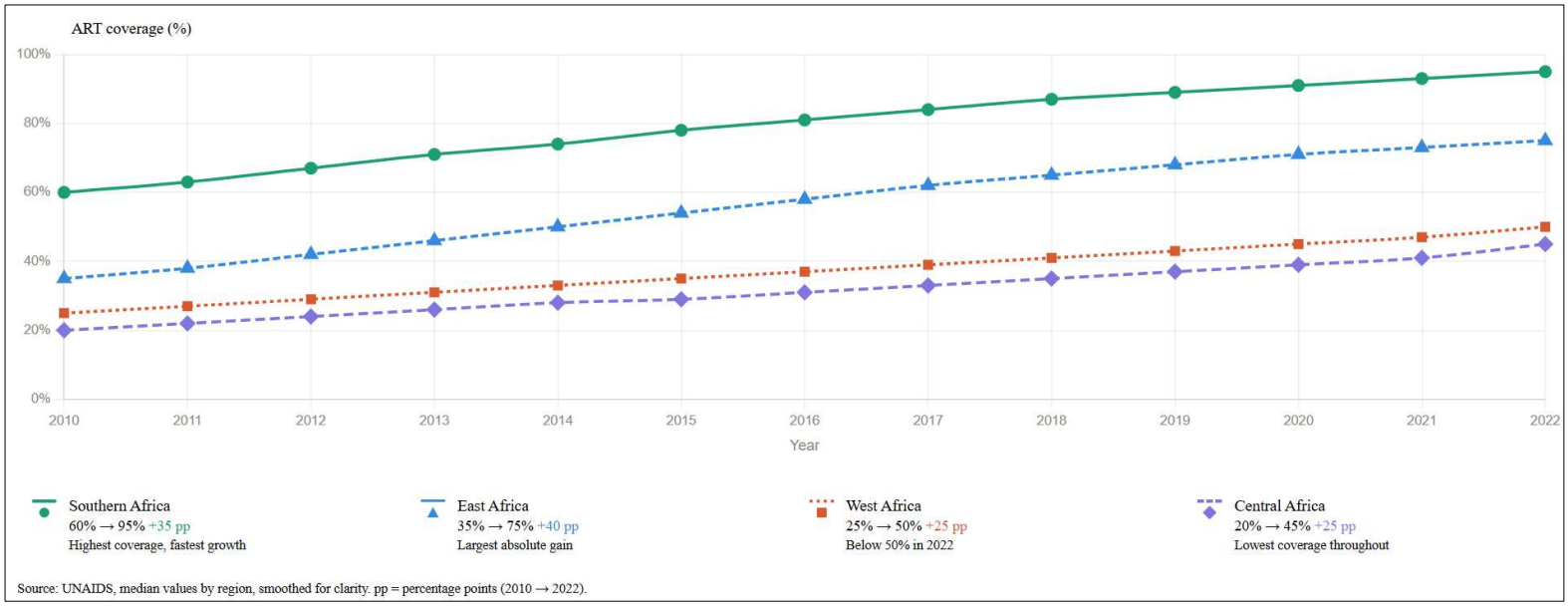


Figure 1. Antiretroviral therapy (ART) coverage trends in sub-Saharan Africa by sub-region, 2010–2022

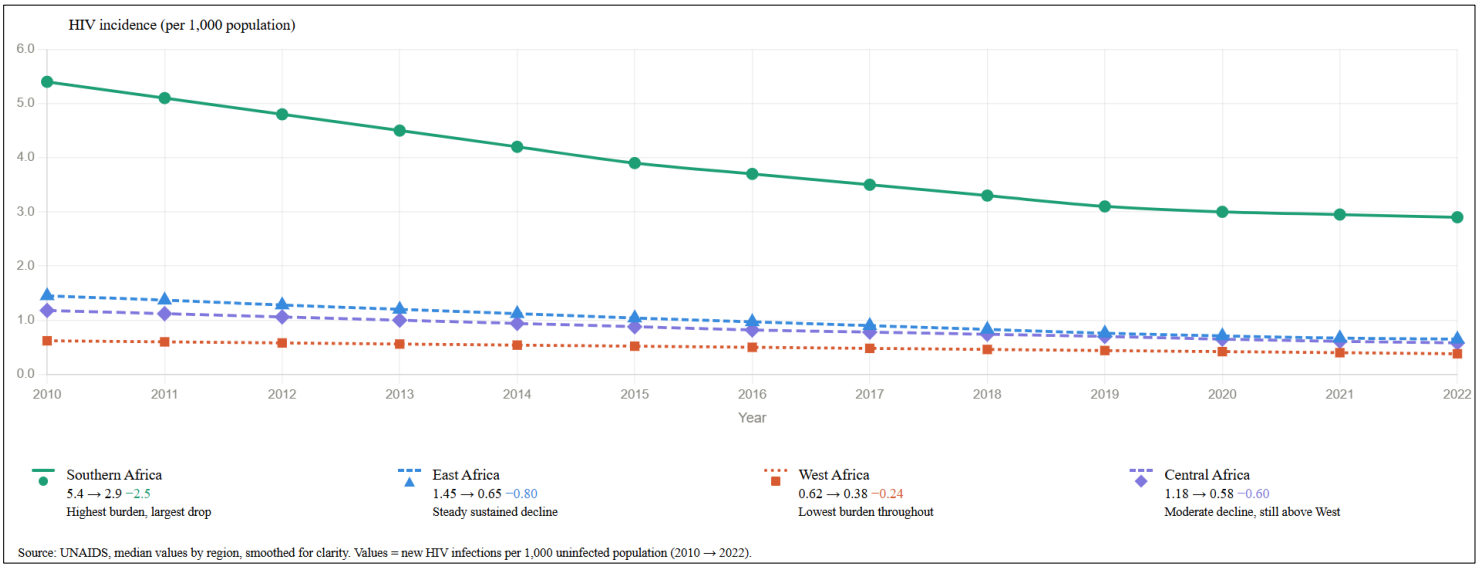


Figure 2A. HIV incidence trends by sub-region, 2010–2022

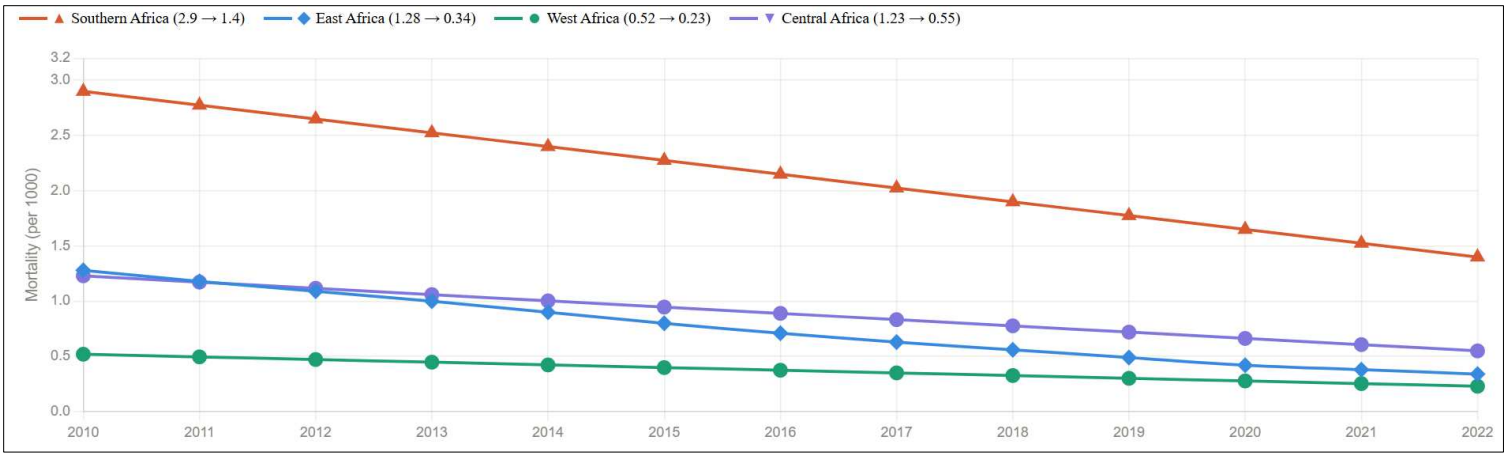


Figure 2B. HIV mortality trends by sub-region, 2010–2022

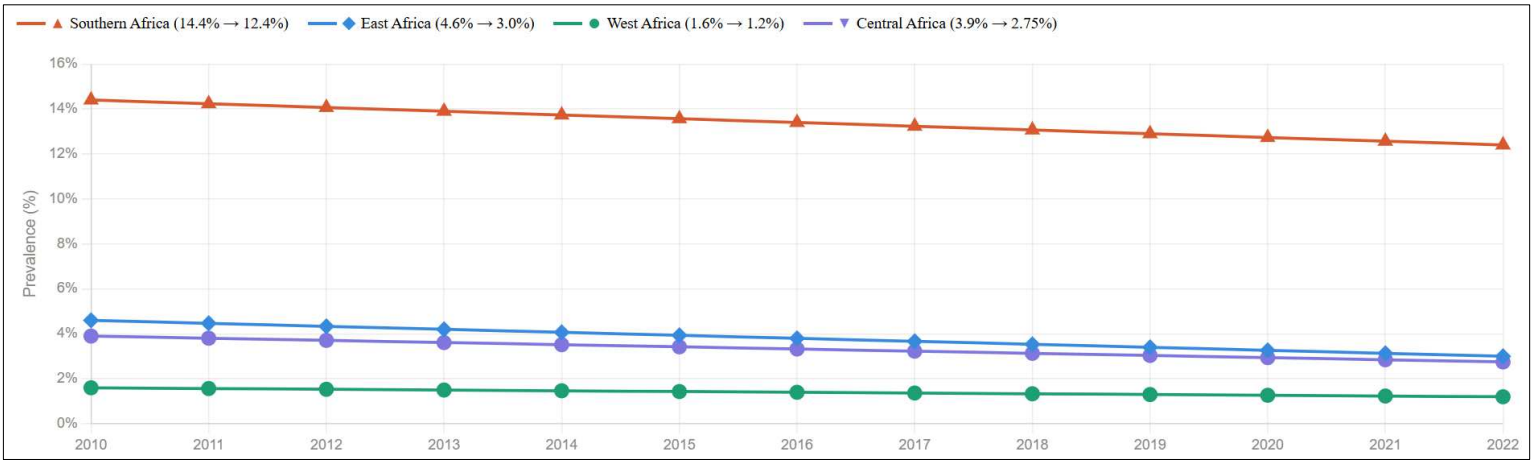


Figure 2C. HIV prevalence trends by sub-region, 2010–2022

Association with HIV incidence

Spearman's rank correlation coefficients between ART coverage and HIV incidence were negative and statistically significant in all four sub-regions (Figure 3): West Africa ($\rho = -0.65$, $p < 0.001$), Southern Africa ($\rho = -0.58$, $p < 0.001$), Central Africa ($\rho = -0.57$, $p < 0.001$), and East Africa ($\rho = -0.49$, $p = 0.002$). These findings indicate that higher ART coverage is consistently associated with lower HIV incidence across sub-Saharan Africa, with the strongest correlation observed in West Africa.

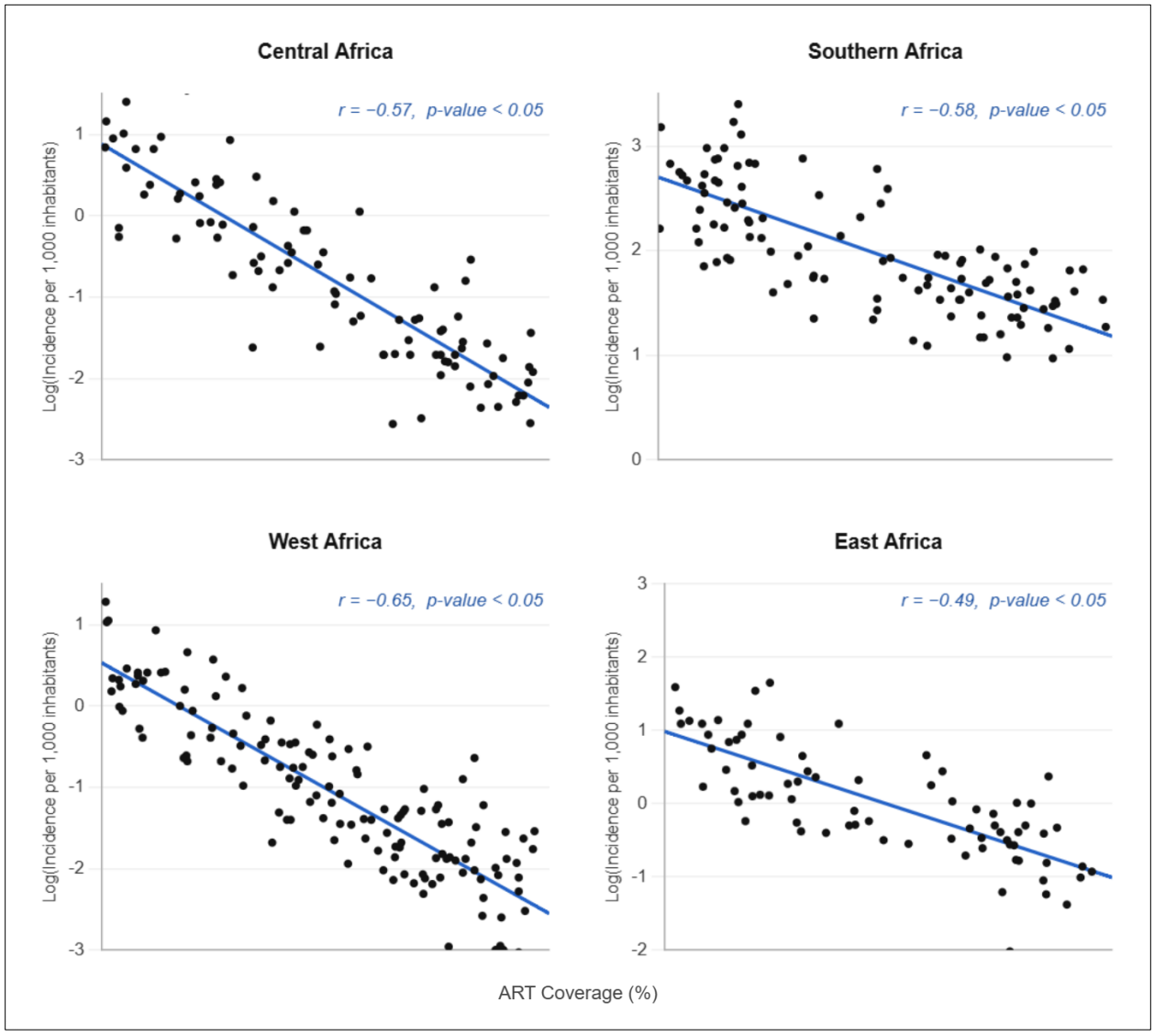


Figure 3. Correlation between ART coverage and HIV incidence across the sub-Saharan African Region

In the fixed-effects model (Table 2), a 10% increase in ART coverage was associated with a 1·6% reduction in HIV incidence in East Africa (β=-0·16, 95% CI -0·24 to -0·08, p<0·001). The effect was similar in Central and Southern Africa (interaction p>0·05 for both). However, in West Africa the effect was significantly attenuated (interaction β=0·14, 95% CI 0·05–0·23, p=0·003), with a real coefficient of -0·02 (0·2% reduction per 10% ART increase).

Other factors significantly associated with lower incidence included higher Human Development Index (β=-0·77, p=0·046), population growth (β=-0·05, p=0·003), working-age population size (β=-0·83, p<0·001) and health expenditure per capita (β=-0·34, p<0·001). Higher fertility rates (β=1·1, p<0·001), health expenditure as a percentage of GDP (β=0·48, p<0·001) and mother-to-child transmission rates (β=0·36, p<0·001) were associated with higher incidence. The model explained 83% of the variance (adjusted R^2=0·83).

Table 2: Fixed-effects panel model for HIV incidence

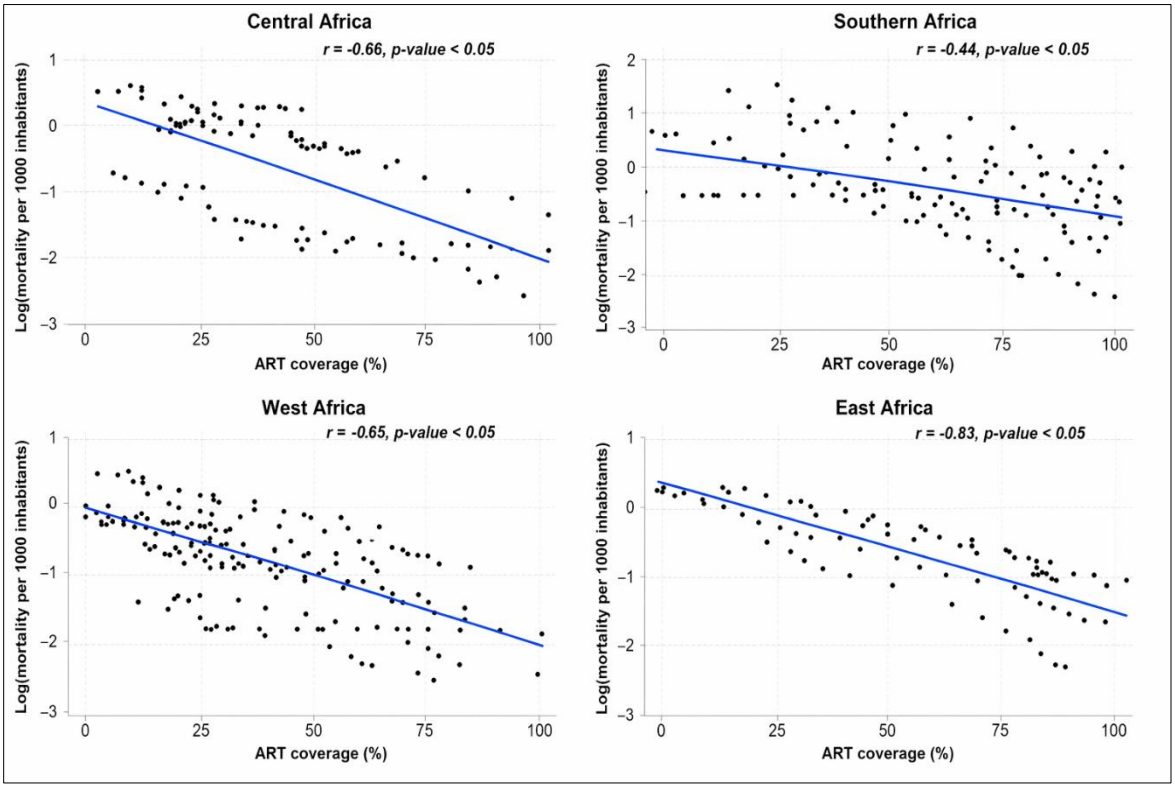
Variable	β	95% CI	p-value
ART coverage (reference: East Africa)	-0·16	(-0·24 to -0·08)	<0·001
Human Development Index	-0·77	(-1·50 to -0·02)	0·046
Population growth rate	-0·05	(-0·09 to -0·02)	0·003
Fertility rate	1·10	(0·60 to 1·50)	<0·001
Population 15–64 years	-0·83	(-1·20 to -0·50)	<0·001
Health expenditure (% GDP)	0·48	(0·39 to 0·58)	<0·001
Health expenditure per capita	-0·34	(-0·44 to -0·25)	<0·001
Political stability	0·07	(0·01 to 0·13)	0·018
Mother-to-child transmission rate	0·36	(0·31 to 0·41)	<0·001
Interactions (ART × region)			
West Africa	0·14	(0·05 to 0·23)	0·003
Southern Africa	0·08	(-0·04 to 0·19)	0·20
Central Africa	-0·08	(-0·18 to 0·01)	0·095
Adjusted R^2 = 0·83			

All continuous variables log-transformed. β = % change in incidence per 1% change in predictor. Real effect in West Africa = –0.16 + 0.14 = –0.02; Southern Africa = –0.16 + 0.08 = –0.08; Central Africa = –0.16 – 0.08 = –0.24

Association with HIV mortality

ART coverage was strongly inversely correlated with HIV-related mortality in all sub-regions (Figure 4). The strongest correlation was found in East Africa (ρ = –0.83, p < 0.001), followed by West Africa (ρ = –0.67, p < 0.001), Central Africa (ρ = –0.64, p < 0.001), and Southern Africa (ρ = –0.44, p = 0.006). The particularly strong correlation in East Africa suggests a close temporal relationship between ART scale-up and mortality reduction in that region.

Figure 4.



Correlation between ART coverage and HIV mortality across the sub-Saharan African Region

In the fixed-effects model (Table 3), a 10% increase in ART coverage in East Africa was associated with a 4·2% reduction in HIV mortality (β=-0·42, 95% CI -0·49 to -0·35, p<0·001). The effect was significantly attenuated in all other regions: West Africa (real β=-0·26, 2·6% reduction, interaction p<0·001),

SouthernAfrica (real β=-0·21, 2·1% reduction, interaction p<0·001) and Central Africa (real β=-0·32, 3·2% reduction, interaction p=0·024).

Table 3: Fixed-effects panel model for HIV mortality

Variable	β	95% CI	p-value
ART coverage (reference: East Africa)	-0·42	(-0·49 to -0·35)	<0·001
Human Development Index	-0·88	(-1·60 to -0·16)	0·017
Population growth rate	-0·07	(-0·10 to -0·04)	<0·001
Population 15–64 years	-0·97	(-1·20 to -0·71)	<0·001
Health expenditure (% GDP)	0·31	(0·22 to 0·40)	<0·001
Health expenditure per capita	-0·32	(-0·42 to -0·23)	<0·001
Mother-to-child transmission rate	0·17	(0·12 to 0·22)	<0·001
Interactions (ART × region)			
West Africa	0·16	(0·07 to 0·24)	<0·001
Southern Africa	0·21	(0·11 to 0·32)	<0·001
Central Africa	0·10	(0·01 to 0·19)	0·024
Adjusted R^2 = 0·81			

All continuous variables log-transformed. β = % change in incidence per 1% change in predictor. Real effect in West Africa = –0.42 + 0.16 = –0.26; Southern Africa = –0.42 + 0.21 = –0.21; Central Africa = –0.42 + 0.10 = –0.32

Association with HIV prevalence

The relationship between ART coverage and HIV prevalence was more heterogeneous (Figure 5). Statistically significant negative correlations were observed in West Africa (ρ = –0.42, p = 0.008) and Central Africa (ρ = –0.48, p = 0.002). In contrast, the correlation was not significant in Southern Africa (ρ = –0.05, p = 0.76) or East Africa (ρ = 0.04, p = 0.81). This heterogeneity reflects the complex interplay between incidence

reduction, improved survival, and demographic growth, which is further explored in the multivariable fixed-effects models below in Table 4.

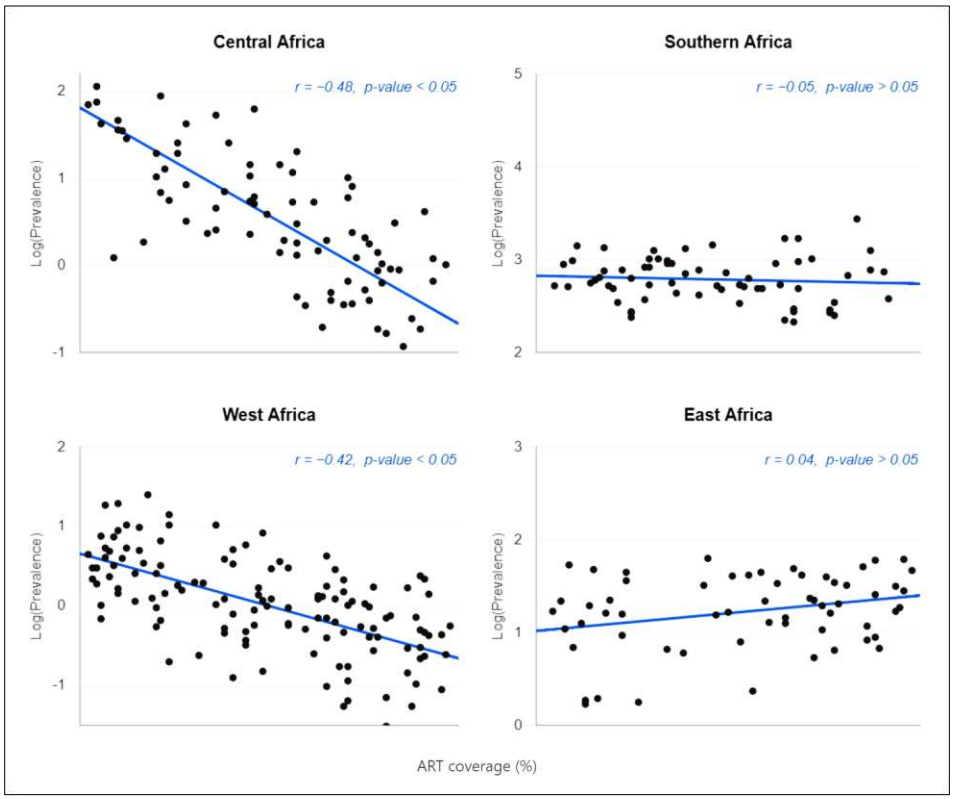


Figure 5. Correlation between ART coverage and HIV prevalence across the sub-Saharan African Region

In the fixed-effects model (Table 4), a 10% increase in ART coverage in East Africa was associated with a 1·0% reduction in HIV prevalence (β=-0·10, 95% CI -0·13 to -0·07, p<0·001). The effect was similar in West Africa (interaction β=0·01, p=0·6). However, the effect was significantly attenuated in Central Africa (interaction β=0·06, p<0·001; real β=-0·04, 0·4% reduction per 10% ART increase) and Southern Africa (interaction β=0·06, p=0·002; real β=-0·04). Crucially, the interaction between ART coverage and the incidence–mortality ratio was strongly positive (β=0·29, 95% CI 0·26–0·32, p<0·001), indicating that ART's effect on prevalence depends heavily on the underlying balance between new infections and deaths.

Table 4: Fixed-effects panel model for HIV prevalence

Variable	β	95% CI	p-value
ART coverage (reference: East Africa)	-0·10	(-0·13 to -0·07)	<0·001
Human Development Index	-0·64	(-0·90 to -0·39)	<0·001
Incidence–mortality ratio	-1·10	(-1·20 to -0·98)	<0·001
Population growth rate	-0·02	(-0·03 to -0·01)	0·005
Population 15–64 years	-0·73	(-0·83 to -0·64)	<0·001
Health expenditure (% GDP)	0·04	(0·01 to 0·08)	0·010
Health expenditure per capita	-0·07	(-0·10 to -0·03)	<0·001
Political stability	0·03	(0·01 to 0·05)	0·008
Interactions			
ART × West Africa	0·01	(-0·02 to 0·04)	0·60
ART × Southern Africa	0·06	(0·02 to 0·10)	0·002
ART × Central Africa	0·06	(0·03 to 0·09)	<0·001
ART × incidence–mortality ratio	0·29	(0·26 to 0·32)	<0·001
Adjusted R^2 = 0·84			

All continuous variables log-transformed. β = % change in incidence per 1% change in predictor. Real effect in West Africa = –0.10 + 0.01 = –0.09; Southern Africa = –0.10 + 0.06 = –0.04; Central Africa = –0.10 + 0.06 = –0.04

Estimated mortality averted

Using our model coefficients, we estimated the number of deaths averted by ART scale-up between 2010 and 2022. Had ART coverage remained at 2010 levels (22% regionally), the mortality rate would have been substantially higher. We estimate that approximately 1·2 million HIV-related deaths were averted across the 38 countries over the study period due to ART expansion (Figure 6).

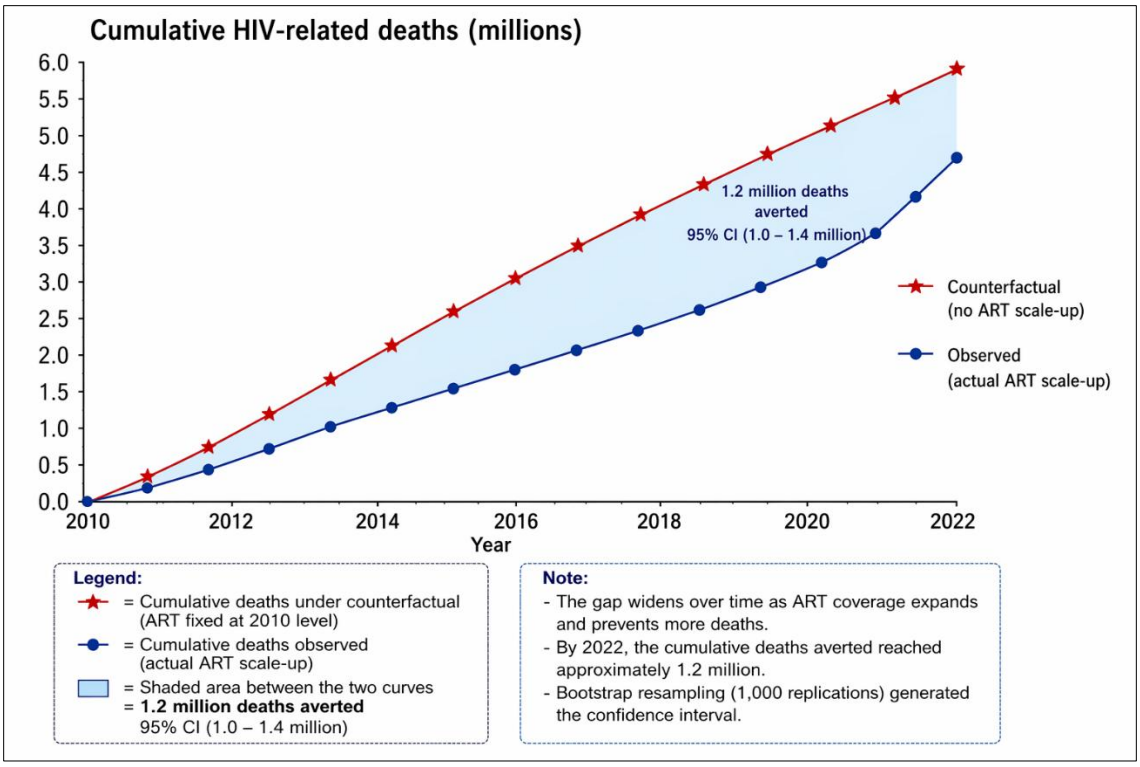


Figure 6. HIV-related deaths averted across 38 SSA countries due to ART expansion between 2010 and 2022.

Discussion

This longitudinal ecological study of 38 sub-Saharan African countries provides three main findings. First, ART scale-up between 2010 and 2022 was associated with substantial reductions in HIV incidence and mortality across all sub-regions. Overall, HIV incidence declined by 65% (95% CI 60–70) and mortality by 72% (68–76) over the period, while prevalence fell by 33% (30–36). Second, the effect varied markedly by region: East Africa achieved the strongest mortality reduction (4.2% per 10% ART increase), whereas West Africa showed a nearly absent incidence effect (0.2% reduction). Third, the association between ART coverage and HIV prevalence was modest and strongly modified by the incidence–mortality ratio (interaction $\beta = 0.29$), indicating that prevalence trends should not be used as standalone indicators of ART programme success. We estimate that ART expansion averted approximately 1.2 million (95% CI 1.0–1.4) deaths.

Comparison with existing evidence

Our incidence findings align with community-level studies from South Africa, where high ART coverage reduced HIV acquisition risk by 38% [9], and with population-based analyses from low-income [13–15] and high-income settings [20–22]. The biological plausibility is well established: ART suppresses viral load, and the HPTN 052 trial demonstrated 96% reduction in transmission among serodiscordant couples when the infected partner received early ART [23].

Our mortality findings corroborate multi-site African surveillance data showing 58% mortality reductions following ART introduction [24], as well as country-specific studies from Uganda [14], Malawi[25] and Kenya [15]. The substantially larger effect in East Africa compared with other regions likely reflects higher PMTCT coverage (80%)[26], earlier treatment initiation and more integrated service delivery. Southern Africa's attenuated mortality effect despite the highest ART coverage (60·5%) is concerning and may reflect advanced HIV disease at presentation, higher baseline mortality, or challenges with retention and adherence in high-burden settings.

The prevalence findings require careful interpretation. While some studies have reported prevalence increases following ART scale-up due to improved survival (South Africa [10], Uganda [11]; others have reported declines (Nigeria [12], Cameroon [13]). Our results reconcile these apparently contradictory observations by demonstrating that the net effect of ART on prevalence is highly context-dependent. The strong positive interaction between ART coverage and the incidence–mortality ratio (β=0·29) shows that where new infections substantially exceed deaths, ART's survival-prolonging effect dominates, potentially increasing prevalence. Conversely, where transmission reductions outpace mortality improvements, prevalence may decline. The observed regional prevalence declines in our aggregated analysis are likely driven partly by demographic dilution: the working-age population grew substantially in all sub-regions, expanding the denominator of the prevalence fraction.

Because our models used log-transformed variables and interaction terms, the real effect of ART in West, Southern and Central Africa is the sum of the reference coefficient (East Africa) and the respective interaction coefficient. A positive interaction coefficient indicates that the protective effect of ART is significantly smaller (attenuated) in that region compared to East Africa. For example, the mortality interaction of +0.21 in Southern Africa means that the mortality reduction per 10% ART increase in that region (2.1%) is only half as large as in East Africa (4.2%). This attenuation was not due to lower ART coverage – Southern Africa had

the highest coverage (60.5%) – but likely reflects later treatment initiation, higher loss to follow-up, or a greater burden of advanced HIV disease and tuberculosis co-infection. Conversely, a non-significant interaction (e.g., incidence in Central Africa) means the effect is statistically indistinguishable from East Africa, though wide confidence intervals may also play a role.

Policy implications

Our findings have four urgent implications for HIV policy in sub-Saharan Africa.

First, sustained investment in ART is non-negotiable. The estimated 1·2 million deaths averted represent a major public health achievement, but with 380,000 deaths still occurring in 2023 [2], the job is far from complete. Funding for ART programmes must be protected and expanded.

Second, regional tailoring is essential. The one-size-fits-all approach to ART deployment is suboptimal. In West Africa, where the incidence effect was weakest, efforts should focus on earlier diagnosis, linkage to care and reducing the substantial pre-treatment loss to follow-up. In Southern Africa, where mortality reduction was attenuated despite high coverage, improving retention in care, adherence support, and management of comorbidities (particularly tuberculosis) should be priorities. In Central Africa, with ART coverage of only 33%, the immediate priority is coverage expansion.

Third, prevalence is an unreliable standalone metric for programme evaluation. Policymakers should resist using prevalence trends to judge ART programme success. Incidence and mortality provide more direct measures of prevention and survival effects. The common practice of citing prevalence declines as evidence of ART effectiveness risks overstatement and may lead to complacency.

Fourth, ART cannot substitute for health system strengthening. The modifying effects of health expenditure per capita, Human Development Index and political stability indicate that ART's impact is amplified by stronger health systems. Investments in laboratory infrastructure (viral load monitoring), supply chains, healthcare worker training and community engagement are complementary necessities.

Strengths and limitations

Major strengths include the large, multi-country sample (38 countries, 494 observations), the 13-year longitudinal design, the use of harmonised data from reputable international sources, and the methodologically rigorous fixed-effects approach that controls for time-invariant country-specific confounding. The inclusion of regional interaction terms and multiple contextual covariates provides policy-relevant granularity.

Several limitations must be acknowledged. First, the ecological design precludes causal inference at the individual level; associations observed at population level may not hold for individuals, and ecological fallacy is a risk [27]. Second, despite extensive covariate adjustment, residual confounding by unmeasured factors (e.g., behavioural changes, condom use, voluntary medical male circumcision coverage, migration patterns) may persist. Third, UNAIDS estimates involve modelling assumptions that introduce uncertainty, particularly in countries with weak vital registration systems. Fourth, the exclusion of ten countries (including several East African nations) due to missing data may limit representativeness for that sub-region. Fifth, the study period (2010–2022) excludes early ART scale-up years (2004–2009), potentially underestimating long-term effects.

Research priorities

Future research should address three priority questions. First, what explains the substantial regional heterogeneity in ART effectiveness? Quantitative analyses linking health system characteristics (e.g., retention rates, viral load suppression rates, time from diagnosis to treatment initiation) to outcomes are needed. Second, what is the optimal ART coverage threshold for achieving population-level incidence reduction? Our data suggest a non-linear relationship that warrants exploration. Third, how will the transition to dolutegravir-based regimens affect the associations we observed? As more countries adopt DTG, updated analyses will be essential.

Conclusion

Between 2010 and 2022, ART coverage expansion in sub-Saharan Africa averted an estimated 1·2 million deaths and substantially reduced HIV incidence, but effects varied markedly by region. The association with prevalence was modest and context-dependent, indicating that prevalence trends should not be used as

standalone indicators of ART programme success. Regional tailoring of ART deployment strategies—intensifying early diagnosis and linkage in West Africa, improving retention and adherence in Southern Africa, expanding coverage in Central Africa—combined with sustained investment in health systems, remains essential for achieving epidemic control.

Declarations

Ethics approval and consent to participate

This study used only publicly available, anonymised, country-level aggregate data from UNAIDS, the World Bank, and the United Nations Development Programme. No primary data collection from human participants was conducted, and no identifiable personal or clinical data were accessed. Therefore, ethical approval and individual consent were not required. All methods were carried out in accordance with relevant guidelines and regulations.

Consent for publication

Not applicable. This manuscript contains no individual person's data in any form (including individual details, images, or videos).

Availability of data and materials

All data used in this study are publicly available from UNAIDS (https://aidsinfo.unaids.org/), the World Bank (https://databank.worldbank.org/), and the United Nations Development Programme (https://hdr.undp.org/data-center). The R analysis code is available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

DEY conceptualised the study, performed data extraction and statistical analysis, and drafted the manuscript. CEB supervised the research, contributed to study design and interpretation, and critically

revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Authors' information

Not applicable.

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