Assessing the potential impact of disruptions due to COVID-19 on HIV among key and lower-risk populations in the largest cities of Cameroon and Benin. Supplement.

Contents

Yaoundé model structure

This section is adapted from the supplementary material for Silhol et al. (JIAS 2021[1])

We adapted[2] and re-coded a dynamic HIV transmission model to reproduce the HIV epidemic in Yaoundé, Cameroon. The model was used to evaluate the population-level impact of condom use and antiretroviral treatment (ART) and the contribution of female sex workers (FSW), clients of FSW (referred to as clients hereafter) and men who have sex with men (MSM) to onward transmissions. The model divides the adult population (age 15-49 years) into six risk groups: lower-risk females ($i = 1$) and males ($i = 2$), clients ($i = 3$), FSW ($i = 4$), younger MSM (< 25 years, $i = 5$) and older MSM (≥ 25 years, $i = 6$) (Figure S1a). Lower-risk individuals refers to men who have never engaged in sex with other men, and to men and women who are not engaged in commercial sex. Lower-risk individuals may include individuals who used to engage in commercial sex.

Individuals enter the modelled population at a rate Φ that balances non-HIV deaths and reflects population growth G_t, with a proportion p (50%) entering into the lower-risk female group and the remainder $(1 - p)$ entering the lower-risk male group. Lower-risk females enter sex work (i.e. enter the FSW strata) at a rate κ and stay as FSW for duration $1/\gamma$ years (Table S1). Similarly, male clients transition from the lower-risk male group at rate k and remain as clients for a period of $1/g$ years before returning to the lower-risk male group. The model assumes that a fraction M of males entering the model are younger MSM, that only a fraction Z of younger MSM have sex with another male partners, and they move from the younger to the older MSM risk group at a rate $\zeta = 1/10$, where they remain until death.

The model captures HIV transmission among all modelled risk groups through vaginal and anal sexual intercourse (VI and AI, respectively) between all males and females, and AI within the MSM group (Figure S1a). The model stratifies the population with respect to HIV infection and disease progression such that for each group i, there is uninfected (S_i), acute infection (E_i), chronic infection (I_i) and on ART (T_i), with $i = 1,2\ldots6$. Upon infection, susceptible individuals move to the acute stage of HIV infection and stay there for a duration of $1/\eta$ before progressing to the chronic stage (Figure S1b). In the chronic stage, people living with HIV (PLHIV) can experience HIV-related mortality at a rate δ, or are recruited onto ART at a (group- and time-dependent) rate $\omega_{i,t}$. A fraction α_t of PLHIV on ART are virally suppressed, with α_t being assumed to be fixed to the 2017 CAMPHIA estimate over 1996-2020[3], and assumed to increase from 2020 to 90% in 2030. HIV-related mortality among the fraction α_t of PLHIV on ART which are virally suppressed is reduced by a factor φ compared to untreated or unsuppressed PLHIV. Individuals on ART can be lost to follow-up at a rate σ, whereupon they return to the chronic infection stage. All modelled risk groups experience non-HIV related death or reach the age of 50 years and leave the model at rates μ_1, μ_2 and μ_3 for females, all males except older MSM, and older MSM, respectively.

The model incorporates HIV transmission in the context of the following partnership types: main between men and women (k=1), casual between men and women (k=2) and commercial sex between FSW and clients only (k=3); and main between MSM (k=4), and casual between MSM (k=5) (Figure S1a). Commercial partnerships can only occur between FSW and their clients. The risk of HIV transmission for a particular individual is related to the HIV prevalence of their sexual partners, with the HIV transmission risk being elevated by a factor ν if they are in the acute stage of infection compared to the transmission risk for the chronic stage, and reduced to 0 if they are virally suppressed (we assume that PLHIV on ART but not virally suppressed have the same transmissibility and mortality as untreated PLHIV). Transmission risk is also related to the average frequency of sex acts (denoted by ${\Psi_{i,j,h}}^k$) for different types of partnerships and between risk groups i and j (with ${\Psi_{i,j,h}}^k =$

$\Psi_{j,i,h}{}^{k}$ to ensure they balance), where k denotes the type of sexual partner (main, casual or commercial) and h denotes the type of sexual act (VI or AI). HIV transmission is reduced through condom use by a factor $\left(1 - \varepsilon\pi_{ijh}^{k}\right)$, where ε is the per-act efficacy of condom use and π_{ijh}^{k} is the fraction of condom use by those in risk groups i and j (with $\pi_{ijh}^{k} = \pi_{jih}^{k}$ to ensure they balance). The fraction of condom use is assumed to be time dependent and varies depending on the type of partnership, and accounts for possible over-reporting, up to 25% (Table S2). The model assumes a proportion ξ of males are circumcised, with these males having a reduced risk of HIV acquisition, modelled by a factor (1-$\xi\vartheta$), where ϑ is the per-partner efficacy of circumcision. More details on the model and its equations are described below.

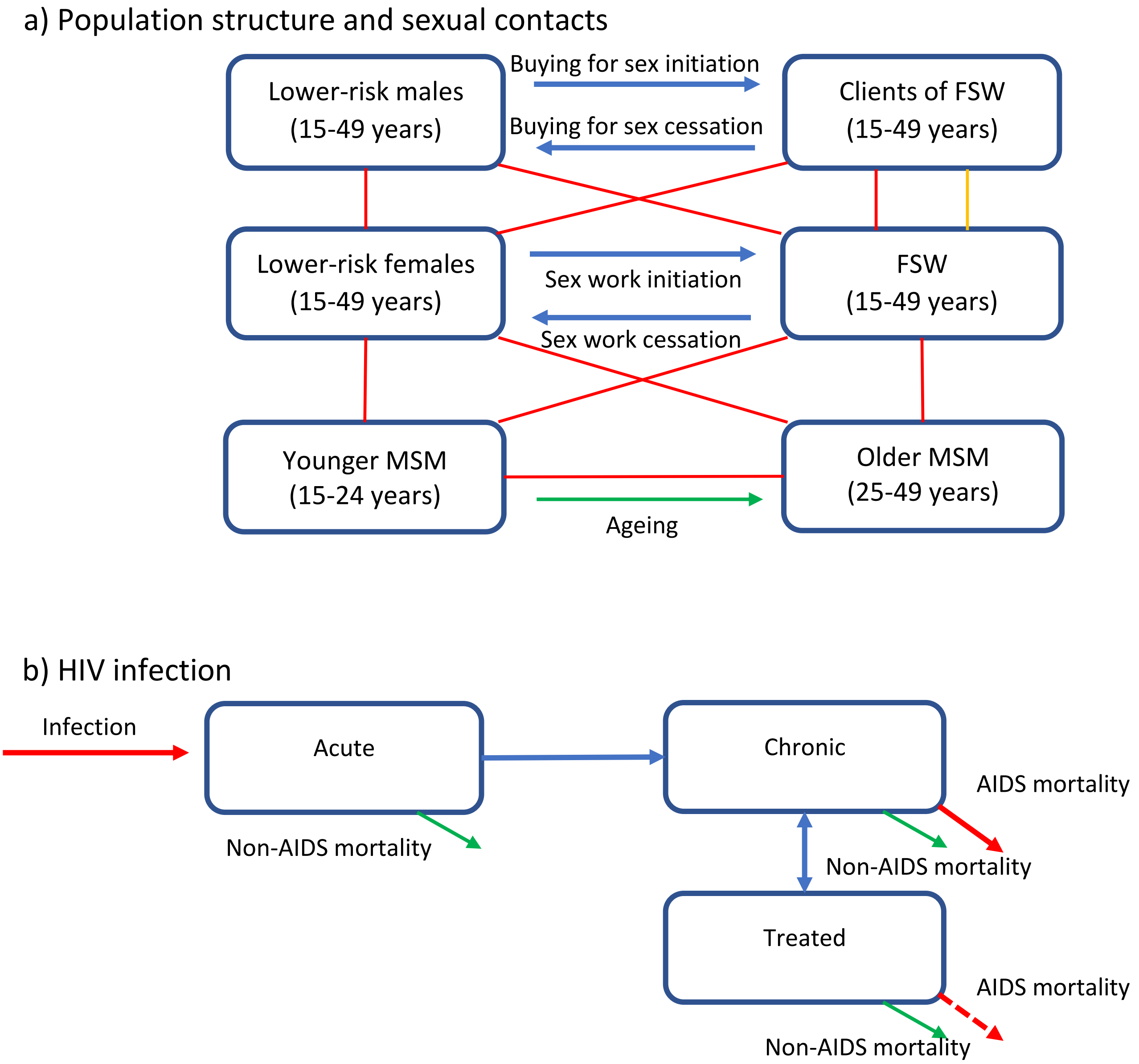


Figure S1. Yaoundé model structure. a) Modelled population structure, population flows (blue arrows), mortality and ageing (green arrows) and sexual partnerships (main/casual: red lines, commercial: orange lines) between the different risk groups. b) Natural history of HIV infection. The model assumes that a proportion α_t of treated PLHIV are virally suppressed.

Yaoundé model equations

The model equations are as follows:

Lower-risk female group:

$$\frac{dS_1}{dt} = \Phi p + \gamma S_4 - (\Lambda_1^1 + \Lambda_1^2)S_1 - (\kappa + \mu_1)S_1$$
$$\frac{dE_1}{dt} = (\Lambda_1^1 + \Lambda_1^2)S_1 + \gamma E_4 - (\kappa + \eta + \mu_1)E_1$$
$$\frac{dI_1}{dt} = \eta E_1 + \sigma T_1 + \gamma I_4 - (\kappa + \omega + \delta + \mu_1)I_1$$
$$\frac{dT_1}{dt} = \omega I_1 + \gamma T_4 - (\kappa + \sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_1)T_1$$

Lower-risk male group:

$$\frac{dS_2}{dt} = \Phi(1-p)(1-M) + gS_3 - (\Lambda_2^1 + \Lambda_2^2)S_2 - (z + \mu_2)S_2$$
$$\frac{dE_2}{dt} = (\Lambda_2^1 + \Lambda_2^2)S_2 + gE_3 - (z + \eta + \mu_2)E_2$$
$$\frac{dI_2}{dt} = \eta E_2 + \sigma T_2 + gI_3 - (z + \omega + \delta + \mu_2)I_2$$
$$\frac{dT_2}{dt} = \omega I_2 + gT_3 - (z + \sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_2)T_2$$

Client risk group:

$$\frac{dS_3}{dt} = zS_2 - (\Lambda_3^1 + \Lambda_3^2 + \Lambda_3^3)S_3 - (g + \mu_2)S_3$$
$$\frac{dE_3}{dt} = (\Lambda_3^1 + \Lambda_3^2 + \Lambda_3^3)S_3 + zE_2 - (g + \eta + \mu_2)E_3$$
$$\frac{dI_3}{dt} = \eta E_3 + \sigma T_3 + zI_2 - (g + \omega + \delta + \mu_2)I_3$$
$$\frac{dT_3}{dt} = \omega I_3 + zT_2 - (g + \sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_2)T_3$$

FSW risk group:

$$\frac{dS_4}{dt} = \kappa S_1 - (\Lambda_4^1 + \Lambda_4^2 + \Lambda_4^3)S_4 - (\gamma + \mu_1)S_4$$
$$\frac{dE_4}{dt} = (\Lambda_4^1 + \Lambda_4^2 + \Lambda_4^3)S_4 + \kappa E_1 - (\gamma + \eta + \mu_1)E_4$$
$$\frac{dI_4}{dt} = \eta E_4 + \sigma T_4 + \kappa I_1 - (\gamma + \omega + \delta + \mu_1)I_4$$
$$\frac{dT_4}{dt} = \omega I_4 + \kappa T_1 - (\gamma + \sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_1)T_4$$

Younger MSM risk group:

$$\frac{dS_5}{dt} = \Phi(1-p)M - (\Lambda_5^1 + \Lambda_5^2 + \Lambda_{5*}^4 + \Lambda_{5*}^5)S_5 - (\zeta + \mu_2)S_5$$
$$\frac{dE_5}{dt} = (\Lambda_5^1 + \Lambda_5^2 + \Lambda_{5*}^4 + \Lambda_{5*}^5)S_5 - (\zeta + \eta + \mu_2)E_5$$
$$\frac{dI_5}{dt} = \eta E_5 + \sigma T_5 - (\zeta + \omega + \delta + \mu_2)I_5$$
$$\frac{dT_5}{dt} = \omega I_5 - (\zeta + \sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_2)T_5$$

Older MSM risk group:

$$\frac{dS_6}{dt} = \zeta S_5 - (\Lambda_6^1 + \Lambda_6^2 + \Lambda_{6*}^4 + \Lambda_{6*}^5)S_6 - \mu_3 S_6$$
$$\frac{dE_6}{dt} = (\Lambda_6^1 + \Lambda_6^2 + \Lambda_{6*}^4 + \Lambda_{6*}^5)S_6 + \zeta E_5 - (\eta + \mu_3)E_6$$
$$\frac{dI_6}{dt} = \eta E_6 + \sigma T_6 + \zeta I_5 - (\omega + \delta + \mu_3)I_6$$
$$\frac{dT_6}{dt} = \omega I_6 + \zeta T_5 - (\sigma + (\alpha\varphi + (1-\alpha))\delta + \mu_3)T_6$$

The terms Λ_i^k correspond to the rate at which susceptible individuals of risk group *i* acquire HIV within sexual partnerships of type *k*, and are calculated as follows:

Force of infection

The parameters β_{rv} , β_{ra}, β_{iv} , β_{ia} represent the HIV acquisition probability per sex act through receptive/insertive VI/AI respectively. The frequency of sex partners of type k for risk group i is given by n_i^k. The terms Ψ_{iv}^k and Ψ_{ia}^k are the total number of vaginal and anal sex acts for the risk group *i* with a partner type *k*. The term B_j reflects the HIV prevalence of the group they are having sex with, which also accounts for the cofactors that increase or decrease HIV transmission risk due to the HIV acute phase E_j (ν), or if on HIV treatment but not virally suppressed $(1-\alpha_j)T_j$, such that $B_j = (\nu E_j + I_j + (1-\alpha_j)T_j)/N_j$, where N_j is the total population for each risk group j.

Let ρ_j^k be the probability of heterosexual mixing of a risk group with group *j* for each type of sexual partnership k (main or casual partnerships), and *j*=1, 2, 3, 4, 5, and 6 denotes the risk groups of lower-risk female, lower-risk male, clients, FSW, younger and older MSM respectively. The subscripts v and a denote VI and AI, respectively, then the force of infection (FOI) Λ_i^k for risk group i due to their k partnership with groups j are:

The probability of mixing with different risk groups j for heterosexual partnership type k, where j=1..6 , is ρ_j^k where:

Probability of mixing with **lower-risk females** for heterosexual main and casual partnerships	$\rho_1^k = \frac{n_1^k N_1}{n_1^k N_1 + n_4^k N_4}$
Probability of mixing with **lower-risk males** for heterosexual main and casual partnerships	$\rho_2^k = \frac{n_2^k N_2}{n_2^k N_2 + n_3^k N_3 + n_5^k N_5 + n_6^k N_6}$
Probability of mixing with **clients of FSW** for heterosexual main and casual partnerships	$\rho_3^k = \frac{n_3^k N_3}{n_2^k N_2 + n_3^k N_3 + n_5^k N_5 + n_6^k N_6}$
Probability of mixing with **FSW** for heterosexual main and casual partnerships	$\rho_4^k = \frac{n_4^k N_4}{n_1^k N_1 + n_4^k N_4}$
Probability of mixing with **younger MSM** for heterosexual main and casual partnerships	$\rho_5^k = \frac{n_5^k N_5}{n_2^k N_2 + n_3^k N_3 + n_5^k N_5 + n_6^k N_6}$
Probability of mixing with **older MSM** for heterosexual main and casual partnerships	$\rho_6^k = \frac{n_6^k N_6}{n_2^k N_2 + n_3^k N_3 + n_5^k N_5 + n_6^k N_6}$

These mixing equations assume that all sexual mixing for casual and main partnerships is proportionate based on the total number of sexual partnerships that each risk group provides.

For females, we allow the sexual behaviour of males with females to determine who the females have sex with and how many new partners they acquire. Therefore, the total number of new sexual partners of type k that males have with females in group (i) is:

$$\rho_i^k \sum_{l=2,3,5,6} n_l^k N_l$$

Where we have summed up all male partnerships of type k and seen how many of these will be with women of risk group i (i=1 or 4). Note, here it is important to emphasise that ρ_i^k is defined in terms of the self-reported frequency of new partnerships by women, but this is then used to define an adjusted frequency of new sexual partnerships that will balance the number reported by males. Therefore, if there are N_i women in that group then each woman in the group has the following adjusted frequency of new male sexual partners of type k:

$$\frac{\rho_i^k}{N_i} \sum_{l=2,3,5,6} n_l^k N_l$$

And so, the adjusted number of new partners each woman in risk group i has with men in each group (j) is

$$\frac{\rho_i^k}{N_i} \rho_j^k \sum_{l=2,3,5,6} n_l^k N_l.$$

We find this simplifies to the following when we substitute the formulation for ρ_j^k:

$$\frac{\rho_i^k}{N_i} n_j^k N_j$$

The risk of acquiring HIV from a specific partner risk group within a specific partnership type with a is modelled as a Bernoulli process, depending on the annual number of vaginal/anal protected/unprotected sex acts, and the probability of acquiring HIV during one such contact. Therefore, the force of infection (FOI) Λ_1^k for the lower-risk female group due to their main ($k = 1$) and casual ($k = 2$) partners is adapted as follows:

$$\Lambda_1^k = \frac{\rho_j^k}{N_1} \sum_{j:2,3,5,6} 1 - \left[(1-\beta_{rv})^{\frac{\Psi_{1v}^k\left(1-\pi_{1jv}^k\right)}{n_1^k}} (1-\beta_{ra})^{\frac{\Psi_{1a}^k\left(1-\pi_{1ja}^k\right)}{n_1^k}} (1-(\beta_{rv}(1-\varepsilon))^{\frac{\Psi_{1v}^k \pi_{1jv}^k}{n_1^k}} (1-\beta_{ra}(1-\varepsilon))^{\frac{\Psi_{1ja}^k \pi_{1ja}^k}{n_1^k}} \right] n_j^k N_j B_j$$

The FOI for the lower-risk male group due to their main ($k = 1$) and casual ($k = 2$) partners is

$$\Lambda_2^k = n_2^k(1-\xi\vartheta) \sum_{j:1,4} 1 - \left[(1-\beta_{iv})^{\frac{\Psi_{2v}^k\left(1-\pi_{2jv}^k\right)}{n_2^k}} (1-\beta_{ia})^{\frac{\Psi_{2a}^k\left(1-\pi_{2ja}^k\right)}{n_2^k}} (1-(\beta_{iv}(1-\varepsilon))^{\frac{\Psi_{2v}^k \pi_{2jv}^k}{n_2^k}} (1-\beta_{ia}(1-\varepsilon))^{\frac{\Psi_{2a}^k \pi_{ija}^k}{n_2^k}} \right] \rho_j^k B_j$$

The force of infection for clients due to their main, casual ($k = 1, 2$) and commercial partners (k=3) are given as:

$$\Lambda_3^{k:1-2} = n_3^{k:1-2}(1-\xi\vartheta)\sum_{j:1,4} 1 - \left[(1-\beta_{iv})^{\frac{\Psi_{3v}^k\left(1-\pi_{3jv}^k\right)}{n_3^k}}(1-\beta_{ia})^{\frac{\Psi_{3a}^k\left(1-\pi_{3ja}^k\right)}{n_3^k}}(1-(\beta_{iv}(1-\varepsilon))^{\frac{\Psi_{3v}^k\pi_{3jv}^k}{n_3^k}}(1-\beta_{ia}(1-\varepsilon))^{\frac{\Psi_{3a}^k\pi_{3ja}^k}{n_3^k}}\right]\rho_j^k B_j$$

$$\Lambda_3^3 = n_3^{k:3}(1-\xi\vartheta)\left\{1 - \left[(1-\beta_{iv})^{\frac{(1-FAI_{co})(1-\pi_{34v}^k)}{n_3^k}}(1-\beta_{ia})^{\frac{FAI_{co}(1-\pi_{34a}^k)}{n_3^k}}(1-(\beta_{iv}(1-\varepsilon))^{\frac{(1-FAI_{co})\pi_{34v}^k}{n_3^k}}(1-\beta_{ia}(1-\varepsilon))^{\frac{FAI_{co}\pi_{34a}^k}{n_3^k}}\right]B_4\right\}$$

Where FAI_{co} is the proportion of commercial sex acts that are anal. As there was no information about the annual number of sex acts per client, we assumed that the total annual number of clients of sex workers corresponded to the total annual number of commercial sex acts that they reported.

Similarly, the FOI for female sex workers is

$$\Lambda_4^{k:1-2} = \frac{\rho_4^k}{N_4}\sum_{j:2,3,5,6} 1 - \left[(1-\beta_{rv})^{\frac{\Psi_{4v}^k\left(1-\pi_{4jv}^k\right)}{n_4^k}}(1-\beta_{ra})^{\frac{\Psi_{4a}^k\left(1-\pi_{4ja}^k\right)}{n_4^k}}(1-(\beta_{rv}(1-\varepsilon))^{\frac{\Psi_{4v}^k\pi_{4jv}^k}{n_4^k}}(1-\beta_{ra}(1-\varepsilon))^{\frac{\Psi_{4a}^k\pi_{4ja}^k}{n_4^k}}\right]n_4^k N_j B_j$$

$$\Lambda_4^3 = n_4^{k:3}\left\{1 - \left[(1-\beta_{rv})^{\frac{(1-FAI_{co})(1-\pi_{43v}^k)}{n_4^k}}(1-\beta_{ra})^{\frac{FAI_{co}(1-\pi_{43a}^k)}{n_4^k}}(1-(\beta_{rv}(1-\varepsilon))^{\frac{(1-FAI_{co})\pi_{43v}^k}{n_4^k}}(1-\beta_{ra}(1-\varepsilon))^{\frac{FAI_{co}\pi_{43a}^k}{n_4^k}}\right]B_3\right\}$$

Men who have sex with men are assumed to have main and casual partnerships with women from the lower risk and FSW risk groups, as well as other MSM. The FOI for younger MSM due to their main and casual ($k = 1,2$) partnerships with females is:

$$\Lambda_5^{k:1-2} = n_5^{k:1-2}(1-\xi\vartheta)\sum_{j:1,4} 1 - \left[(1-\beta_{iv})^{\frac{\Psi_{5v}^k\left(1-\pi_{5jv}^k\right)}{n_5^k}}(1-\beta_{ia})^{\frac{\Psi_{5a}^k\left(1-\pi_{5ja}^k\right)}{n_5^k}}(1-(\beta_{iv}(1-\varepsilon))^{\frac{\Psi_{5v}^k\pi_{5jv}^k}{n_5^k}}(1-\beta_{ia}(1-\varepsilon))^{\frac{\Psi_{5a}^k\pi_{5ja}^k}{n_5^k}}\right]\rho_j^k B_j$$

For MSM sexual intercourse with their male sexual partners, we assume that the per-act risk of HIV acquisition during sex between males was the average between the risk during insertive and receptive anal sex ($\frac{\beta_{ia}+\beta_{ra}}{2}$). The asterisk (*) show parameters related to MSM with their male partners. Then, the FOI for younger MSM due to their main and casual ($k = 4{,}5$) partnerships with other MSM is:

$$\Lambda_{5*}^{k:4-5} = n_5^{k:4-5}(1-\xi\vartheta)\sum_{j:5,6} 1 - \left[(1-\frac{\beta_{ia}+\beta_{ra}}{2})^{\frac{\Psi_{5*}^k\left(1-\pi_{5j*}^k\right)}{n_{5*}^k}}(1-\frac{\beta_{ia}+\beta_{ra}}{2}(1-\varepsilon))^{\frac{\Psi_{5*}^k\pi_{5j*}^k}{n_{5*}^k}}\right]\rho_{j*}^k B_j$$

.

Where ρ_{5*}^k is the probability of mixing to form MSM male sexual partnerships with younger or older MSM, and is given by $\rho_{5*}^k = (n_{5*}^k N_5(1-Z))/((n_{5*}^k N_5(1-Z)) + n_{6*}^k N_6)$ and $\rho_{6*}^k = n_{6*}^k N_6/((n_{5*}^k N_5(1-Z)) + n_{6*}^k N_6)$, with $(1-Z)$ being the fraction of younger MSM that has sex with other males.

Similarly, the FOI for older MSM due to their female main and casual ($k = 1, 2$) partners

$$\Lambda_6^{k:1-2} = n_6^{k:1-2}(1-\xi\vartheta)\sum_{j:1,4} 1 - \left[(1-\beta_{iv})^{\frac{\Psi_{6v}^k\left(1-\pi_{6jv}^k\right)}{n_6^k}}(1-\beta_{ia})^{\frac{\Psi_{6a}^k\left(1-\pi_{6ja}^k\right)}{n_6^k}}(1-(\beta_{iv}(1-\varepsilon))^{\frac{\Psi_{6v}^k\pi_{6jv}^k}{n_6^k}}(1-\beta_{ia}(1-\varepsilon))^{\frac{\Psi_{6a}^k\pi_{6ja}^k}{n_6^k}}\right]\rho_j^k B_j$$

And due to their main and casual ($k = 4{,}5$) partnerships with other MSM

$$\Lambda_{6*}^{k:4-5} = n_6^{k:4-5}(1-\xi\vartheta)\sum_{j:5,6} 1 - \left[(1-\frac{\beta_{ia}+\beta_{ra}}{2})^{\frac{\Psi_{6*}^k\left(1-\pi_{6j*}^k\right)}{n_{6*}^k}}(1-\frac{\beta_{ia}+\beta_{ra}}{2}(1-\varepsilon))^{\frac{\Psi_{6*}^k\pi_{6j*}^k}{n_{6*}^k}}\right]\rho_{j*}^k B_j$$

Yaoundé model parameterisation and fitting

The Yaoundé model was coded in C programming language, numerically solved using a Runge-Kutta four method,[4] and fitted using the importance resampling method [5,6] which accounts for uncertainties in parameters and fitting outcome estimates: First, we defined the prior ranges of demographic, sexual behaviour, epidemiological and intervention parameter values and 40 fitting outcomes (Table S3), mostly from Yaoundé or, if unavailable, from other Cameroonian studies (Tables S1, S2). Second, we sampled 20 million parameter combinations and retained those (n=20744) which produced epidemics compatible with 40 conservative pre-specified targets for each fitting outcome (i.e. 2.5 time the bounds of the 95%CI of each data point, except for UNAIDS ART coverage and KP size estimates, see Table S3) (referred to as the 1st level sample). Third, each parameter set in the 1st level sample was attributed an overall log-likelihood by summing the log-likelihood of the predicted value of each of the 23 fitting outcomes for which a sample size was available (out of the 40 outcomes). Finally, we generated a set of 1000 posterior simulations, our baseline scenario, by resampling the pool of 20744 parameter sets in our 1st level sampling, with resampling probability proportional to the overall likelihood of each fitted parameter set. Model outcomes are expressed using their median and 95% uncertainty interval (UI, 2.5th and 97.5th percentiles across the 1000 posterior simulations).

Yaoundé model parameters (Tables S1, S2)

Overview

Several data sources informed model parameters (Tables S1, S2) and our 40 calibration targets (Table S3).

Most Yaoundé model parameters were sourced from demographic, sexual behaviour and HIV prevalence data from the Census and United Nations Population Division, several Demographic Health Surveys (DHS) (1997, 2004, 2011, 2018),[7-11] and the 4-city study.[12-14] The sexual behaviours and levels of HIV interventions among KPs were based on surveys conducted in the city, including a recent Integrated Biological and Behavioral Surveillance Survey (IBBS, 2016) conducted among FSW and MSM, and a study conducted among clients in 2017.[15,16] The Yaoundé model was fitted to 40 empirical demographic, HIV prevalence and intervention coverage data points including: total population size, HIV prevalence among all 15-49 years old females and males[7,8,17,18], HIV prevalence among FSW,[12,15,17,19-23] their clients,[16] and among MSM.[15,24,25] The model was also fitted to national UNAIDS estimates of ART coverage by gender, and recent estimates of viral suppression among PLHIV by gender,[3] and for KPs.[15,16]

Demography and population structure

Data from the Census and United Nations Population Division informed the demographic parameters and fitting outcomes (e.g. population growth rate, population size, non-AIDS related mortality (as life expectancy at age 15 years)).[26-28] Prior distributions of the FSW and client recruitment rates κ and k were fixed over time but varied across simulations and sampled assuming wide uniform ranges, as no data was available. The duration of sex work (for FSW) and buying sex (for clients) $1/\gamma$ and $1/g$ were also fixed over time but varied across simulations, and were informed by several studies reporting relatively similar durations of 4-10 years for FSW,[15,23,29,30] whereas only one recent (2017) estimate was available for clients[16] reporting 4-14 years as duration of buying sex. These rates and durations were fitted to empirical estimates of KP population sizes (described in the fitting section). The proportion of MSM among newly sexually active males (M) was also sampled using wide conservative ranges and fitted to empirical estimates, while we assumed that up to 50% of younger MSM don't have sex with other males (parameter), based on the reported age at first sex with another male by Cameroonian MSM (around 19 years) in [31,32].

Sexual behaviours

Several Demographic Health Surveys (DHS) (1997, 2004, 2011, 2018)[7-11] and the 4-city household based study[12-14] informed the sexual behaviour of the lower-risk groups in Yaoundé (e.g. number of partners/sex acts, condom use). The annual number of new main and casual partnerships among the lower-risk groups was calculated using empirical estimates of the reported lifetime number of partners in the DHS and 4 cities study.[7,8,14,33] The annual number of sex acts of the lower-risk groups $\Psi_{i=1-2}$ was taken from the 4-cities study weekly estimates,[34] and the specific number of acts with main and casual partners were calculated on the proportion of all sex acts with casual partners (20%) in the 1998 DHS.[9] Clients of FSW in the 2017 "Modes of transmission" study[16] reported around twice as many partners as lower-risk males in the DHS, with 2 main partners in the last year, and 2 casual partners in the last 3 months, thus we assumed that for clients the number of new main and casual partners and sex acts per year was between 1.5 and 2.5 fold higher compared to lower-risk males.

The annual number of new partners and sex acts of FSWs were taken from the 2016 IBBS survey in Yaoundé,[15] except for commercial partners, where a wider range was selected from all available estimates for Yaoundé.[12,15,22,35,36] As no data was available on the number of sex acts per client, the model assumes that the number of commercial sex acts of FSW correspond to their number of clients.

The annual number of new partners and sex acts of MSMs were also taken from the 2016 IBBS survey in Yaoundé.[15] As the data did not show significant differences in reported numbers by age, we assumed that age did not affect sexual activity.

The model assumes that fractions of heterosexual sex acts are anal. The proportion of anal sex acts differed by risk group and partnership type, but data was only available for commercial acts (4-5% in the 4-cities study)[12] and the sex acts between MSM and their main or casual female partners (in the 2016 IBBS).[15] As no data was available on anal sex among lower-risk groups, we derived their proportion of anal acts by multiplying the fraction reported by FSW with the relative-risk of lifetime prevalence of anal sex among all females vs higher-risk females in a review of the practice of anal sex in South Africa (RR between 0.5 and 1).[37]

Interventions: Male circumcision

Over 90% of males are circumcised in Cameroon[7,8,33] (reflected by the parameter ξ). The per-partner effect of male circumcision in decreasing HIV acquisition risk among males was (1- $\xi\vartheta$), with ϑ reflecting per-partner efficacy.[38]

Interventions: Condom use (Table S2)

The model reflected reported changes in condom-use (reported at last sex) over time among the different risk groups, and partnership types by assuming linear trends between empirical estimates over time, and accounted for plausible levels of over reporting[39] (up to 25%, Figure 1a-c, Tables S1, S2). Our model reflected higher levels of condom use among KP than lower-risk groups in 2016 and the larger fraction of sex acts protected by condoms reported by FSW during commercial sex than during non-commercial sex (Figure 1b), while MSM reported similar levels of condom use with male and female partners.[15] Condom use between key and lower-risk populations was assumed to be at the level reported by key populations. We assumed that levels of condom use over the period 2019-2030 remained at the 2018 levels. Condom reduced the per-act probability of transmission by 71-98%,[40-42] with the parameter ε reflecting per-act efficacy.

Interventions: ART/Viral suppression

The model represented a rate of initiating ART $\omega_{i,t}$ which varied over time and across risk groups.[43] These were calculated using a "base" initiation rate among lower-risk females over 2010-2013 (when eligibility was CD4<350) $\omega_{i=1,t=2010-2013}$, multiplied by a set of cofactors reflecting change in initiation rates over time and across risk groups. The parameters $RR_{\omega}^{t=1996-2000}$, $RR_{\omega}^{t=2000-2007}$, $RR_{\omega}^{t=2007-2010}$, $RR_{\omega}^{t=2013-2020}$, and $RR_{\omega}^{t=2020-2030}$ reflect relative risks of ART initiation compared to the period 2010-2013, with year cut-offs corresponding to changes in treatment guidelines in Cameroon. ART initiation rates before 2000 was assumed to be extremely low (up to non-existent), whereas rates after 2020 were assumed to be constant and up to 5-fold higher than for the period 2013-2020, in order to reflect the impact of free ART testing and treatment in Cameroon from January 2020 [44]. The parameters $RR_{\omega}^{i=2-3}$, $RR_{\omega}^{i=4}$, $RR_{\omega}^{i=5-6}$ reflect relative risks of ART initiation among the risk groups compared to lower-risk females.

Around 80% of PLHIV on ART were virally suppressed in Cameroon in 2017,[3] with no estimates prior to this date. The model assumed that a constant proportion α_t ranging from 75% to 85% of PLHIV on ART are virally suppressed until 2020, this proportion linearly increasing to 90% in 2030. Viral suppression was associated with a decrease in HIV mortality by a factor (1-φ), based on trends in the mortality rates of PLHIV before and after the introduction of ART in sub-Saharan settings.[45] Viral suppression was assumed to fully prevent HIV transmission to partners.[46] The "base" ART initiation rate and all cofactors were sampled using wide prior ranges, and fitted to ART coverage by sex, as well as viral suppression coverages by risk group (see Table S3 and model fitting section).

Empirical estimates of ART failure or drop-out in Yaoundé only described the first year of initiation(corresponding to only around 60% retention over one year).[47-49] We assumed a relatively high drop-out rate σ of 10% given these relatively low retention estimates of the first year of initiation.

Yaoundé model fitting outcomes

The Table S3 describes each outcome – including their prior targets and sample sizes – used to calculate each simulation overall log-likelihood.

The size of the overall population aged 15-49 years in Yaoundé was fitted to a World Bank estimate based on Census data for 2015,[15] which was previously used to estimate the size of the FSW and MSM risk groups in Yaoundé in the 2016 IBBS (Figure S2a).

The fraction of FSW among females in 2016 was obtained using the minimum and maximum estimate from three recent studies conducted in Yaoundé which all reported similar point-estimates [15,26,36] (Figure S2b). The fraction of male clients among all males was defined based on several studies conducted in Yaoundé which reported heterogeneous estimates [7-9,12,33] (Figure S2c). The fraction of MSM among all males was obtained minimum and maximum estimate of two studies recently conducted in Yaoundé (Figure S2d).

The HIV prevalence among all females and all males in Yaoundé was fitted to DHS as well as 4-cities study estimates in 1997, 2004, 2011[7,8,17,18], and cross-validated with the household surveys Cameroon Population-based HIV Impact Assessment (CAMPHIA)[3] and DHS[11] estimates for 2017 and 2018, respectively (Figure 1a,b).

There was no HIV incidence data available for Yaoundé specifically, but a rough estimate for number of incident HIV infections in the city was obtained by multiplying the estimated national number of incident infections occurring in Cameroon over 2009-2018 by UNAIDS (307000 (95%CI: 268000-345000)) by the fraction of PLHIV in Cameroon residing in Yaoundé in the 2011 DHS (17.5%), leading to an estimate of 53673 (95%CI: 46854-60316) incident infections over 2009-2018. In comparison, our model estimated that 56363 (95%UI: 462769-68800) incident infections occurred in Yaoundé over the same period (not shown).

The HIV prevalence among FSW in Yaoundé was compared to five local estimates spanning from 1991 to 2016, including a recent IBBS [12,15,17,19-23] (Figure 1d). The model was also fitted to a recent estimate of the HIV prevalence among male clients of FSW conducted in Yaoundé [16], and cross-validated with HIV prevalence estimates among males reporting having paid for sex in the past 12 months in the 2004 and 2011 DHS (Figure 1c). The HIV prevalence among younger and older MSM was fitted to two time points in 2011 and 2016[15,24,25] (Figure 1e,f).

We screened-out simulations which were not compatible with UNAIDS estimates of ART coverage among all females and all males living with HIV[50] (Figure S3). Finally, the coverage of viral suppression among all females and all males living with HIV was compared to recent national CAMPHIA estimates,[3] whereas the coverage among each key population was compared to recent local estimates in 2016 for MSM and FSW[15], and 2017 for clients of FSW[16] (Figure S4).

Epidemic dynamics in Yaoundé

The results of the 1000 model posterior fits were in good agreement with to the available empirical demographic, epidemiological and intervention model fitting outcomes (baseline scenario). The model reproduced HIV prevalence across all groups (Figure 2), although the limited survey data available among young MSM are more suggestive of a plateau than a decline. The model also reflected data on viral suppression coverage in each risk group over time (Figure 1d-f) increasing to 42.7% (95%UI: 39.1-46.9) in 2018 overall, and ART coverage (Figure S3).

Modelled HIV prevalence peaked around 2003 in lower-risk groups and a few years earlier among KP. Overall HIV prevalence was predicted to have declined by 37% relatively over 2005-2018, with a larger decline among FSW and their clients (48% and 44%, respectively). By 2018, the predicted overall HIV prevalence was 4.4% (3.6-5.1) compared to 4.0% (2.9-5.3), 16.2% (14.1-18.9), and 36.0% (32.2-39.4) among clients, FSW, and MSM, respectively. Model results suggest that overall HIV incidence rate peaked in 1997, then rapidly declined (Figure S5).

Table S1: Model parameters for Yaoundé, Cameroon

Model inputs annotated with "†" correspond to inputs for which a notation was not needed since not directly used as parameters in the model nor represented in model equations.

Types of model input / risk group	Notation	Male	Female	References and comments

Demography				
Annual population growth rate	G_t	3.1% before 2000 2.9% after 2000		US Census bureau database [27] (national estimates).
Rate at which individuals die from non-AIDS mortality or reach the age of 50 years in the model.	μ_1, μ_2, μ_3	$\mu_2 = \frac{1}{47.3} + \frac{1}{35}$	$\mu_1 = \frac{1}{49.3} + \frac{1}{35}$	National estimate of the life expectancy at age 15 from [28] averaged over 1980-2015 are added to rate at which individuals reach the age of 50 years. The rate $\mu_3 = \frac{1}{47.3} + \frac{1}{25}$ is used for older MSM.
Population Structure				
Duration of sex work (for FSW) or buying for sex (for clients) in years	$1/\gamma$, $1/g$	4-14	4-10	FSW: range based on relatively consistent published estimates.[15,23,29,30] Clients: interquartile range of the time since first commercial sex in the 2017 MOT survey.[16]
FSW and client annual recruitment rates	κ, k	0.0001-0.06	0.0001-0.02	Wide prior range as no data available, fitted to population size estimates (**Table S3**)
Proportion of MSM among newly sexually active males	M	0.0015-0.03%	--	Fitted to data (**Table S3**)
Proportion of younger MSM that don't have sex with another males	Z	0-50%	--	Based on reported age at first sex with another male by MSM (around 19 years) in [31,32].
Sexual activity of lower risk groups				
Annual number of new main partnerships	n^m_{1-2}	0.4-0.7	0.3-0.5	Calculated from reported lifetime number of partners in the DHS and 4 cities study.[7,8,14,33]
Total annual number of sex acts	Ψ_{1-2}	52-104	52-104	Based on 4-cities study weekly estimates [34]. This total number is combined with the proportion of all sex acts of lower-risk groups which are with casual partners to define numbers of sex acts with main and casual partners ${\Psi_{i=1-2}}^m$ and ${\Psi_{i=1-2}}^c$
Proportion of all sex acts with casual partners†		20%	20%	1998 DHS[9]
Annual number of new casual partnerships	n^c_{1-2}	0.1-1.6	0.1-1.6	Broad prior range based on the very heterogeneous number of extra-partners over the last year reported by females (0.1) and males (1.6, for an total of 2.6 partners in the last year) in the 1998 DHS.[9]
Sexual activity of clients of FSW				
Relative risk of the number of new main and casual partners and sex acts per year of clients compared to lower-risk males[a]†		1.5-2.5	--	Triangulated from the 2017 "Modes of Transmission" clients study [16] and DHS and 4-cities study estimates for lower-risk populations
Sexual activity of FSW				
Annual number of new main partnerships	n^m_4	--	0.6 - 0.7	2016 IBBS in Yaoundé.[15]
Annual number of sex acts with main partners	${\Psi_4}^m$	--	135 – 192	2016 IBBS in Yaoundé.[15]

Annual number of new casual partnerships	n_4^c			No direct estimate. Range calculated as the product of the annual number of casual partners (originally reported over one month), and the proportion of these partners that were new partners. See following two estimates.
Annual number of casual partnerships†		--	9.6 - 34	2016 IBBS in Yaoundé [15], reported over a 1-month recall period
Proportion of these casual partnerships that were new†		--	8%-100%	No data available. Fraction of all partnerships over one year that would have been reported over only one month.[15]
Annual number of sex acts with casual partners	$\Psi_4{}^c$	--	83 – 125	2016 IBBS in Yaoundé[15]
Annual number of clients of FSW[b]	$n_4{}^{co}$	NA	104-1200	Wide range based on multiple surveys in Yaoundé.[12,15,22,35,36] As no data was available on the number of acts per client, the model assumes that the number of commercial sex acts of FSW correspond to their number of clients.
MSM		**Male partners**	**Female partners**	
Annual number of new stable partnerships	n_{5*}^m , n_5^m	1.5-2.2	0.3-2	2016 IBBS [15]
Total annual number of sex acts with main partner	$\Psi_{5*}{}^m$, $\Psi_5{}^m$	101-135	78-104	2016 IBBS [15]
Annual number of new casual partnerships	n_{5*}^c , n_5^c	11-18	4-6	2016 IBBS [15]
Total annual number of sex acts with casual partner	$\Psi_{5*}{}^c$, $\Psi_5{}^c$	57-114	23-47	2016 IBBS [15]
Risk ratio of the increase in the number of partners and sex acts of older MSM compared to younger MSM†		1	1	Based on 2016 IBBS[15]: No significant difference in number of partners and sex acts over the last months reported by 18-24 year old and 25+ year olds MSM.
Heterosexual anal sex				
Fraction of all commercial sex acts that are anal	FAI_{co}	4-5%		[12]
Relative risk of the fraction of sex acts with main and casual partners that are anal (compared to commercial partners) †		0.5-1		Range around the RR of lifetime prevalence of anal sex among all females vs higher-risk females (0.75)[37]
Fraction of sex acts between MSM and their main female partners that are anal†		--	15-18%	2016 IBBS,[15] reported as average number of vaginal/anal sex acts in an average week.
Fraction of sex acts between MSM and their female casual partners that are anal†		--	30-47%	2016 IBBS,[15] reported as average number of vaginal/anal sex acts in an average week.
HIV acquisition and natural history parameters				
Per-act probability of HIV acquisition (receptive vaginal sex)	β_{rv}	0.0006-0.0063		Combined range from,[51] using pooled estimates from developed and developing countries.

Relative risk of HIV acquisition during insertive vaginal sex (vs receptive vaginal sex)	$RR\_\beta_{iv \mid rv}$	0.5-1		$RR\_\beta_{iv \mid rv}$= 0.5 in [51] for developed countries (0.0004/0.0008), but around 1 for developing countries (0.0038/0.0030)
Relative risk of HIV acquisition during receptive anal sex (vs receptive vaginal sex)	$RR\_\beta_{ra \mid rv}$	2-10		From[52]
Relative risk of HIV acquisition during insertive anal sex (vs insertive vaginal sex)	$RR\_\beta_{ia \mid iv}$	1-2		Adapted from[52], where the ranges of per act HIV transmission risk during insertive anal sex are 0.09%-0.31%, vs 0.01%-0.14%.
Average duration of the HIV acute stage in months	$1/\eta$	1.2-4.6		[53]
Relative risk of HIV transmission during the acute stage (vs during the chronic stage)	ν	4.5-18.8		[51]
Average duration of untreated HIV (= 1 / HIV-related death rate) in years	$1/\delta$	14.6		[54]
HIV interventions				
Proportion of males that are circumcised	ξ	94-99%	--	[7,8,33]
Per-partner efficacy of male circumcision in reducing HIV acquisition risk among males	ϑ	38-66%	--	[38]
Relative risk of actual condom use at past sex (vs reported condom use at last sex).	U	0.75-1		Conservative assumption based on studies using biomarkers.[55,56]
Per-act condom efficacy in reducing HIV acquisition risk	ε	71-98%		[40-42]
Proportion of PLHIV on ART virally suppressed	α_t	75-85% over 1996-2020, then linearly increases to 90% in 2030		Uncertainty around the CAMPHIA estimate (80.0% of PLHIV on ART are virally suppressed)[3]
Efficacy of viral suppression in reducing HIV transmissibility per sex act†		100%		[46]
Relative risk of HIV-related mortality when virally suppressed compared to not virally suppressed	φ	0.16-0.42		From [45] (minimum and maximum impacts of ART on HIV mortality across ALPHA sites)
ART initiation rates	$\omega_{i,t}$			Calculated using a "base" initiation rate among lower-risk females over 2010-2013 $\omega_{i=1,t=2010-2013}$ (when eligibility was CD4<350), multiplied by a set of cofactors reflecting change in initiation rates over time and across risk groups (see specific section).
Annual ART drop-out rate	σ	10%		Assumed, as data only described the first year of initiation, associated with low retention.[47-49]

[a] Median of 2 main partners in the past 12 months in the (IQR: 1-3) and 2 (IQR: 1-3) casual female partners in the past 3 months, for a total of 13 sex acts a month (twice the numbers reported by lower-risk populations in the 4-cities study).

[b] Multiple studies where FSW reported more than 1000 partners a year, based on weekly or monthly recall periods, but the median number of clients in the past week reported by FSW in the 4-cities study in Yaoundé was only 2 (IQR: 0-4),[12] and was selected as a lower bound.

Table S2: Condom-use consistency in Yaoundé.

Fraction of sex acts involving the use of condoms (π_{ijh}^{k}). The model assumes a linear increase between estimates. The model assumes that condom use is <2% before 1985 for all partnerships.

Year	Empirical estimate	Plausible range assumed	References/comments
Between lower-risk individuals in a main partnership			
1990	1%	1-5%	DHS,[10] reported as "current use" of condoms as mean of contraception.
1998	6.8% (4.7-9.8)	5-11%	DHS,[9] reported by females
1998	7.6% (5.0-11.0)	5-11%	DHS,[9] reported by males
2011	19% (18-20)	19-37%	DHS,[7] reported by females
2011	37% (36-38)	19-37%	DHS,[7] reported by males
Between lower-risk individuals in a casual partnership			
1990	1%	1-5%	DHS,[10] reported as "current use" of condoms as mean of contraception.
1998	2.2% (1.0-4.7)	1-30%	DHS,[9] reported by females
1998	7.6% (3.8-14.8)	1-30%	DHS,[9] reported by males
1998	26%	1-30%	4-cities study,[13,57] reported by females
1998	18%	1-30%	4-cities study,[13,57] reported males
2004	54.7% (51-58)	51-74%	DHS,[8,58] reported by females
2004	69.6% (65-74)	51-74%	DHS,[8,58] reported by males
2018	50.3% (38.6-61.9)	39-77%	DHS,[11] reported by females
2018	72.3% (66.4-77.4)	39-77%	DHS,[11] reported by males
Between FSW and their main partners			
1996	22% (20-24)	15-28%	From[29]. Expanded uncertainty around estimate for sex with non-clients.
2013	24.5% (21-28)	21-28%	Interpreted from[36,59] (reported as levels of consistent condom use)
2016	45% (40-50)	40-50%	From[15]
Between FSW and their casual partners			
1996	22% (20-24)	15-28%	From[29]. Expanded uncertainty around estimate for sex with non-clients.
2016	91% (86-94)	86-94%	From[15]
Between FSW and their clients			
1990	7% (4-12)	Used for cross-validation	From[30]. This early data was used as cross-validation as a study conducted the same year showed that 20% and 12% of FSW in Yaoundé reported using condoms "always" and "most of the time", respectively[19]
1997	49% (46-52)	20-55%	From[60]
1998	28% (23-33)		4-cities study[12]
2004	88% (75-95)	Used for cross-	Reported by male clients[8]
2011	58% (45-71)	validation	Reported by male clients[7]
2009	83% (75-89)	75-89%	From[22,23]
2013	84-92%	Used as cross-validation	Interpreted from[36,59] (reported as levels of consistent condom use)
2016	93% (90-95)	90-98%	From[15], for regular clients
2016	97% (95-98)		From[15], for casual clients
Between MSM and their male partners			
2011	33% (28-37)	28-37%	From[32]

2013	70-77%	Used as cross-validation	Interpreted from [36,59]
2016	73% (68-77)	68-78% (main)	From[15], for main male partners
2016	85% (81-88)	81-88% (casual)	From[15], for casual male partners
Between MSM and their female partners			
2011	50% (43-57)	43-57%	From[32]
2013	43-49%	Used as cross-validation	Interpreted from[36,59] (reported as levels of consistent condom use)
2016	71% (65-76)	65-76% (main)	From[15], for main male partners
2016	84% (78-88)	78-88% (casual)	From[15], for casual male partners

Table S3: Fitting data for the Yaoundé model

List of data and the 40 demographic, epidemiological, and intervention fitting outcomes used for model fitting (Yaoundé)

Year	Point estimate (sample size)	Original 95%CI	Prior constraint	Reference
Total population size (aged 15-49 years)				
2015	1217440	N.A.	1156568-1278312	[15]
Fraction of FSW among all females				
1985[a] and 2016	1.7%	N.A.	0.47-3.36%	[b]Combination of three studies in Yaoundé[15,26,36]
Fraction of male clients among all males				
1985[a] and 2016	NA	N.A.	2-20%	[c]Adapted from several studies conducted in Yaoundé[7-9,12,33]
Fraction of MSM among all males				
1985[a] and 2016	1.05%	N.A.	0.51-2.25%	[d]Combination of two studies in Yaoundé[15,36]
HIV prevalence among all females				
1997	8.4% (n=942)	6.8-10.3%	4.4-13.2%	[33] (4-cities study)
2004	10.7% (n=538)	8.4-13.6%	5.0-25.5%	[8] (DHS) table 16.4
2011	8.8% (n=847)	7.1-10.9%	4.6-14.1%	[7] (DHS) table 15.4
HIV prevalence among all males				
1997	4.4% (n=811)	3.2-6.0%	1.4-8.4%	[17,18] (4 cities study)
2004	6.0% (n=550)	4.3-8.3%	1.8-11.8%	[8] (DHS) table 16.4
2011	3.6% (n=778)	2.5-5.2%	0.9-7.6%	[7] (DHS) table 15.4
HIV prevalence among female sex workers				
1991	26.6% (n=262)	21-32%	12.6-40.1%	[19]
1998	34.0% (n=320)	29.2-39.9%	22-48.8%	[12] (4-cities study)
2004	25.7% (n=325)	21.2-30.7%	14.5-38.2%	[21] (Grand South region)
2009	33.3% (n=114)	25.3-42.4%	13-55.5%	[22]
2016	21.1% (n=574)	18-24.6%	13.4-28.9%	[15]
HIV prevalence among clients of sex workers				
2017	3.0% (n=596)	1.9-4.7%	0.3-7.3%	[16]
HIV Prevalence among 15-24 years old MSM				
2011	36.5% (n=104)	27.9-46.1%	14.5-50.5%	[24,25]
2016	39.2% (n=186)	32.5-46.4%	21.5-49.5%	[15]
HIV Prevalence among 25-49 years old MSM				
2011	58.8% (n=102)	49.1-67.9%	34.0-72.5%	[24,25]
2016	54.1% (n=120)	45.2-62.8%	31.5-67.5%	[15]
ART coverage among all females living with HIV[e]				
2012	26.0% (n=50)	NA	16-40%	UNAIDS national estimates [50]
2013	28.0% (n=100)	NA	20-37%	
2014	32.0% (n=100)	NA	24-42%	
2015	37.0% (n=100)	NA	28-47%	
2016	45.0% (n=100)	NA	36-55%	
2017	56.0% (n=100)	NA	46-65%	
ART coverage among all males living with HIV[e]				
2012	21.0% (n=50)	NA	12-34%	UNAIDS national estimates [50]
2013	22.0% (n=100)	NA	15-31%	
2014	24.0% (n=100)	NA	17-33%	
2015	28.0% (n=100)	NA	20-37%	
2016	34.0% (n=100)	NA	25-44%	
2017	42.0% (n=100)	NA	33-52%	
Viral suppression coverage among all females living with HIV				
2017	42%[f]	33-52%	19.5-67%	[3]

Viral suppression coverage among all males living with HIV				
2017	38%[f]	29-48%	15.5-63%	3
Viral suppression coverage among clients of FSW living with HIV				
2017	35% (n=17)	17-58%	0-93%	16
Viral suppression coverage among FSW living with HIV				
2016	69% (n=133)	61-76%	49-86.5%	15
Viral suppression coverage among MSM living with HIV				
2016	33% (n=138)	26-41%	15.5-53%	15

[a]Upper bounds of Key population size fitting targets in 1985 were increased by 2 percentage points to reflect uncertainty in size estimates in the early days of the epidemic

[b]Combined three studies to create a plausible range (point estimate= average point estimate, upper bound = maximum observed, lower bound = minimum observed), with 2016 IBBS [15]: 1.27% (0.99 - 1.65), 2013 R2P [36]: 1.88% (1.15-2.61), 2015. WorldBank [26]: 1.91% (0.47–3.36). A sample size of n=200 was assumed for this proportion in 2016.

[c]Empirical estimates up to 24.7% in the 1998 DHS (fraction of males reporting having sex in exchange for money, favours or goods in the past 12 months [9].

[d]Combined three studies to create a plausible range (point estimate= average point estimate, upper bound = maximum observed, lower bound = minimum observed), with 2016 IBBS[15]: 0.71% (0.59 - 0.86), 2013 R2P[36]: 1.38% (0.51 - 2.25). A sample size of n=200 was assumed for this proportion in 2016.

[e]Sample sizes not available for UNAIDS estimates, and were assumed

[f]A sample size of n=100 was assumed for the likelihood calculation

Yaoundé model fits

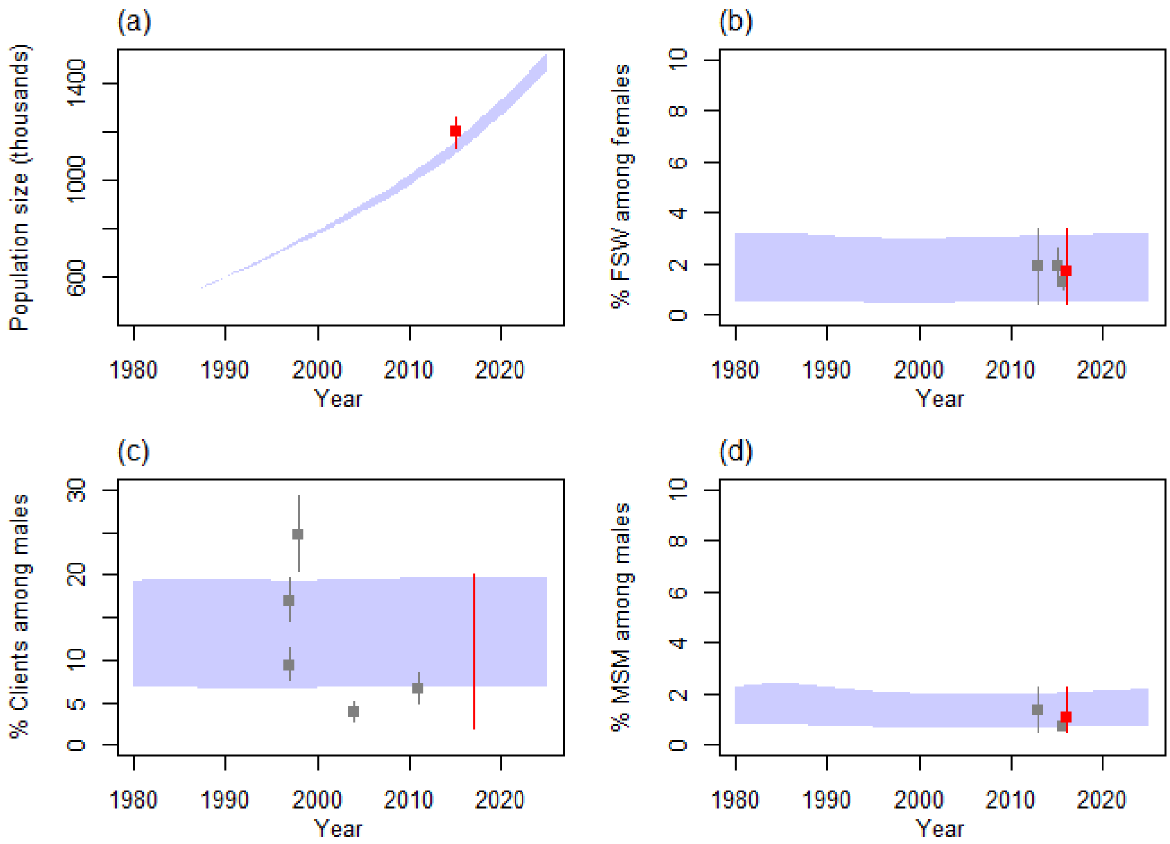


Figure S2. Model fits to sociodemographic outcomes in Yaoundé, Cameroon: a) total 15-49 year-old population size, fractions of b) FSWs among all females, c) Clients among all males, d) MSM among all males. Blue shades represent model outcomes 95%UI over 1980-2025. Red dots and intervals are outcomes used for fitting and represent estimates from Cameroon census bureau from a), and empirical estimates for key population sizes described in table S1. Light grey dots represent empirical estimates described in Table S3 which were used to derive the fitting outcomes.

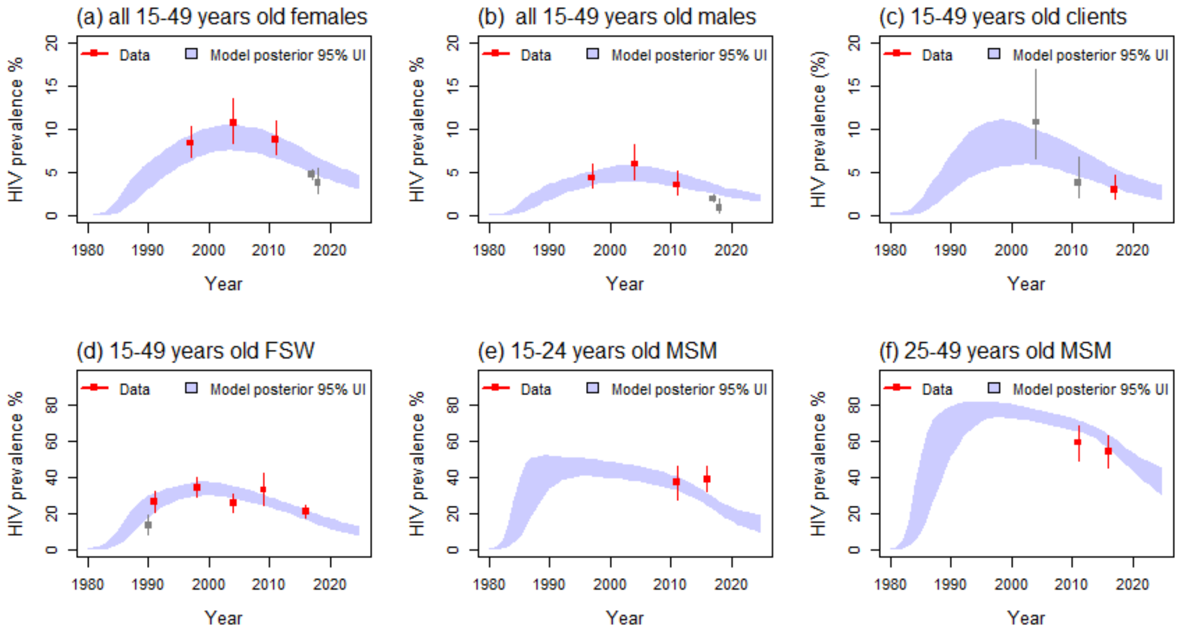


Figure S3. Trends in empirical and modelled HIV prevalence among a) all 15-49 years old females, b) all 15-49 years old males, c) all 15-49 years old clients of FSW, d) all 15-49 years old FSW, and all MSM aged e) 15-24 years and f) 25-49 years over 1980-2025 in Yaoundé, Cameroon. Red squares and interval represent empirical estimates use for model fitting (Table S2), while blue shade represent model 95% uncertainty interval. Grey squares and intervals reflect estimates only used for comparison.[3,7,8,11,61]

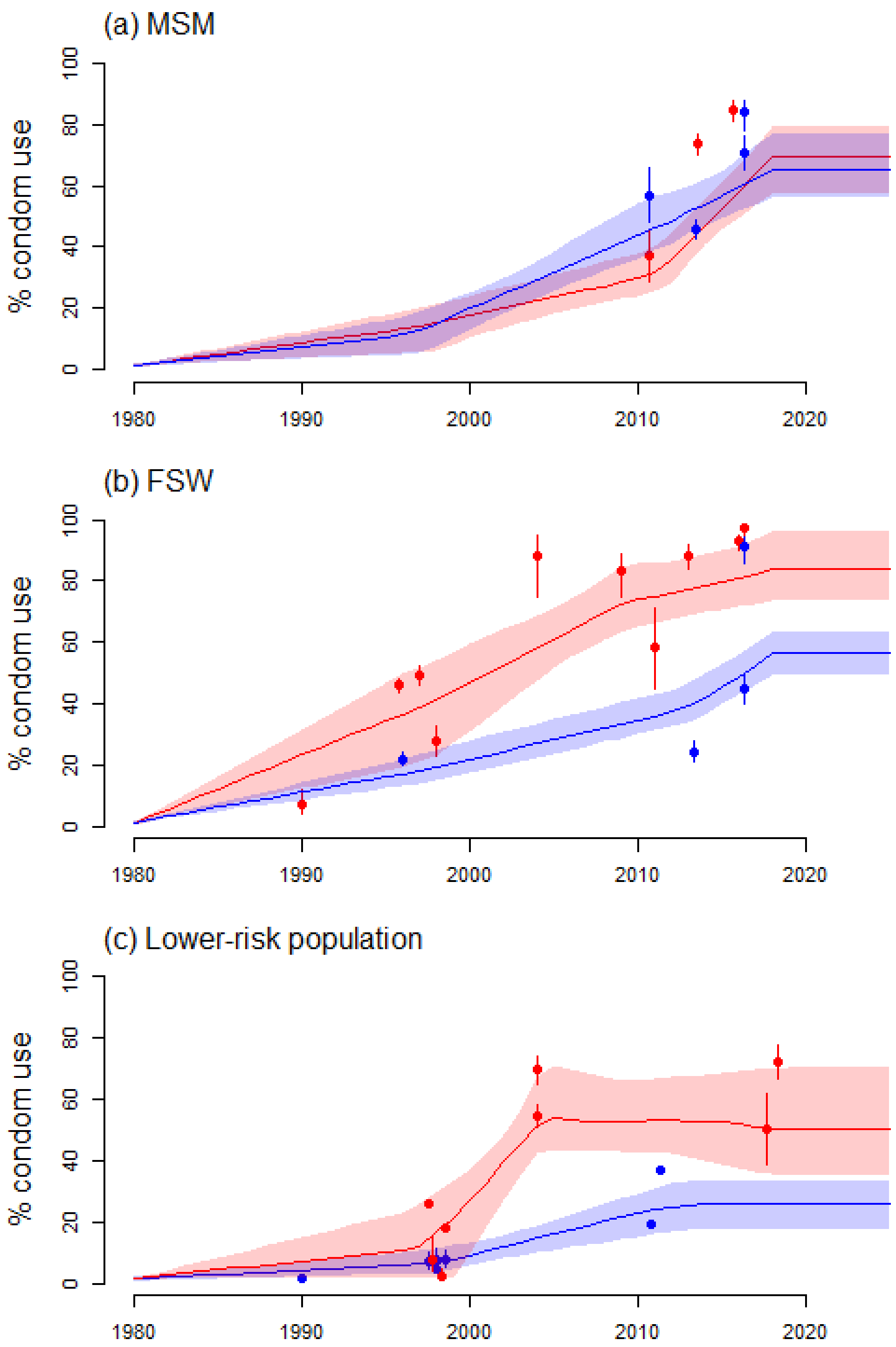


Figure S4. Proportion of sex acts protected by condoms for a) MSM with their male (red) and female (blue) partners, b) FSW and their commercial (red) and non-commercial (blue) partners, c) lower-risk individuals with their main (blue) and casual (red) partners. Condom-use data is described in Table S2.

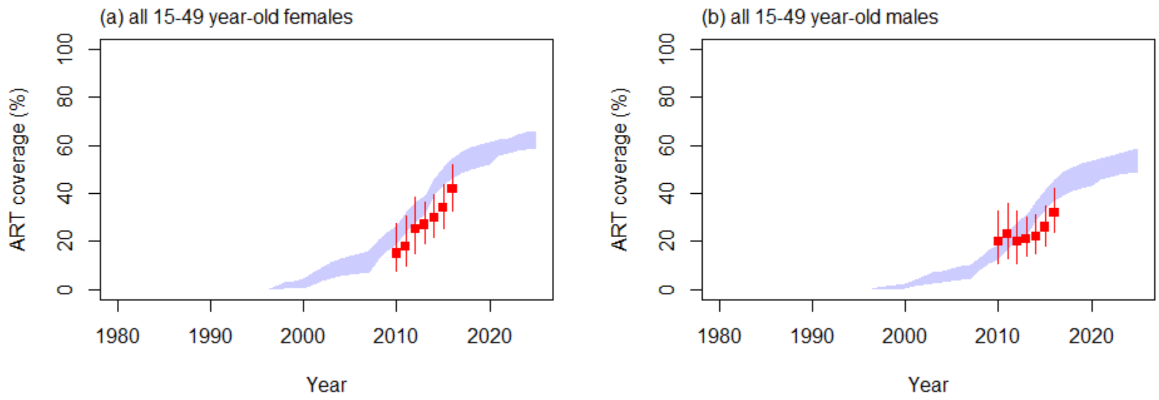


Figure S5. Empirical (UNAIDS national estimates for Cameroon) and posterior simulated ART coverage among all HIV+ a) females and b) males over 1980-2025. Blue shades represent model outcomes 95%UI, while red dots and intervals represent UNAIDS estimates.

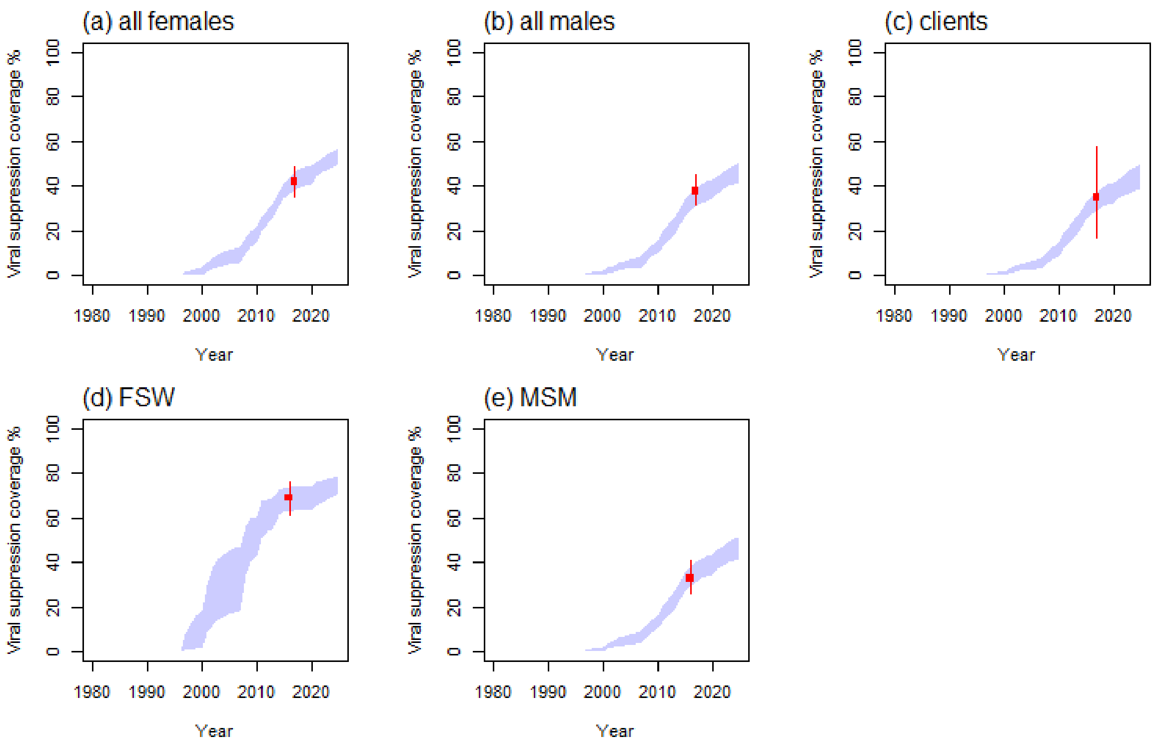


Figure S6. Empirical and simulated levels of viral suppression coverages among a) all females, b) all males, c) FSW, d) clients of FSW, e) all MSM, living with HIV over 1980-2025 in Yaoundé, Cameroon. Blue shades represent model outcomes 95%UI, while red dots and intervals represent empirical estimates from CAMPHIA for all females and males,[3] MOT survey among clients,[16] IBBS 2016 among FSW and MSM.[15]

Cotonou model structure

This section is adapted from the supplementary material for Geidelberg et al. (JAIDS 2021 [62])

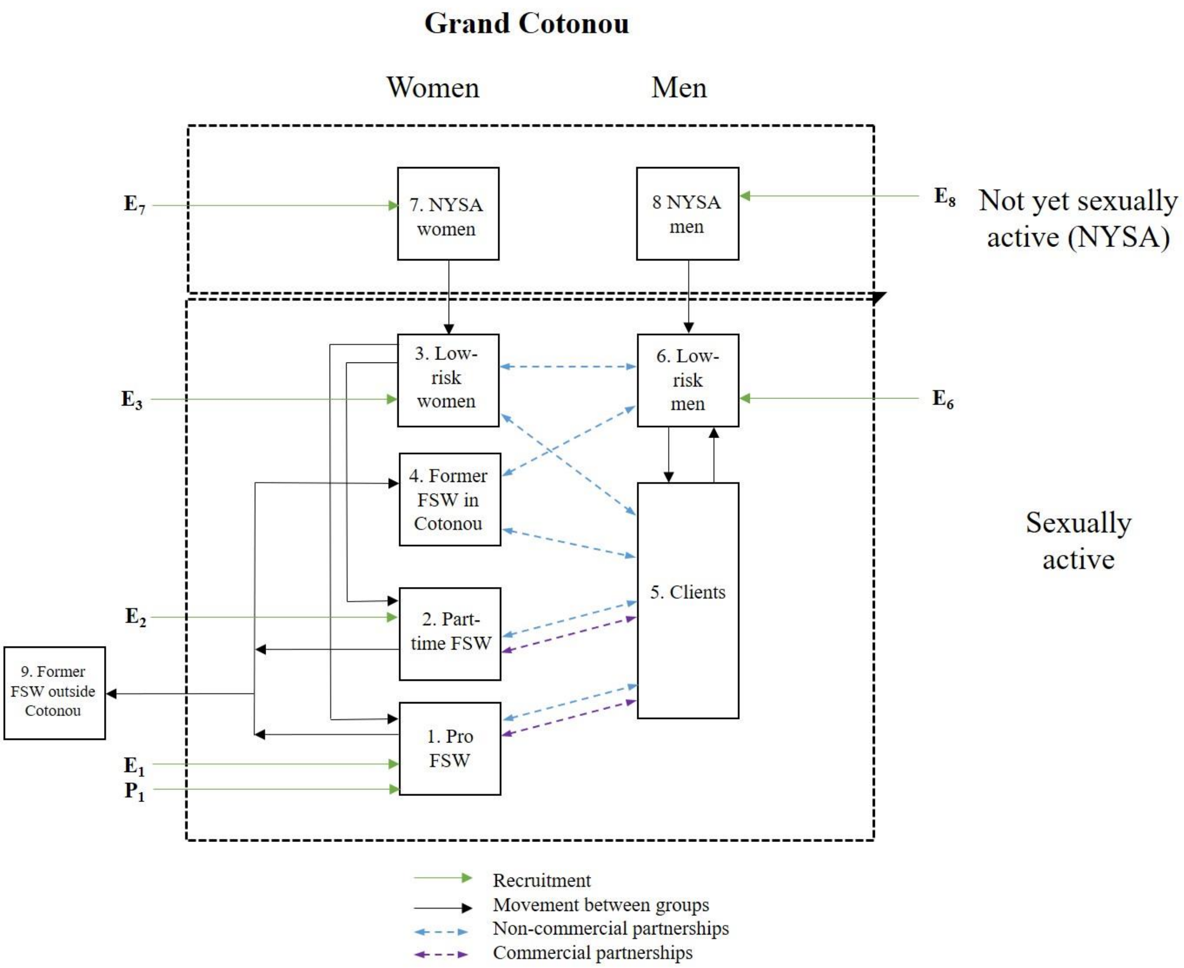


Figure S7. Recruitment, movement and sexual mixing between groups, represented by green, black and blue lines respectively. Groups within the dashed rectangles form the sexual transmission network of Grand Cotonou. E_i represents the numbers of HIV- individuals in group i recruited to the model (Equation 2a); P_1 represents the number of HIV+ professional FSW recruited (Equation 2b). Commercial partnerships are only formed between professional and part-time FSW and clients. NYSA = not yet sexually active. FSW = female sex worker.

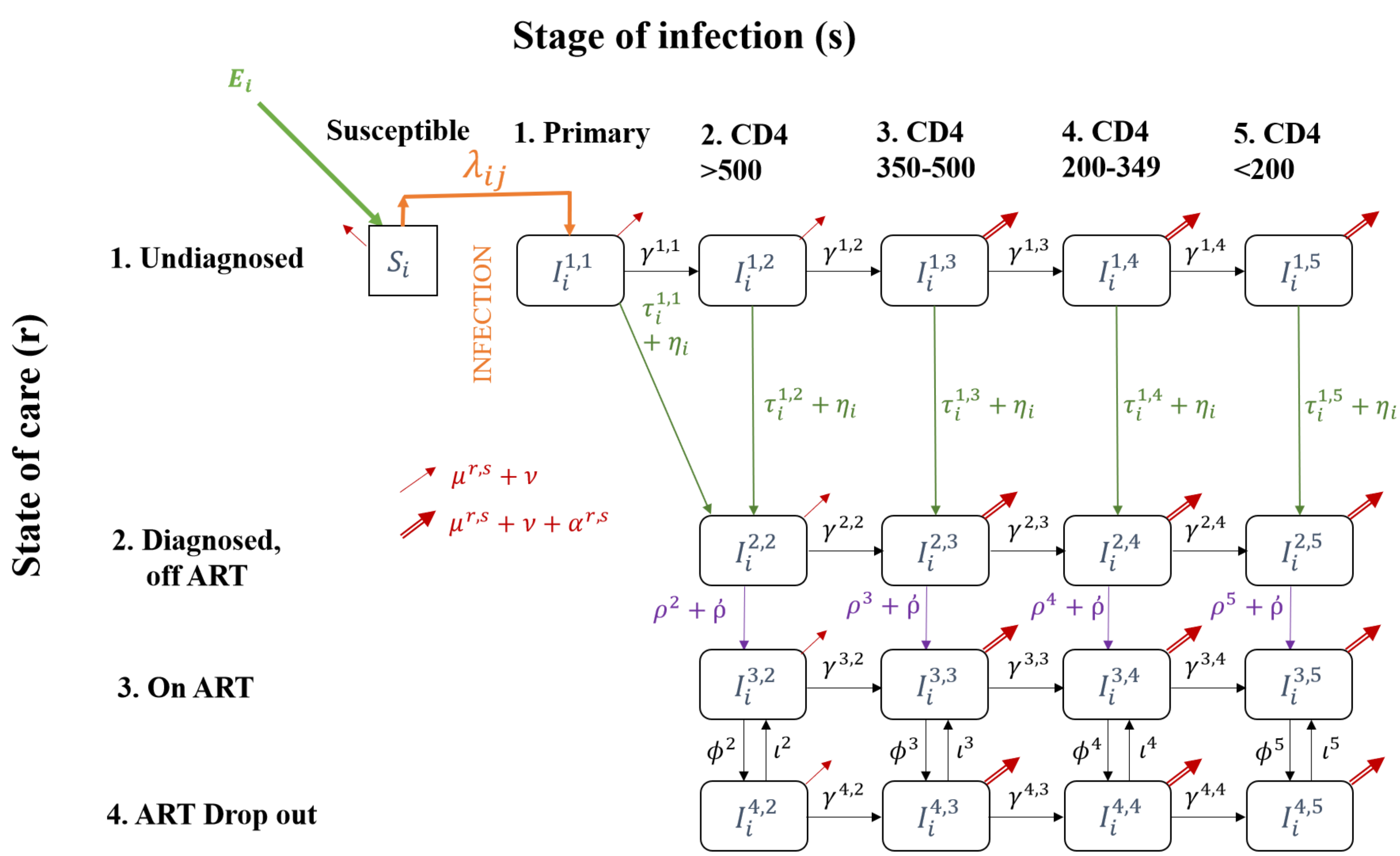


Figure S8. The model flow diagram, representing progression through state of care (r) and stage of infection (s). HIV testing, and ART initiation are represented by green and purple arrows respectively. Red arrows represent mortality and ageing; double red arrow indicates increased mortality due to HIV infection. Orange arrow represents HIV infection. Not shown in diagram is recruitment of HIV+ professional FSW into compartments I^{01} - I^{05}.

Cotonou model description

We developed a deterministic model of sexual HIV transmission and HIV interventions (ART, condom use) in the heterosexual adult population of Grand Cotonou (abbreviated GC; comprising Cotonou Centrale, Abomey-Calavi and Seme-Kpodji). The model represents an open and growing population aged 15-59 years old, stratified in 9 risk groups (subscript *i*): 2 types of active female sex workers (professional, part-time), their male clients, 2 types of former FSWs (those who remain and those who leave GC), low-risk women and men, not yet sexually active (NYSA) women and men.

New susceptible individuals can join the population at time varying rates that reflect changes in the total population size of Cotonou. They are distributed between six risk groups (NYSA women & men, low-risk women & men and professional & low-level FSWs) according to relative population sizes. E_i represents the number of new susceptible recruits joining the population in each group *i*. NYSA women and men enter the sexually active but susceptible low-risk population at per capita rates u_7 and u_8 determined by the average age at sexual debut, respectively. Professional and part-time FSWs are recruited directly from the low-risk women population of GC at low-risk population HIV prevalence at per capita rates $v_{1,3}$ and $v_{2,3,}$ respectively, or from outside of GC (from both inside and outside Benin) at rates E_1 and E_2 respectively, reflecting HIV prevalence of neighbouring countries at time *t*. Professional and part-time FSW cease sex work and join the former FSW categories at rates u_1 and u_2, reflecting duration in sex work, respectively; the factor $p_{foreign}$ determines the fraction that leaves GC upon ceasing sex work. Low-risk population males become clients at a per capita rate u_6 and return at per capita rate u_5, reflecting duration of paying for sex. Individuals leave the modelled population due to aging, HIV-related and unrelated mortality. Movement between groups applies equally to all care states and stages of infection.

Apart from a fraction of professional FSW, all individuals enter the population in the susceptible category (S_i). Professional FSWs can retire from sex work and move to the former FSW groups inside or outside GC. Sexually active susceptible individuals are assumed to get infected at a per capita force of infection λ_{ij}^{rs} that depends on their number and type of sexual partners, HIV prevalence among partners, sexual mixing patterns between risk groups, the fraction of sex acts effectively protected by condoms, the partner's infectiousness (i.e., varying by disease stage, ART treatment). The protective effect of male circumcision on HIV acquisition risk was captured in the per-act HIV transmission probability since more than 99% of men in GC are circumcised.[63,64] Only vaginal sex was modelled, as the available data suggested no meaningful frequency of oral or anal sex.[63-76] Infected individuals are represented in the model as $I_i^{r,s}$, for risk group *i*, care state *r* and stage of infection *s*.

Following infection, the model represents the course of disease progression stratified by CD4 cell count levels and different levels of engagement in the care and treatment cascade. Untreated undiagnosed HIV-positive individuals progress through a short highly infectious primary infection followed by 4 longer disease stages defined based on CD4 cell counts, at rates $\gamma^{r,s}$ that reflect care status (*r*) and stage of infection (*s*). Individuals in infected stages CD4 350-500, CD4 200-349 and CD4 <200 (*s* = 3, 4, 5 respectively) die at AIDS mortality rate α^{rs}.

All undiagnosed individuals in these 5 stages are tested for HIV at a per capita rate τ_i^{rs}, depending on group *i*, care status *r* and stage of infection *s*, moving to the diagnosed off ART category, who experience the same disease progression as undiagnosed individuals.

Diagnosed individuals initiate treatment at a per capita rate ρ_i^s that depends on group *i*, calendar year (due to changes in eligibility criteria) and stage of infection s. Compared to those not on ART, treated individuals have slower rates of disease progression and reduced HIV-related mortality, represented by factors $prog_{ART}$ and $mort_{ART}$ respectively. Finally, some individuals may experience a therapeutic failure or discontinue ART, at rate φ^s, in which case the disease follows its natural progression unless these individuals re-initiate treatment at rate ι_i^s.

Individuals leave the population at per capita rates ν, μ^{rs} and α^{rs}, which represent aging, background and AIDS-related mortalities, respectively. The full system of ODEs is presented in Section 2.

HIV was seeded at the initial prevalence π_i, and the system of ODEs was solved numerically from 1986 – 2035 using the lsoda algorithm (Petzhold and Hindmarsh) with a variable time step.[77] The model was coded in R, using "odin",[78] a wrapper around the deSolve package for solving ordinary differential equations.[79]

Cotonou model equations

S2a: Ordinary differential equations (ODEs)

Figure S2 shows the care state *r* and stage of infection *s* categories for each group *i*. S_i^r and $I_i^{r,s}$ represent susceptible and infected individuals respectively.

Testing/ART care-state (*r*):

1. Undiagnosed
2. Diagnosed, off ART
3. Diagnosed, on ART
4. ART dropout

Stage of infection (*s*):

1. Primary phase
2. CD4 >500 cells/µl
3. CD4 350-500 cells/µl
4. CD4 200-349 cells/µl
5. CD4 <200 cells/µl

$$N(t) = \sum_{i=1}^{i=8} \sum_{r=1}^{r=4} \left(S_i^r(t) + \sum_{s=1}^{s=5} I_i^{rs}(t) \right) \qquad 1$$

N(t) is the total population of GC at time *t*; and $S_i^r(t)$ and $I_i^{rs}(t)$ are the susceptible and infected populations respectively, of group *i*, care state *r* and disease state *s*. Note that N(t) does not include former FSWs outside of GC (*i*=9).

The following equations describe the recruitment of new individuals ($E(t)$) into the population. Due to the population growth of GC, new people are added to the population every timestep dependent on the growth rate $\varepsilon(t)$.

$$E_i(t) = (\varepsilon(t) + \mu_i + \nu)\, N(t)\, \omega_i, \qquad i \neq 1 \qquad 2a$$

Where $E(t)$ is the number of new susceptible people entering the sexually active population into group *i*; $\varepsilon(t)$ is the total population growth rate; μ_i is the natural mortality rate; ν is the rate of exit due to ageing; $N(t)$ is the total population size at time *t* as defined in Equation 1; ω_i is the proportion of new people distributed into group *i*.

Professional FSW

For the numbers of professional FSWs to be maintained, they have an extra term to account for those who retire from sex work and leave Grand Cotonou. Additionally, professional FSWs enter the model at a prevalence of the neighbouring countries to Benin (Nigeria, Togo and Ghana) at time *t*:

$$F_i(t) = (\varepsilon(t) + \mu_i + \nu)\, N(t)\, \omega_i + \frac{1}{dur_{PFSW}} * N_{PFSW}(t) * frac_{FSWforeign}, \qquad i = 1 \qquad 2bi$$

$$E_i(t) = F_i(t) * \left(1 - prev_{FSW_{foreign}}(t)\right), \qquad i = 1 \qquad 2bii$$

$P_i(t) = F_i(t) * prev_{FSW_{foreign}}(t), \qquad i = 1$ 2biii

$F_i(t) = 0, \qquad i \neq 1$ 2biv

$P_i(t) = 0, \qquad i \neq 1$ 2bv

Where $F_i(t)$ is the total number of new individuals in group *i* entering the model at time *t*, $E_i(t)$ is the number of susceptible individuals in group *i* entering the model at time *t*, $P_i(t)$ is the number of infected individuals in group *i* entering the model at time *t*, dur_{PFSW} is the duration of sex work for professional FSWs, $N_{PFSW}(t)$ is the number of professional FSW at time *t*, $frac_{FSWforeign}$ is the fraction of FSW that are foreign-born and $prev_{FSW_{foreign}}(t)$ is the prevalence of FSWs in neighbouring countries.

Susceptible:

Susceptible:

$$\frac{dS_i(t)}{dt} = E_i(t) - S_i(t)\left(\sum_j \left(\lambda_{ij}(t)\right) + \mu_i + \nu\right) + T_i^0 \qquad 3$$

Where $E(t)$ is the number of new susceptible people entering the sexually active population into group i as described in Equation 2; where μ_i is the background mortality rate of group *i*; $\lambda_{ij}(t)$ is the force of infection from group *j* to group *i*; ν is the rate of exit due to ageing; T_i^{as} is the sum of the movement of people to and from group *i*.

Undiagnosed

Primary infection

As detailed in Equation 2biii, the number of new infected professional FSWs entering the model depends on a changing prevalence in neighbouring countries over time ($P_i(t) = F_i(t) * prev_{FSW_{foreign}}(t)$ for i=1). There are no infected individuals entering the model from any other group ($P_i(t) = 0$ for i≠1). The infected professional FSWs entering the model are divided into the 5 stages of infection in the undiagnosed care state, proportional to the relative duration of each disease state (d^s).

$$\frac{dI_i^{1,1}(t)}{dt} = d^1\, P_i(t) + S_i(t)\sum_j \left(\lambda_{ij}(t)\right) - I_i^{1,1}(t)\left(\gamma^{1,1} + \tau_i^{1,1}(t) + \eta_i(t) + \mu_i + \nu\right) + T_i^{0,1}(t) \qquad 9$$

Where γ^{rs} is disease progression from care state *r* and disease stage *s*; $\tau_i^{as}(t)$ is testing rate; α_i^r is mortality from AIDS in care state *r*.

CD4 > 500 undiagnosed

$$\frac{dI_i^{1,2}(t)}{dt} = d^2\, P_i(t) + \gamma^{1,1}\, I_i^{1,1}(t) - I_i^{1,2}(t)\left(\gamma^{1,2} + \tau_i^{1,2}(t) + \eta_i(t) + \mu_i + \nu\right) + T_i^{1,2}(t) \tag{11}$$

CD4 350 - 500 undiagnosed

$$\frac{dI_i^{1,3}(t)}{dt} = d^3\, P_i(t) + \gamma^{1,2}\, I_i^{1,2}(t) - I_i^{1,3}(t)\left(\gamma^{1,3} + \tau_i^{1,3}(t) + \eta_i(t) + \alpha_i^{1,3} + \mu_i + \nu\right) + T_i^{1,3}(t) \tag{12}$$

CD4 200 - 349 undiagnosed

$$\frac{dI_i^{1,4}(t)}{dt} = d^4\, P_i(t) + \gamma^{1,3}\, I_i^{1,3}(t) - I_i^{1,4}(t)\left(\gamma^{1,4} + \tau_i^{1,4}(t) + \eta_i(t) + \alpha_i^{1,4} + \mu_i + \nu\right) + T_i^{1,4}(t) \tag{13}$$

CD4 < 200 undiagnosed

$$\frac{dI_i^{1,5}(t)}{dt} = d^5\, P_i(t) + \gamma^{1,4}\, I_i^{1,4}(t) - I_i^{1,5}(t)\left(\tau_i^{1,5}(t) + \eta_i(t) + \alpha_i^{1,5} + \mu_i + \nu\right) + T_i^{1,5}(t) \tag{14}$$

Diagnosed infection, not on ART:

CD4 > 500 diagnosed, off ART

$$\frac{dI_i^{2,2}(t)}{dt} = \left(\tau_i^{1,1}(t) + \eta_i(t)\right) I^{1,1}(t) + \left(\tau_i^{1,2}(t) + \eta_i(t)\right) I^{1,2}(t) - I_i^{2,2}(t)(\gamma^{2,2} + \rho_i^2(t) + \dot{\rho}_i(t) + \mu_i + \nu) + T_i^{2,2}(t) \tag{15}$$

Where $\rho_i^s(t)$ is rate of ART uptake in group *i*, disease state *s*.

CD4 350 - 500 diagnosed, off ART

$$\frac{dI_i^{2,3}(t)}{dt} = \gamma^{2,2}\, I_i^{2,2}(t) + \left(\tau_i^{1,3}(t) + \eta_i(t)\right) I^{1,3}(t) - I_i^{2,3}(t)\left(\gamma^{2,3} + \rho_i^3(t) + \dot{\rho}_i(t) + \alpha_i^{2,3} + \mu_i + \nu\right) + T_i^{2,3}(t) \tag{16}$$

CD4 200 - 349 diagnosed, off ART

$$\frac{dI_i^{2,4}(t)}{dt} = \gamma^{2,3}\, I_i^{2,3}(t) + \left(\tau_i^{1,4}(t) + \eta_i(t)\right) I^{1,4}(t) - I_i^{2,4}(t)\left(\gamma^{2,4} + \rho_i^4(t) + \dot{\rho}_i(t) + \alpha_i^{2,4} + \mu_i + \nu\right) + T_i^{2,4}(t) \tag{17}$$

CD4 < 200 diagnosed, off ART

$$\frac{dI_i^{2,5}(t)}{dt} = \gamma^{2,4}\, I_i^{2,4}(t) + \left(\tau_i^{1,5}(t) + \eta_i(t)\right) I^{1,5}(t) - I_i^{2,5}(t)\left(\rho_i^5(t) + \dot{\rho}_i(t) + \alpha_i^{2,5} + \mu_i + \nu\right) + T_i^{2,5}(t) \tag{18}$$

Diagnosed infection, on ART:

CD4 >500 diagnosed, on ART

$$\frac{dI_i^{3,2}(t)}{dt} = (\rho_i^2(t) + \dot{\rho}_i(t))\, I_i^{2,2}(t) + \iota_i^2 I_i^{4,2}(t) - I_i^{3,2}(t)(\gamma^{3,2} + \varphi_i^2(t) + \mu_i + \nu) + T_i^{3,2}(t) \qquad 19$$

Where $\iota_i^s(t)$ is rate of ART re-initialisation in group *i*, disease state *s*; φ_i^s is rate of ART dropout.

CD4 350 - 500 diagnosed, on ART

$$\frac{dI_i^{3,3}(t)}{dt} = \gamma^{3,2}\, I_i^{3,2}(t) + (\rho_i^3(t) + \dot{\rho}_i(t))\, I_i^{2,3}(t) + \iota_i^3 I_i^{4,3}(t) - I_i^{3,3}(t)\left(\gamma^{3,3} + \varphi_i^3(t) + \alpha_i^{3,3} + \mu_i + \nu\right) + T_i^{3,3}(t) \qquad 20$$

CD4 200 - 349 diagnosed, on ART

$$\frac{dI_i^{3,4}(t)}{dt} = \gamma^{3,3} I_i^{3,3}(t) + (\rho_i^4(t) + \dot{\rho}_i(t))\, I_i^{2,4}(t) + \iota_i^4 I_i^{4,4}(t) - I_i^{3,4}(t)\left(\gamma^{3,4} + \varphi_i^4(t) + \alpha_i^{3,4} + \mu_i + \nu\right) + T_i^{3,4}(t) \qquad 21$$

CD4 < 200 diagnosed, on ART

$$\frac{dI_i^{3,5}(t)}{dt} = \gamma^{3,4} I_i^{3,4}(t) + \left(\rho_i^5(t) + \dot{\rho}_i(t)\right) I_i^{2,5}(t) + \iota_i^5 I_i^{4,5}(t) - I_i^{3,5}(t)\left(\varphi_i^5(t) + \alpha_i^{3,5} + \mu_i + \nu\right) + T_i^{3,5}(t) \qquad 22$$

Diagnosed infection, ART dropout / therapeutic failure:

CD4 > 500 ART drop out / therapeutic failure

$$\frac{dI_i^{4,2}(t)}{dt} = \varphi_i^2(t)\, I_i^{3,2}(t) - I_i^{4,2}(t)(\gamma^{4,2} + \iota_i^2(t) + \mu_i + \nu) + T_i^{4,2}(t) \qquad 23$$

CD4 350 - 500 ART drop out / therapeutic failure

$$\frac{dI_i^{4,3}(t)}{dt} = \gamma^{4,2}\, I_i^{4,2}(t) + \varphi_i^3(t) I_i^{3,3}(t) - I_i^{4,3}(t)\left(\gamma^{4,3} + \iota_i^3(t) + \alpha_i^{0,3} + \mu_i + \nu\right) + T_i^{4,3}(t) \qquad 24$$

CD4 200 - 349 ART drop out / therapeutic failure

$$\frac{dI_i^{4,4}(t)}{dt} = \gamma^{4,3}\, I_i^{4,3}(t) + \varphi_i^4(t) I_i^{3,4}(t) - I_i^{4,4}(t)\left(\gamma^{4,4} + \iota_i^4(t) + \alpha_i^{0,4} + \mu_i + \nu\right) + T_i^{4,4}(t) \tag{25}$$

CD4 < 200 ART drop out / therapeutic failure

$$\frac{dI_i^{4,5}(t)}{dt} = \gamma^{4,4}\, I_i^{4,4}(t) + \varphi_i^5(t) I_i^{3,5}(t) - I_i^{4,5}(t)\left(\iota_i^5(t) + \alpha_i^{0,5} + \mu_i + \nu\right) + T_i^{4,5}(t) \tag{26}$$

S2b: Linear interpolation of parameters

We assume that certain parameters vary over time. For example, the fraction of sex acts that are protected by a condom will generally increase over time. Estimates for this fraction will be taken from surveys (e.g. 2008 and 2011). We linearly interpolate between these years in order to get a value for every year. We assume all parameters to remain fixed at their 2015 value when simulating the epidemic beyond this year.

For non-commercial condom use ($f_{ij}^N(t)$), we calculate its value over time as follows:

$$f_{ij}^N(t) = \begin{cases} f_{ij1998}^N, & t < 2008 \\ f_{ij1998}^N + zt, & 2008 \le t \le 2011 \\ f_{ij2008}^N, & t > 2011 \end{cases}$$

Where z is the annual increase in condom use, calculated as follows:

$$z = \frac{f_{ij2008}^N - f_{ij1998}^N}{2011 - 2008}$$

S2c: Entering the population

New people entering the population are distributed into the 9 groups at fractions determined by the parameter ω_i.

$$\omega_{PFSW} = frac_F * frac_{FPFSW} * frac_{FSWforeign}$$

$$\omega_{LFSW} = frac_F * frac_{FPFSW} * ratio_{LFSW} * frac_{FSWforeign}$$

$$\omega_{GPF} = frac_F - \omega_{PFSW} - \omega_{LFSW} - \omega_{VF}$$

$$\omega_{GPM} = (1 - frac_F) * frac_{MSA}$$

$$\omega_{VF} = frac_F * (1 - frac_{FSA})$$

$$\omega_{VM} = (1 - frac_F) * (1 - frac_{MSA})$$

$$\omega_C = \omega_{FFSWinCot} = \omega_{FFSWoutCot} = 0$$

$$\sum_{i=1}^{i=9} \omega_i = 1$$

Where ω_i is the fraction of new individuals entering group *i*; PFSW, LFSW, GPF, GPM, VF, VM, C, FFSWinCot and FFSWoutCot represent professional female sex workers, part-time female sex workers, low risk women and men, not yet sexually active women and men, clients, former female sex workers in GC and former female sex workers outside of GC respectively; $frac_F$ is the fraction of individuals that are female; $frac_{FPFSW}$ is the fraction of women that are professional sex workers; $ratio_{LFSW}$ is the ratio of number of part-time sex workers to professional sex workers; $frac_{FSWforeign}$ is the fraction of sex workers that are non-Beninese; $frac_{MSA}$ is the fraction of men that are sexually active; $frac_{FSA}$ is the fraction of women that are sexually active.

S2d: Turnover:

Turnover between compartments is a critical component of the model, spreading infections from high risk to low risk groups, and is also important for maintaining the correct demographic patterns in the population. Turnover is represented by two separate parameters, moving out (u_i) and moving in (v_{ij}). The former is the rate of leaving a group *i*, thus need only apply to the group in question. The latter is the rate of entering a group *i* from group *j* which capture the correct prevalences of care-state *r* and stage of disease *s*.

Turnover applies equally to both susceptible and infected states (whereby $X = S$ and $X = I$ respectively), and applies to all care states and stages of infection. Thus, the movement into states S_i and $I_i^{4,5}$ will arrive from states S_j and $I_j^{4,5}$ respectively. As such, when considering the movement of people from group *j* to group *i*, it will be at the HIV prevalence of group *j*.

Movements in and out are combined into the turnover $T_i^{rs}(t)$ as follows:

$$T_i^{r,s}(t) = -X_i^{r,s}(t) * u_i + \sum_{j=1}^{j=9} v_{ij} * X_j^{r,s}(t)$$

Where $T_i^{r,s}(t)$ is the turnover of group *i*, care-state *r* and disease state *s*; $X_i^{r,s}(t)$ is the current number of individuals in the state, u_i is the rate of leaving of group *i*; v_{ij} is the rate of entering in group *i* from group *j*.

Groups (*i*):

1. Professional FSW
2. Part-time FSW
3. Low-risk women
4. Former FSW in GC
5. Clients
6. Low-risk men
7. Not yet sexually active women
8. Not yet sexually active men
9. Former FSW outside model

Not yet sexually active men and women

Not yet sexually active (NYSA) men and women enter the sexually active population and do not go back. NYSA women (*i* = 7) move into the low-risk women category (*i* = 3); NYSA men (*i* = 8) move into the low-risk men category (*i* = 6).

Rate of leaving NYSA woman group (u_7):

$$u_7 = \frac{1}{\chi_7 - 15}$$

Rate of leaving NYSA men group (u_8):

$$u_8 = \frac{1}{\chi_8 - 15}$$

Where u_7 and u_8 are the rate leaving of NYSA women and men groups respectively; χ_i is the average age of sexual debut of group *i*. 15 is the youngest age in the model, thus $\chi_8 - 15$ represents the length of time spent NYSA.

This results in the movement of NYSA women and men to be expressed as follows:

$$T_7^{r,s}(t) = -X_7^{r,s}(t) * u_7$$
$$T_8^{r,s}(t) = -X_8^{r,s}(t) * u_8$$

Where $T_7^{r,s}(t)$ and $T_7^{r,s}(t)$ are the movements of NYSA women and men respectively of care state *r* and stage of infection *s*; $X_i^{r,s}$ is either a susceptible (X = S) or infected (X = I) individual in group *i*, care state *r* and stage of infection *s* at time *t*.

Professional and part-time female sex workers

Professional and part-time FSWs are recruited from either outside of sexual network of GC, or recruited from the low-risk population. Both FSW groups retire to former FSW groups (both inside and outside GC).

Rate of leaving sex work is equal to the inverse of the duration of sex work ($\frac{1}{dur_{PFSW}}$ and $\frac{1}{dur_{LFSW}}$ for professional and part-time FSW respectively).

Rate of leaving professional sex work (u_1):

$$u_1 = \frac{1}{dur_{PFSW}}$$

Rate of leaving part-time sex work (u_2):

$$u_2 = \frac{1}{dur_{LFSW}}$$

Where dur_{PFSW} and dur_{LFSW} is the duration of professional and part-time sex work respectively.

The movement rates of FSWs from the low-risk women group are calculated as follows:

Rate of entering professional sex work from low-risk women:

$$v_{1,3} = \left(\frac{1}{dur_{PFSW}} + \mu_F + \nu\right) \frac{N_1(0)}{N_3(0)} \left(1 - frac_{FSWforeign}\right)$$

Rate of entering part-time sex work from low-risk women:

$$v_{2,3} = \left(\frac{1}{dur_{LFSW}} + \mu_F + \nu\right) \frac{N_2(0)}{N_3(0)} \left(1 - frac_{FSWforeign}\right)$$

Where μ_F is female baseline mortality; ν is the rate of ageing; $N_i(0)$ is the initial population size of group i; $frac_{FSWforeign}$ is the fraction of sex workers that are non-Beninese. If $frac_{FSWforeign} = 0$, all FSWs are recruited from the low-risk women group of GC; if $frac_{FSWforeign} = 1$, all FSWs are recruited from outside GC within the rate of entry E_1 and E_2 for professional and part-time sex workers respectively. The ratio of professional FSW and part-time FSW to low-risk women ($\frac{N_1(0)}{N_3(0)}$ and $\frac{N_2(0)}{N_3(0)}$ respectively) is required to ensure that the approximately the same numbers of FSWs that retire from sex work are recruited from the low-risk women group. μ_F and ν are also required to recruit FSWs at the rate at which they age and die.

Total movement for professional and part-time FSW ($T_1^{r,s}(t)$ and $T_2^{r,s}(t)$ respectively), including leaving and entering, are thus expressed as follows:

$$T_1^{r,s}(t) = -X_1^{r,s}(t) * u_1 + v_{1,3} * X_3^{r,s}(t)$$

$$T_2^{r,s}(t) = -X_2^{r,s}(t) * u_2 + v_{2,3} * X_3^{r,s}(t)$$

Where u_1 and u_2 are rates of leaving professional and part-time sex work respectively, which is multiplied by the number of individuals in each care state *r* and stage of infection *s* at time *t* ($X_1^{r,s}(t)$ and $X_2^{r,s}(t)$ respectively); $v_{1,3}$ and $v_{2,3}$ are the rates of entering professional and part-time sex work respectively, which are multiplied by the number of individuals in the low-risk women ($X_3^{r,s}(t)$) of care state *r* and stage of infection *s*.

Low-risk women

The rate of leaving of low-risk women group (u_3) is the combination of the rates $v_{1,3}$ and $v_{2,3}$ as calculated in the following equations:

$$u_3 = \left(\frac{1}{dur_{PFSW}} + \mu_F + \nu\right)\frac{N_1(0)}{N_3(0)}\left(1 - frac_{FSWforeign}\right) + \left(\frac{1}{dur_{LFSW}} + \mu_F + \nu\right)\frac{N_2(0)}{N_3(0)}\left(1 - frac_{FSWforeign}\right)$$

The rate of entering of low-risk women group is equal to the rate of leaving of the NYSA women group as shown in the following equation:

$$v_{3,7} = \frac{1}{\chi_7 - 15}$$

Total movement for low-risk womens ($T_3^{r,s}(t)$), including leaving and entering, is expressed as follows:

$$T_3^{r,s}(t) = -X_3^{r,s}(t) * u_3 + v_{3,7} * X_7^{r,s}(t)$$

Where $X_3^{r,s}(t)$ is the number of low-risk womens individuals in care state *r* and stage of infection *s* at time *t*; u_3 is the leaving rate of low-risk women; $v_{3,7}$ is the entering rate of low-risk women from the NYSA women group; $X_7^{r,s}(t)$ is the number of NYSA women in the same care state and stage of infection.

Former FSWs inside and outside Grand Cotonou

Professional and part-time FSWs retire to become former FSWs, either inside or outside of GC (as shown in following equations). The parameter $frac_{FSWforeign}$ represents the fraction of FSW that were foreign-born, which determines how many FSW that leave GC upon retirement.

Rate of entering former FSW in GC from professional FSW category:

$$v_{4,1} = \frac{1}{dur_{PFSW}} \left(1 - frac_{FSWforeign}\right)$$

Rate of entering former FSW in GC from part-time FSW category:

$$v_{4,2} = \frac{1}{dur_{LFSW}} \left(1 - frac_{FSWforeign}\right)$$

Rate of entering former FSW outside GC from professional FSW category:

$$v_{9,1} = \frac{1}{dur_{PFSW}} \, frac_{FSWforeign}$$

Rate of entering former FSW outside GC from part-time FSW category:

$$v_{9,2} = \frac{1}{dur_{LFSW}} \, frac_{FSWforeign}$$

Total movement for former FSW inside ($T_4^{r,s}(t)$) and outside GC ($T_9^{r,s}(t)$) are calculated as follows:

$$T_4^{r,s}(t) = v_{4,1} * X_1^{r,s}(t) + \; v_{4,2} * X_2^{r,s}(t)$$

$$T_9^{r,s}(t) = v_{9,1} * X_1^{r,s}(t) + \; v_{9,2} * X_2^{r,s}(t)$$

Where $X_1^{r,s}(t)$ and $X_2^{r,s}(t)$ represent the number of professional and part-time FSWs respectively, in care state *r* and stage of infection *s* at time *t*.

Clients

Clients are recruited only from the low-risk men population, at a rate inversely proportional to the duration of being a client ($\frac{1}{dur_{client}}$).

Rate of leaving client group (u_5):

$$u_5 = \frac{1}{dur_{client}}$$

In order to keep the proportion of men that are clients approximately the same over time, the rate of entering the client group from the low-risk men group ($v_{5,6}$) scales the rate of leaving of the client group by the fraction of men that are clients at seeding ($\frac{N_5(0)}{N_6(0)}$). The background male mortality and ageing rates (μ_M and ν respectively) are included to replace the clients that are leaving due to death or ageing. The rate of entering the client category from the low-risk men ($v_{5,6}$) is calculated as follows:

$$v_{5,6} = \left(\frac{1}{dur_{client}} + \mu_M + \nu\right) \frac{N_5(0)}{N_6(0)}$$

Total movement for clients is thus calculated as follows:

$$T_5^{r,s}(t) = -X_5^{r,s}(t) * u_5 + v_{5,6} * X_6^{r,s}(t)$$

Where $X_6^{r,s}(t)$ is the number of low-risk men in care state *r* and stage of infection *s* at time *t*.

Low-risk men

Low-risk men leave at rate u_6, which is calculated as follows, as in the following equation:

$$u_6 = \left(\frac{1}{dur_{client}} + \mu_M + \nu\right)\frac{N_5(0)}{N_6(0)}$$

Rate of entering low-risk men from the client category ($v_{6,5}$) is calculated as follows:

$$v_{6,5} = \frac{1}{dur_{client}}$$

Rate of entering low-risk men from the NYSA men category ($v_{6,8}$) is calculated as follows:

$$v_{6,8} = \frac{1}{\chi_8 - 15}$$

Where χ_8 is the average age of sexual debut of NYSA men.

Total movement for the low-risk men category ($T_6^{r,s}(t)$) combines the turnover with clients with the movement from NYSA men (following equation), and is calculated as follows:

$$T_6^{r,s}(t) = -X_6^{r,s}(t) * u_6 + v_{6,5} * X_5^{r,s}(t) + v_{6,8} * X_8^{r,s}(t)$$

Where $X_5^{r,s}(t)$ and $X_8^{r,s}(t)$ are the numbers of clients and NYSA men respectively, in care state *r* and stage of infection *s*.

S2e: Testing rates

Household, IBBA and DHS surveys provided estimates on the probability of being tested in the last year for FSWs and men and women in GC. After interpolating over time yearly estimates of testing coverage (see parameter table), every time step we estimate the rate of undergoing testing with the following equation:

$$\tau_i^{r,s} = -\ln(1 - ptest_i)$$

Where $\tau_i^{r,s}$ is the rate of testing of group *i*; $ptest_i$ is the probability of being tested last year of group *i*.

There is one case where this is different:

Individuals in $I_i^{1,5}$ have an increased testing rate ($\tau_i^{1,5}$) as calculated below

$$\tau_i^{1,5} = -\ln(1 - ptest_i) * RR_{testCD4200}$$

Where $RR_{testCD4200}$ is the increase in testing due to a CD4 count <200, which is associated with symptoms of AIDS.

S2f: ART initiation rates

ART initiation rate is represented by ρ_i^s, varying by group *i* and stage of infection *s*. Eligibility of ART has historically depended on CD4 count according to national and WHO recommendations; the rates of ART initiation in the model reflect this. Prior to 2012, only those with a CD4 count below 350 were eligible for ART (s=4,5); in 2015 this was extended to those below 500 (s=3,4,5), and in 2016 all stages of infection were eligible.

S2g: Force of infection:

The force of infection ($\lambda_{ij}(t)$) is defined as the per capita rate at which susceptible individuals of risk group *i* and care state *r* are infected by individuals of risk group *j*. It is derived from the total risk of infection from commercial (C) and non-commercial partnerships (N), all care states *r* and stages of infection *s*, including sex acts with and without protection from condoms.

$$\lambda_{ij}(t) = p_{ij}^{C}\, c_i^{C} \sum_{r=1}^{r=4}\sum_{s=1}^{s=5}\left(\frac{I_j^{r,s}(t)}{\sum_{r=1}^{r=4}\sum_{s=1}^{s=5}\left(I_j^{r,s}(t)+S_j^{r,s}(t)\right)}\left(1 - \left(1-\ \beta_{ij}\, R^{r,s}\ \right)^{n_{ij}^{C}(t)\left(1-f_{ij}^{C}(t)\right)} \times \left(1-\left(1-ec_{ij}\right)\ \beta_{ij}\, R_j^{r,s}\ \right)^{n_{ij}^{C}(t)\, f_{ij}^{C}(t)}\right)\right) + p_{ij}^{N}\, c_i^{N} \sum_{r=0}^{r=4}\sum_{s=1}^{s=5}\left(\frac{I_j^{r,s}(t)}{\sum_{r=0}^{r=4}\sum_{s=1}^{s=5}\left(I_j^{r,s}(t)+S_j^{r,s}(t)\right)}\left(1 - \left(1-\ \beta_{ij}\, R^{r,s}\ \right)^{n_{ij}^{N}(t)\left(1-f_{ij}^{N}(t)\right)} \times \left(1-\left(1-ec_{ij}\right)\ \beta_{ij}\, R_j^{r,s}\ \right)^{n_{ij}^{N}(t)\, f_{ij}^{N}(t)}\right)\right)$$

Where p_{ij}^{C} and p_{ij}^{N} are the probability of sexual contact between groups *i* and *j* for commercial and non-commercial partnerships respectively; c_i^{C} and c_i^{N} are the rates of new partner acquisition for commercial and non-commercial partnerships respectively; β_{ij} and β_{ij} are the commercial and non-commercial probability of HIV transmission per sex act from *j* to *i* respectively; $R_j^{r,s}$ is a matrix containing the scaling factors for risk of transmission based on care state *r* and stage of infection *s* of transmitter *j*; $n_{ij}^{C}(t)$ and $n_{ij}^{N}(t)$ are the commercial and non-commercial number of sex acts per partnership, $f_{ij}^{C}(t)$ and $f_{ij}^{N}(t)$ are the proportion of commercial and non-commercial sex acts protected by a condom, ec_{ij} is the condom efficacy.

The total force of infection experienced by individuals of group *i*, and care state *r* $\left(\lambda\mathrm{tot}_i^{r}(t)\right)$ is the sum of the forces of infection contributed by each type of partnership they have.

$$\lambda\mathrm{tot}_i^{r}(t) = \sum_j \lambda_{ij}^{r}(t)$$

S2h: Balancing of partnerships

Commercial partnerships

The total number of commercial partnerships as declared by women (*i* = 1, 2) must match the total number of commercial partnerships as declared by men (*i* = 5), such that the following equation is satisfied:

$$c_1^{C} N_1 + c_2^{C} N_2 = c_5^{C} N_5$$

Where c_i^{C} is the commercial partner change rate of group *i*; N_i is the total number of individuals in group *i*. We use two methods (one of which is randomly chosen in each simulation) in order to ensure that this equation is fulfilled:

1. Either we change the partner change rate of the professional FSWs every timestep in order to balance

$$c_1^{C\prime} = \frac{c_5^{C} N_5 - c_2^{C} N_2}{N_1}$$

Where $c_1^{C\prime}$ is the balanced partner change rate of professional FSWs, which will be applied in the force of infection.

2. Or we change the partner change rate of the clients every timestep in order to balance

$$c_5^{C\prime} = \frac{c_1^C N_1 + c_2^C N_2}{N_5}$$

Where $c_5^{C\prime}$ is the balanced partner change rate of clients, which will be applied in the force of infection.

Non-commercial partnerships

The number of non-commercial partnerships as declared by women (i = 1, 2, 3, 4) must match the number of partnerships as declared by men (i = 5, 6), such that the following equation is satisfied:

$$\sum_{i=1}^{i=4} c_i^N N_i = \sum_{i=5}^{i=6} c_i^N N_i$$

$$c_1^N N_1 + c_2^N N_2 + c_3^N N_3 + c_4^N N_4 = c_5^N N_5 + c_6^N N_6$$

We change the partner change rate of low-risk women (i=3) and former FSW (i=4) in GC every timestep to balance partnerships:

$$c_3^{N\prime} = c_4^{N\prime} = \frac{c_5^N N_5 + c_6^N N_6 - c_1^N N_1 - c_2^N N_2}{N_3 + N_4}$$

Low-risk women and former FSW in GC share the same non-commercial partner change rate ($c_3^{N\prime}$ and $c_4^{N\prime}$ respectively).

Sex acts per partnership

This parameter is equal between each pairing, i.e. professional FSW have the same number of sex acts per commercial partnerships with clients, as clients have with professional FSW. The value of this parameter is drawn from a range whose uncertainty encompasses estimates from professional FSW and client data.

S2i: Probability of sexual contact

The contact matrices M_{ij}^C and M_{ij}^N determine whether commercial and non-commercial partnerships are formed between groups *i* and *j*.

$$M_{ij}^C =$$

		j								
		Pro FSW	Part-time FSW	Low-risk women	Former FSW in Cotonou	Client	Low-risk men	NYSA women	NYSA men	Former FSW not in Cotonou
i	Pro FSW	0	0	0	0	1	0	0	0	0
	Part-time FSW	0	0	0	0	1	0	0	0	0
	Low-risk women	0	0	0	0	0	0	0	0	0
	Former FSW in Cot	0	0	0	0	0	0	0	0	0
	Client	1	1	0	0	0	0	0	0	0
	Low-risk men	0	0	0	0	0	0	0	0	0
	NYSA women	0	0	0	0	0	0	0	0	0

	NYSA men	0	0	0	0	0	0	0	0	0
	Former FSW not in Cot	0	0	0	0	0	0	0	0	0

$$M_{ij}^{N} =$$

		j								
		Pro FSW	Part-time FSW	Low-risk women	Former FSW in Cotonou	Client	Low-risk men	NYSA women	NYSA men	Former FSW not in Cotonou
i	Pro FSW	0	0	0	0	1	0	0	0	0
	Part-time FSW	0	0	0	0	1	0	0	0	0
	Low-risk women	0	0	0	0	1	1	0	0	0
	Former FSW in Cot	0	0	0	0	1	1	0	0	0
	Client	1	1	1	1	0	0	0	0	0
	Low-risk men	0	0	1	1	0	0	0	0	0
	NYSA women	0	0	0	0	0	0	0	0	0
	NYSA men	0	0	0	0	0	0	0	0	0
	Former FSW not in Cot	0	0	0	0	0	0	0	0	0

The probabilities of commercial and non-commercial sexual contact of an individual from group *i* with an individual from group *j* (p_{ij}^{C} and p_{ij}^{C} respectively) is determined by the proportion of partnerships declared by group *j* out of the total number of partnerships, calculated as follows:

$$p_{ij}^{C}(t) = \begin{cases} \dfrac{c_j^{C} N_j}{\sum_{j=1}^{9} c_j^{C}\ N_j\ M_{ij}^{C}}, & M_{ij}^{C} = 1 \\ 0, & M_{ij}^{C} = 0 \end{cases}$$

$$p_{ij}^{N}(t) = \begin{cases} \dfrac{c_j^{N} N_j}{\sum_{j=1}^{9} c_j^{N}\ N_j\ M_{ij}^{N}}, & M_{ij}^{N} = 1 \\ 0, & M_{ij}^{N} = 0 \end{cases}$$

Where c_j^{C} and c_j^{N} represent the commercial and non-commercial partner change rates of group *j* respectively, *after balancing.*

S2j: HIV transmission probability per sex act

From Boily et al. 2009, we obtain ranges for the baseline probability of HIV transmission from men to women (β) [51]. We estimate the per sex act probability of transmission from men to women (and vice versa) which depends on: relative risk of HIV transmission probability (RR) with concurrent HSV-2 infection in the acquirer, female-to-male transmission, circumcision, and HSV-2 prevalence in the acquirer. We assume all males are circumcised [63,64,66], which confers lower risk of HIV acquisition in men but not transmission from men.

HIV transmission probability per sex act from men to women (β_{MF}):

$$\beta_{MF} = \beta * (1 + (RR_j^{HSV2} - 1) * \pi_j^{HSV2})$$

Where RR_j^{HSV2} is the RR of transmission probability if acquirer group *j* is HSV-2 infected; π_j^{HSV2} is the prevalence of HSV-2 in group *j*.

HIV transmission probability per sex act from women to men (β_{FM}):

$$\beta_{FM} = \beta * RR^{\beta FM} * RR^{\beta circum} * \left(1 + (RR_j^{HSV2} - 1) * \pi_j^{HSV2}\right)$$

Where $RR^{\beta FM}$ is the RR of female-to-male transmission; $RR^{\beta circum}$ is RR of male circumcision.

S2k: Relative risk of transmission

Transmission probability per sex act will also depend on the care state (r) and the stage of infection (s) of the transmitter.

Relative risk of transmission ($R_j^{r,s}$)		Stage of infection (s) of the transmitter (j)				
		1. Primary	2. CD4 >500	3. CD4 350 - 500	4. CD4 200 - 349	5. CD4 <200
Care state (r) of the transmitter (j)	1. Undiagnosed	$RR^{primary}$	1	1	1	RR^{AIDS}
	2. Diagnosed off ART	-	1	1	1	RR^{AIDS}
	3. On ART	-	RR_j^{ART}	RR_j^{ART}	RR_j^{ART}	RR_j^{ART}
	4. ART Drop out	-	1	1	1	RR^{AIDS}

Where $RR^{primary}$ is the relative risk of infection per sex act if the transmitter is in primary stage of infection; RR^{AIDS} is the relative risk of infection per sex act if the transmitter is in AIDS stage; RR^{ART} is the relative risk of infection if the transmitter is on ART. RR_j^{ART} is calculated as follows:

$$RR_j^{ART} = 1 - VS_j * eff^{ART}$$

Where VS_j is the proportion of individuals that are virally suppressed in group j, and eff^{ART} is the efficacy of ART when virally suppressed.

S2l: Disease progression and AIDS-related mortality

Progression through the stages of infection occurs at rate $\gamma^{r,s}$ for each care state r and current stage s.

The duration of the entire infection ($dur_{SCdeath}$, seroconversion to death) is estimated, as well as the duration of primary phase ($\frac{1}{\gamma^{01}}$), infection stage CD4 200-349 ($\frac{1}{\gamma^{04}}$) and CD4 <200 ($\frac{1}{\alpha^{05}}$). The durations of stages CD4 >500 ($\frac{1}{\gamma^{02}}$) and CD4 350-500 ($\frac{1}{\gamma^{03}}$) are calculated as follows:

$$\frac{1}{\gamma^{02}} = \frac{1}{\gamma^{03}} = dur_{SCdeath} - \frac{1}{\gamma^{01}} - \frac{1}{\gamma^{04}} - \frac{1}{\alpha^{05}}$$

Progression happens at the same rate when undiagnosed off PrEP, undiagnosed on PrEP, diagnosed off PrEP or in ART dropout (r = 0, 1, 2, 4); progression is slowed by a factor of $prog_{ART}$ for those on ART (r = 3) such that:

$$\gamma^{32} = \frac{\alpha^{03}}{prog_{ART}} * VS_j + \gamma^{02}\left(1 - VS_j\right)$$

$$\gamma^{33} = \frac{\alpha^{04}}{prog_{ART}} * VS_j + \gamma^{03}\left(1 - VS_j\right)$$

$$\gamma^{34} = \frac{\alpha^{05}}{prog_{ART}} * VS_j + \gamma^{04}\left(1 - VS_j\right)$$

Where VS_j is the proportion of individuals that are virally suppressed in group *j*.

If an individual on PrEP is infected (stage $I_i^{1,1}$), they progress at the same rate as if not on PrEP:

$$\gamma^{1,1} = \gamma^{0,1}$$

There is no AIDS-related mortality for those who are susceptible, primary phase of infection, or CD4 >500 (s = 0, 1, 2). It occurs for CD4 350-500, CD4 200-249, CD4 <200 (s = 3, 4, 5). AIDS related mortality for those on ART (r = 3) is slowed by a factor of $mort_{ART}$, such that:

$$\alpha^{33} = \frac{\alpha^{13}}{mort_{ART}} * VS_j + \alpha^{13}(1 - VS_j)$$

$$\alpha^{34} = \frac{\alpha^{14}}{mort_{ART}} * VS_j + \alpha^{14}(1 - VS_j)$$

$$\alpha^{35} = \frac{\alpha^{15}}{mort_{ART}} * VS_j + \alpha^{15}(1 - VS_j)$$

Cotonou model outcomes

Outcomes estimated for each scenario to evaluate impact:

Statistic	Calculation
Cumulative HIV infections (CI_i)	Cumulative HIV infections (CI_i) are calculated as follows: $$\frac{dCI_i}{dt} = S_i(t) \sum_{j=1}^{j=9} \lambda_{ij}(t)$$ Where $S_i^s(t)$ represents susceptible inidividuals in group i at time t, and $\lambda_{ij}(t)$ represents the force of infection from group j to group i at time t.
HIV-related deaths (H_i)	Cumulative HIV-related deaths (H_i) are calculated as follows: $$\frac{dH_i}{dt} = \sum_{r=1}^{r=4} \sum_{s=1}^{s=5} \alpha_i^{r,s} I_i^{r,s}(t)$$ Where $I_i^{r,s}(t)$ represents infected individuals in group i, in care-state r, stage of infection s at time t, and $\alpha_i^{r,s}$ represents the AIDS-related mortality rate in group i, care state r, stage of infection s.

Cotonou model parameters

Most Cotonou model parameters and fitting data were sourced from demographic, sexual behaviour and HIV prevalence data from local census,[80-83] the UN World Population Prospect,[84] studies among KP[66,85-88] (including IBBS studies[65,67,70-74]). Sexual behaviour parameters were informed by several rounds of FSW over time and client IBBS in Cotonou and three household-based general population surveys.[63-66,70,71,73,74] Cotonou FSW HIV incidence (2015) and biological parameters for HIV natural history and infectivity were sourced from published literature.[51,89-103] Data on HIV prevalence by risk group, HIV testing, ART (available in Benin since 2002[75]) uptake and coverage, adherence (viral suppression) and dropout among FSW and other groups were also derived from the IBBS, household-based surveys in Cotonou,[63,64,66] and government reports.[73,75,76,104,105]

Table 1 below displays full details of the parameters in the model: demographic, sexual behaviour, biological and intervention. Some parameters were sampled in a Latin Hypercube from a uniform distribution of the range given in the table, others were fixed and not sampled. Some parameter values were sampled at certain timepoints (e.g. commercial partner change range); we assume that parameter values between sampled timepoints are linearly interpolated between them.

Model parameters are derived from several sources. Where there were multiple sources estimating the same parameter, a prior range was defined encompassing all estimates, and sampled in the Latin Hypercube. Parameter estimates sourced from the published literature assumed the 95% CI as the prior range.

Table S4: Demographic parameters

Name (units)	Risk group	Year	Symbol	Value/Range	Source
Year of seeding of epidemic	NA	NA	t_0	1986	106
Total population aged 15-59 at seed	All	NA	N_0	286114	82,83
Population growth rate (per year)	All	1979-1992	ε	0.059	80-83
	All	1993-2002		0.048 - 0.058	
	All	2002-2013		0.027	
	All	2014-		0.027	
Proportion of population that is female at seeding	NA	1986-2035	$prop_F$	0.512 - 0.520	80-83
Proportion of women that are professional FSW at seeding	Pro FSW	1986-2035	$prop_{PFSW}$	0.0024 - 0.00715	80-83,87,88 88
Ratio of women that are part-time FSW to Pro FSW at seeding	Part-time FSW	1986-2035	$ratio_{LFSW}$	1 - 2	87
Proportion of women that are former FSW at seeding	Former FSW in Cotonou	1986-2035	$prop_{FFSW}$	Same as proportion that are professional FSW	Assumption
Proportion of men that are clients at seeding	Client	1986-2035	$prop_C$	0.066 - 0.30	80-83,86,107
Fraction of the 15-59 population that is not yet sexually active at seeding	Low-risk women	1986-2035	$prop_{FV}$	0.079 - 0.20	64,67
	Low-risk men	1986-2035	$prop_{MV}$	0.070 - 0.17	64,66

Prevalence of HIV at seeding	FSW	NA	π_{FSW}	0.0132 - 0.0659	106
	Client	NA	π_C	0.000313 - 0.00294	108
	Low-risk women	NA	π_F		
	Low-risk men	NA	π_M		
Rate of leaving by ageing (per year)	All	1986-2035	ν	0.022	Assumption
Background mortality rate (per year)	Women	1986-2035	μ	0.0187 - 0.0200	84
	Men			0.0194 - 0.0220	
Rate of leaving of sex work (per year)	Pro FSW & part-time FSW	1986-2035	1 / dur_{FSW}	0 - 0.55	65,67,72,109
Proportion of FSW that are non-Beninese	Pro FSW	1986-2035	$frac_{FSWforeign}$	0.5 - 0.9	65,67,72,74
Prevalence of incoming professional FSWs	Pro FSW	1986 - 1993		0 - 0.163	65,66,72,74,110
		1986 - 2015		Linearly interpolated	
		2015 -		0 - 0.046	
Rate of leaving of client category (per year)	Client	1986-2035	1 / dur_{client}	0 - 0.295	70,72,73
Rate of entering the sexual population (per year)	Not yet sexually active female	1986-2035	χ_F	0.2 - 0.5	64,66
	Not yet sexually active male	1986-2035	χ_M	0.2 - 0.5	64,67
Proportion of people that are sexually active at 15	Women	1986-2035	$frac_{WSA}$	0.12 – 0.17	64,67
	Men	1986-2035	$frac_{MSA}$	0.18 – 0.35	64,66

Table S5: Sexual behaviour parameters

Name	Group	Year	Symbol	Value	Source
Commercial partner change rate (per year)	Professional FSW	1986 - 1993	c^C_{PFSW}	192 - 1277	65,66,72,74
		1993 - 2005		Linearly interpolated	
		2005 -		81 - 562	
	Part-time FSW	1986-2035	c^C_{LFSW}	26 - 78	Personal communication
	Client	1986 - 1998	c^C_C	8.4 - 32	70,71,73
		1998 - 2002		Linearly interpolated	

		2002 -		11.1 - 19.8	
Non-commercial partner change rate (per year)	Professional FSW	1986-2035	c^{N}_{PFSW}	0.31 – 0.86	[65,67,72,74]
	Part-time FSW	1986-2035	c^{N}_{LFSW}	0.41 – 1.04	[72,74]
	Client	1986-2035	c^{N}_{C}	1.6 – 3.3	[70,71,73]
	GPF	1986 - 1998	c^{N}_{F}	0.93 - 0.99	[64,66]
		1998 - 2008		Linearly interpolated	
		2008 -		0.77 - 0.82	
	GPM	1986 - 1998	c^{N}_{M}	1.25 - 1.43	[64,66]
		1998 - 2008		Linearly interpolated	
		2008 -		0.73 - 0.84	
Commercial number of sex acts per partnership (per year)	Professional FSW	1986-2035	n^{C}_{PFSW}	1 - 3	[65,66,72,74]
	Part-time FSW	1986-2035	n^{C}_{LFSW}	1	Assumption
Non-commercial number of sex acts per partnership (per year)	Professional and part-time FSW	1986 - 2002	n^{N}_{PFSW}	13.0 - 20.0	[65,67,72,73]
		2002 - 2015		Linearly interpolated	
		2015 -		38.2 - 60.0	
	Clients	NA	n^{N}_{C}	Matching the partner in their respective partnerships	Assumption
	GPF - GPM	1998	n^{N}_{F}	35 - 44	[64,66]
		1998 - 2011		Linearly interpolated	
		2011		29 - 38	
Proportion of commercial sex acts protected by condom	Professional FSW & clients	1986	$fc^{C}_{PFSWclient}$	0 - 0.18	[65,67,70,72,109]
		1986 - 1993		Linearly interpolated	
		1993		0.18 - 0.33	
		1993 - 1998		Linearly interpolated	
		1998		0.4 - 0.73	
		1998 - 2002		Linearly interpolated	
		2002		0.61 - 0.99	
		2002 - 2008		Linearly interpolated	
		2008		0.86 - 0.99	

	Part-time FSW & clients	1986	$fc^{C}_{LFSWclient}$	0	Assumption
		1986 - 2015		Linearly interpolated	
		2015		0.25 – 0.52	[70-74]
Proportion of non-commercial sex acts protected by condom	Professional FSW & clients	1986	fc^{N}_{FSW}	0	[65,67,70,72,73]
		1986 - 2002		Linearly interpolated	
		2002 -		0.19 - 0.62	
	Part-time FSW & clients	1986	$fc^{C}_{LFSWclient}$	0	Assumption
		1986 - 2015		Linearly interpolated	
		2015		0.138 – 0.383	[70,72,74]
	Clients	1986-2035	fc^{N}_{C}	Same as FSW or GPF in respective partnerships	Assumption
	GPF	1986 - 1998		0.033 - 0.05	[64,66]
		1998 - 2011		Linearly interpolated	
		2011 -		0.16 - 0.26	
	GPM	Same as GPF	fc^{N}_{M}	Same as GPF	

Table S6: Biological parameters

Name	Group	Year	Symbol	Value	Source
HIV baseline transmission probability male to female per sex act	All	1986-2035	β	0.0006 - 0.00109	[51]
RR HIV transmission risk female to male	All	1986-2035	$RR^{\beta FM}$	0.53 - 2	[51]
RR transmission probability with HSV-2 infection in acquirer commercial	Professional FSW	1986-2035	RRj^{HSV2}	0.9 – 2.3	[111]
RR transmission probability with HSV-2 infection in acquirer commercial	Women who are not professional FSW	1986-2035	RRj^{HSV2}	1.8 – 3.4	
RR transmission probability with HSV-2 infection in acquirer commercial	Clients	1986-2035	RRj^{HSV2}	1.5 – 2.2	
RR transmission probability with HSV-2 infection in acquirer commercial	Men who are not clients	1986-2035	RRj^{HSV2}	2.2 – 4.3	
Prevalence of HSV-2	Pro FSW & part-time FSW	1986-2035	πj^{HSV2}	0.87 - 0.94	[86]

Prevalence of HSV-2	Clients	1986-2035	πj^{HSV2}	0.18 - 0.28	112
Prevalence of HSV-2	GPF	1986-2035	πj^{HSV2}	0.27 - 0.32	86
Prevalence of HSV-2	GPM	1986-2035	πj^{HSV2}	0.098 - 0.14	86
RR transmission circumcision	All	1986-2035	$RR^{\beta circum}$	0.34 - 0.72	38,113
RR of transmission during primary phase	All	1986-2035	$RR^{primary}$	4.5 - 18.8	51
RR of transmission during AIDS (CD4 <200) phase	All	1986-2035	RR^{AIDS}	4.5 - 11.9	51
Efficacy of ART if virally suppressed regarding reduction in onward transmission	All	1986-2035	eff^{ART}	0.96 - 0.99	114
Fraction of other groups virally suppressed	Low-risk	1986-2035	$VS_{2\text{-}9}$	0.42 - 0.85	105,109
Fraction of professional FSW virally suppressed	Professional FSW	1986 - 2015	VS_1		
Condom efficacy	All	1986-2035	ec	0.58-0.95	42
Duration between seroconversion and death (years)	All	1986-2035	$dur_{SCdeath}$	8.7 - 12.3	94,95,97-100,102,103
Duration of primary phase (years)	All	1986-2035	$1/\gamma_{01}$	0.25 - 0.42	51,95
Duration of CD4 200-349 (years)	All	1986-2035	$1/\gamma_{04}$	2.3 - 4.4	91,97,99
Duration in CD4 <200 (years)	All	1986-2035	$1/\alpha_{05}$	0.58 - 3.17	90,93,96-98,101,103
Duration of CD4 >500 (years)	All	1986-2035	$1/\gamma_{02}$	Derived from other sampled parameters	Derived: ($dur_{SCdeath}$ - γ_{01} - γ_{04} - α_{05}) gives the time after primary phase until CD4 200-349. Dividing this time by 2 gives the duration of both CD4 >500 and CD4 350-500, assuming they have the same duration
Duration of CD4 350-500 (years)	All	1986-2035	$1/\gamma_{03}$		
Death rate CD4 350-500 (per year)	All	1986-2035	α_{03}	0.01 - 0.05	84,90
Death rate CD4 200-349 (per year)	All	1986-2035	α_{04}	0.03 - 0.10	
Reduction in progression for individuals on ART	All	1986-2035	$prog_{ART}$	4.82 - 10.2	115
Reduction in mortality for individuals on ART	All	1986-2035	$mort_{ART}$		

Table S7: Intervention parameters

Name	Group	Year	Symbol	Value	Source
Probability of having been tested in last year*	Professional FSW	1986 - 2005	τ	0	Personal communication
		2005 - 2013		Linearly interpolated	
		2013		0.65	[116]
		2013 - 2015		Linearly interpolated	
		2015 -		0.68	[74]
	Low-risk women	1986 - 2001		0	Personal communication
		2001 - 2006		Linearly interpolated	
		2006		0.14	[68,69]
		2006 - 2008		Linearly interpolated	
		2008		0.21	[66]
		2008 - 2011		Linearly interpolated	
		2011 -		0.33	[64]
	Low-risk men	1986 - 2001		0	Personal communication
		2001 - 2006		Linearly interpolated	
		2006		0.098	[68,69]
		2006 - 2008		Linearly interpolated	
		2008		0.1	[66]
		2008 - 2011		Linearly interpolated	
		2011 -		0.058	[64]
Relative increase in testing at CD4 stage <200	All	1986-2035	$RR_{test200}$	1 - 5.4	[117]
ART initiation rate (per year)	Professional FSW	1986-2035	ρ	0.25 - 6	[105]
	Rest of population	1986-2035		6 - 12	
ART dropout rate (per year)	Professional FSW	1986-2035	ϕ_{PFSW}	0.023 - 0.11	[75,117]
	Client	1986-2035	ϕ_C	0.023 - 0.11	
	Low-risk women	1986-2035	ϕ_F		
	Low-risk men	1986-2035	ϕ_M		
ART re-initiation rate (per year)	Professional FSW	1986-2035	ι_{FSW}	0.25 - 1.5	[105]
	Other groups	1986-2035	ι_{rest}	0.25 - 1.5	

Table S8: Cotonou model fitting data

Fitting outcomes	**Year (start)**	**Target range/estimate**	**Source**
A) Pre-study fitting			
Stage 1 (1986-2015): Demographic			
Total population size of sexually active adult population of Grand Cotonou (N)	1992	343,705 – 465,013	[80-83]
	2002	579,325 – 783,793	
	2013	776,076 – 1,049,985	
	2020	959,418 – 1,298,036	
	2030	1,210,305 – 1,637,471	
Percentage of women who are professional FSW (%)	All	0.19 – 0.72	[80-83,87,88 88]
Number of professional FSW (N)	2012	889 – 1,391	[87]
Percentage of women who are active FSW (professional + part-time) (%)	All	0.48 – 1.4	[80-83,87,88 88]
Percentage of men who are clients (%)	All	7.4 – 30	[80-83,86,107]
Percentage of women who are not yet sexually active (%)	All	7.9 – 20	[64,66,67]
Percentage of men who are not yet sexually active (%)	All	7 – 17	[63,64,66]
Stage 2 (1986-2015): Epidemiological			
HIV prevalence professional FSW (%)	1993	48 – 58	[65,67,72,109]
	2002	32 – 46	
	2008	25 – 34	
	2015	14 – 22	
HIV prevalence clients (%)	2002	6.8 – 12.0	[70,71,73]
HIV prevalence all women (%)	2011	1.3 – 3.5	[64]
HIV prevalence all men (%)	2011	0.75 – 2.9	[64]
HIV incidence rate professional FSW (% infected per person-year)	2015	0 – 3	[89]
Stage 2 (1986-2015): ART coverage			
Professional HIV infected FSW on ART (N)	2015	42 – 56	[104]
Men and women on ART combined (N)	2017	8524 – 18273	[105]
ART coverage of men and women combined (%)	2011	33 – 52	[75,105]
ART coverage of men and women combined (%)	2017	60 – 91	[75,104,105]
Ratio of women to men on ART	2017	1.5 – 3.0	[104]

Cotonou model cross validation data

Table S9: Cotonou model cross validation data

Outcome	Year	Value	Source
HIV prevalence professional FSW (%)	1995	43.0 – 54.4	[65,67,72,118]
	1998	36.6 – 44.7	
	2005	30.4 – 39.4	
	2012	23.0 – 32.2	
HIV prevalence clients (%)	1998	5.9 – 11.6	[70,71,109]
	2002	6.8 – 11.6	
	2008	3.5 – 9	
	2012	1.3 – 5.2	
	2015	0.6 – 3.5	
HIV prevalence all women (%)	1998	2.4 – 4.8	[63,64,67]
	2008	3.0 – 5.3	
HIV prevalence all men (%)	1998	2.3 – 4.7	
	2008	1.2 – 3.0	
Deaths due to AIDS (all groups)	1990	100 – 300	[110]
	1991	100 – 300	
	1992	100 – 300	
	1993	100 – 300	
	1994	100 – 300	
	1995	100 – 400	
	1996	100 – 400	
	1997	100 – 500	
	1998	200 – 600	
	1999	200 – 900	
	2000	200 – 1200	
	2001	500 – 1500	
	2002	500 – 1500	
	2003	500 – 1500	
	2004	500 – 1500	
	2005	500 – 2000	
	2006	500 – 2000	
	2007	500 – 2000	
	2008	500 – 2000	
	2009	200 – 900	
	2010	200 – 900	
	2011	200 – 800	
	2012	200 – 1300	
	2013	200 – 1300	
	2014	200 – 1300	
	2015	200 – 1300	
	2016	100 – 700	
Proportion of HIV+ on ART and virally suppressed (all groups combined)	2015	14 – 30	[110]
	2016	15 – 32	
	2017	28 – 60	

Cotonou model fits

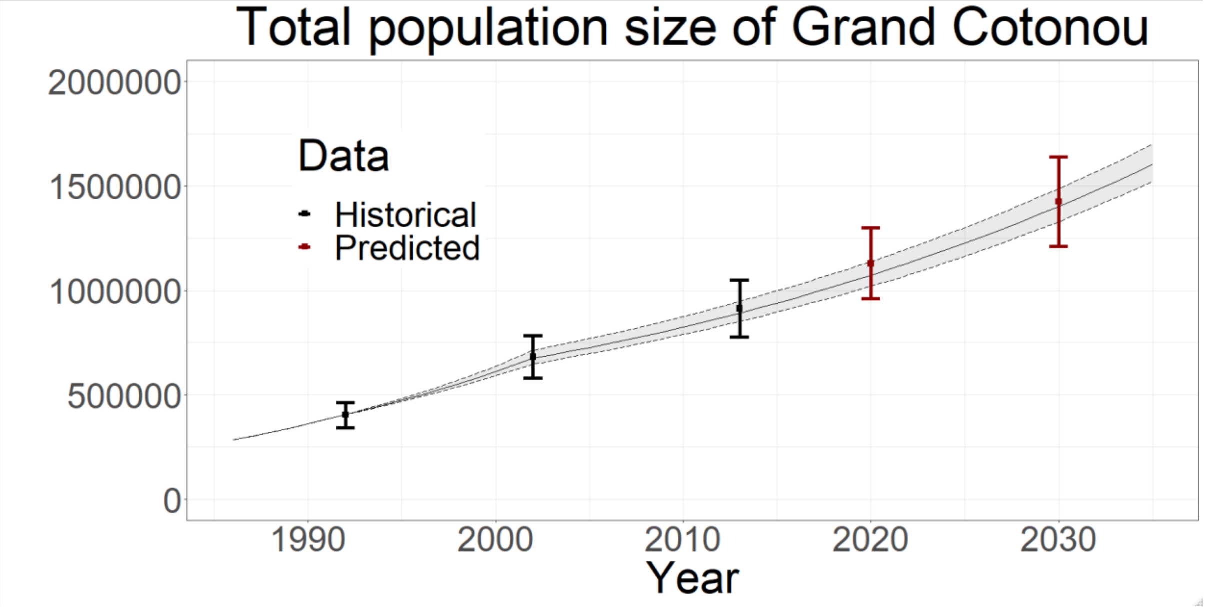


Figure S9. Posterior model predictions for total population size of Grand Cotonou from the 111 posterior parameter sets, showing median (solid line) and 95%UI across all fits (shaded regions) of base-case scenario, compared to available fitting historical demographic data shown in thick bars (black) and estimated future prediction assuming constant population growth rate (red).

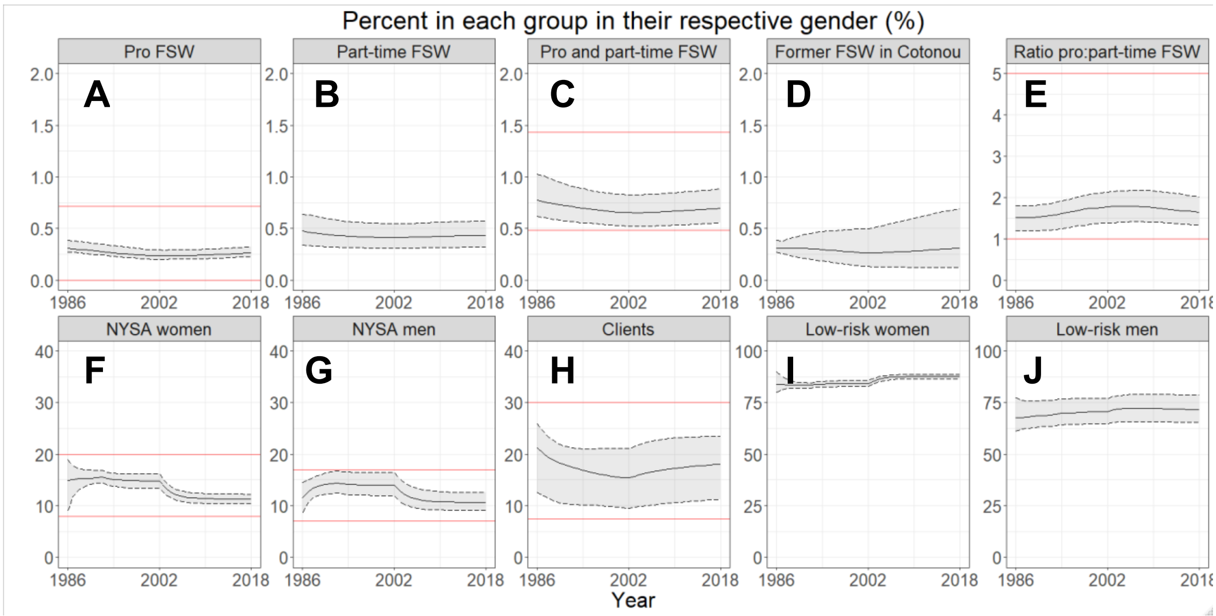


Figure S10. Posterior model predictions for the percent of each group in their respective gender (e.g. the percent of women who are professional FSW), from the 111 posterior parameter sets, showing median (solid line) and 95%UI across all fits (shaded regions) of base-case scenario, compared to available fitting historical demographic data shown in red lines.

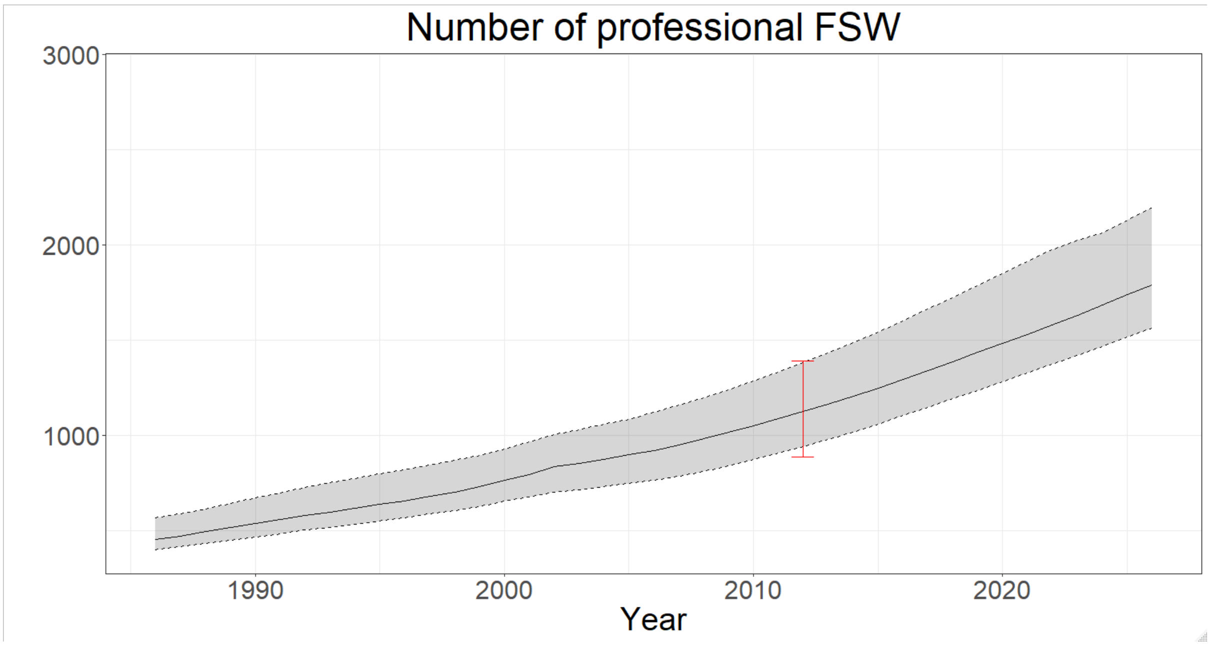


Figure S11. Posterior model predictions of number of professional FSW from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) of base-case scenario, compared to available fitting historical demographic data shown with a red bar.

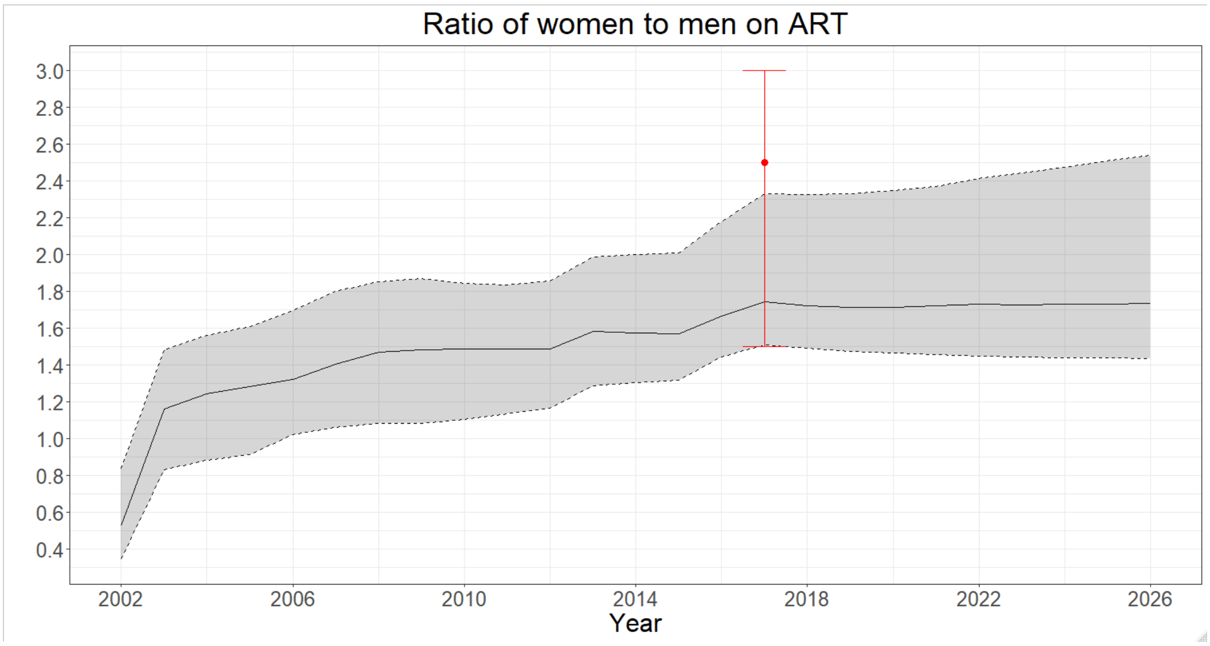


Figure S12. Posterior model predictions of the ratio of women to men on ART from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) of base-case scenario, compared to available fitting intervention data shown with a red bar.

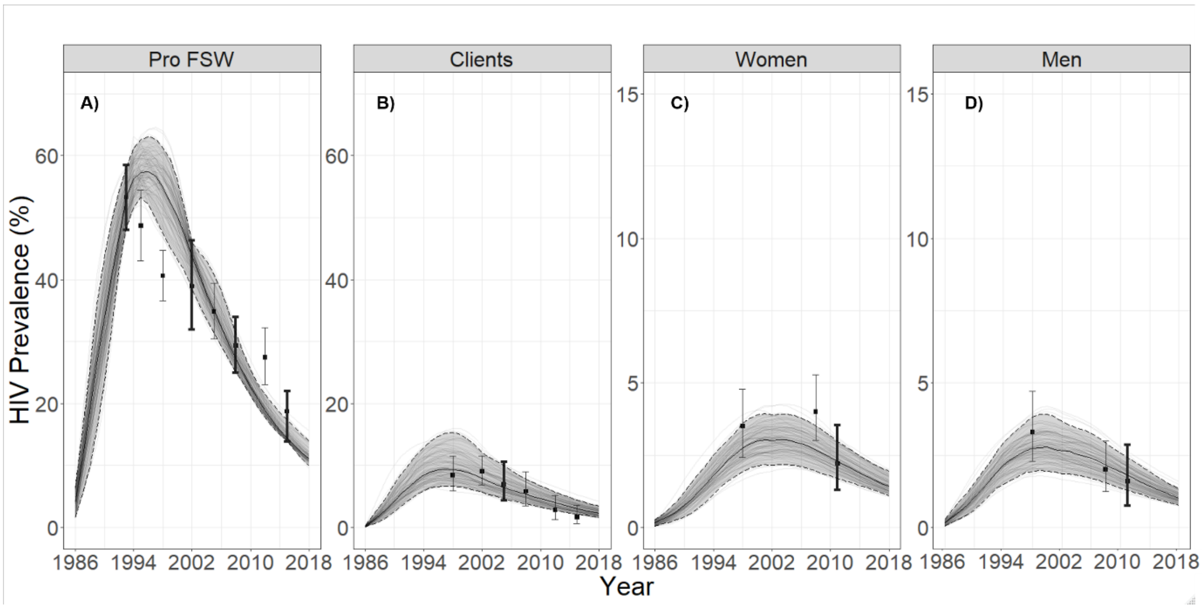


Figure S13. Model predictions from the 111 posterior parameter sets in grey solid lines (median) and shaded regions (95%UI across all fits) representing pre-study scenarios, compared to available fitting (thick bars) and cross-validation (thin bars) HIV prevalence data. Results are shown for HIV prevalence (%) among A) professional FSW, B) clients, C) all women in Cotonou, D) all men in Cotonou.

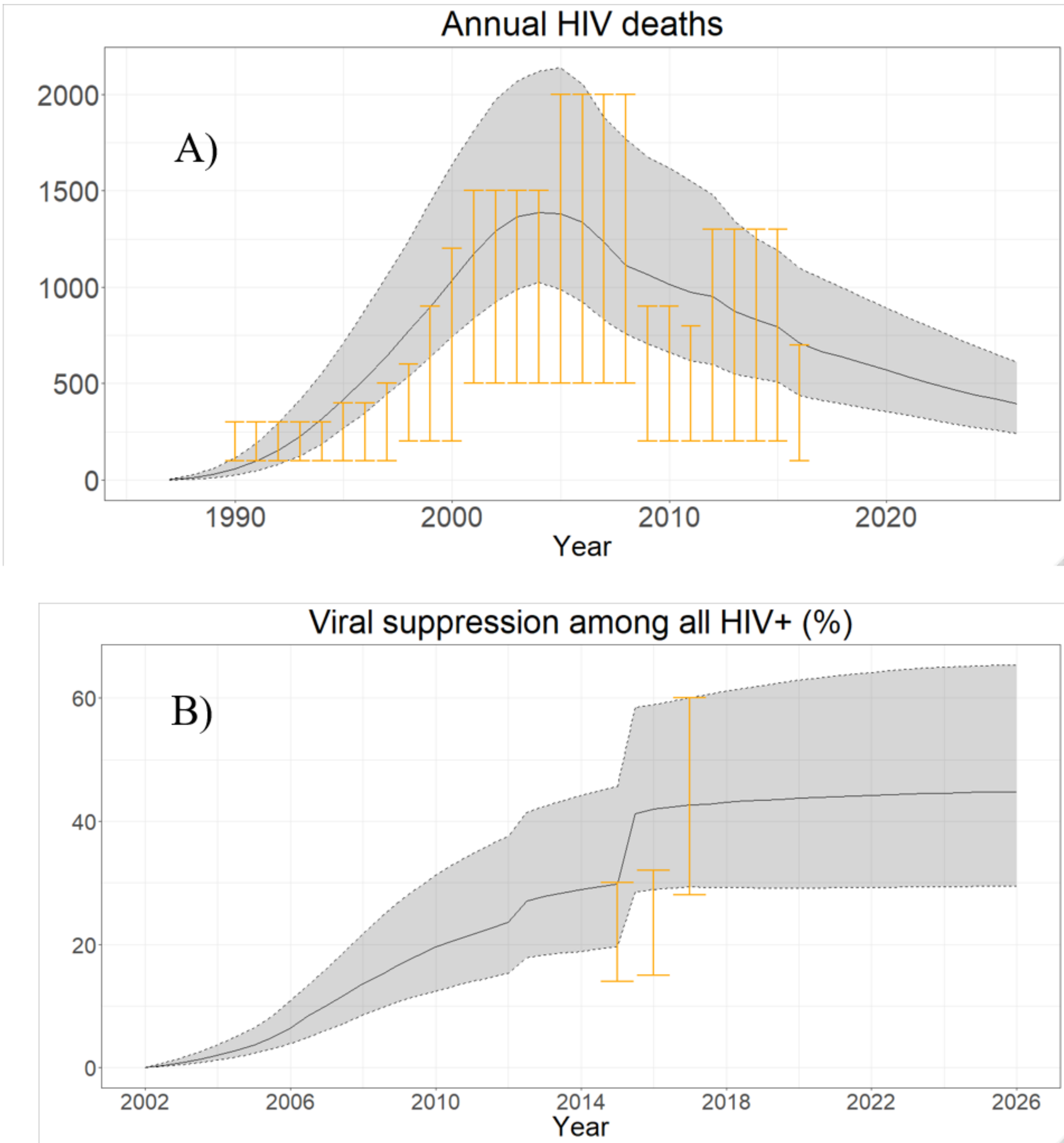


Figure S14. Posterior model predictions from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) of base-case scenario, of A) annual deaths due to HIV infection and B) proportion of HIV+ on ART and virally suppressed, compared to available cross-validation UNAIDS Reference Group Spectrum model estimates (orange bars) in Cotonou (equivalent to "Littoral").[110]

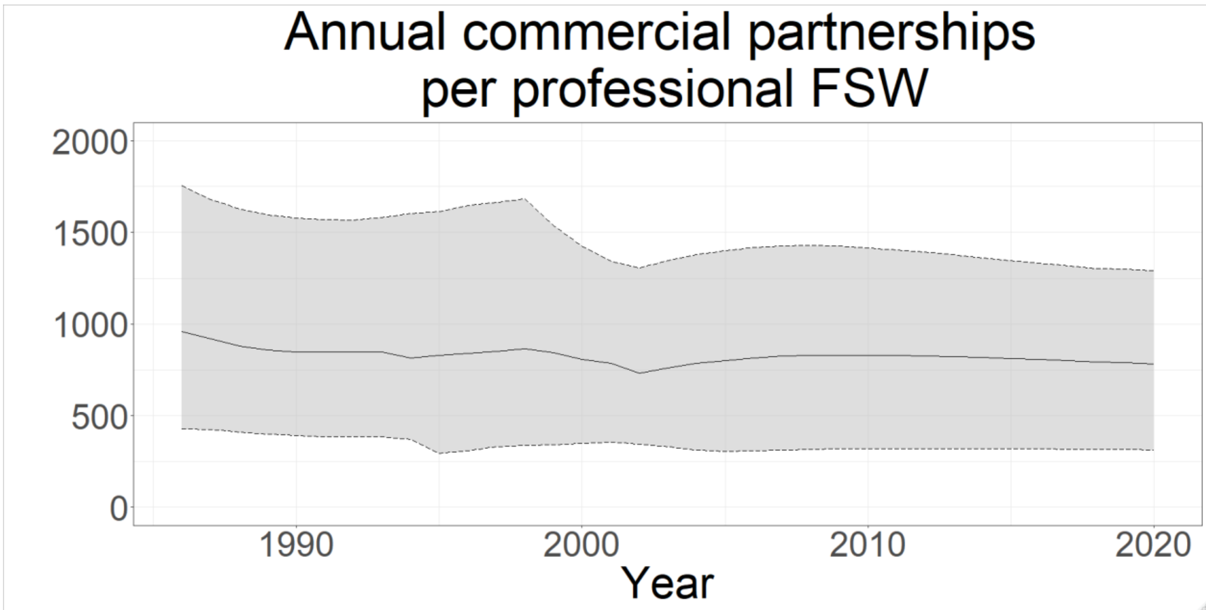


Figure S15. Posterior annual number of commercial partnerships between professional FSW and clients from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) of base-case scenario.

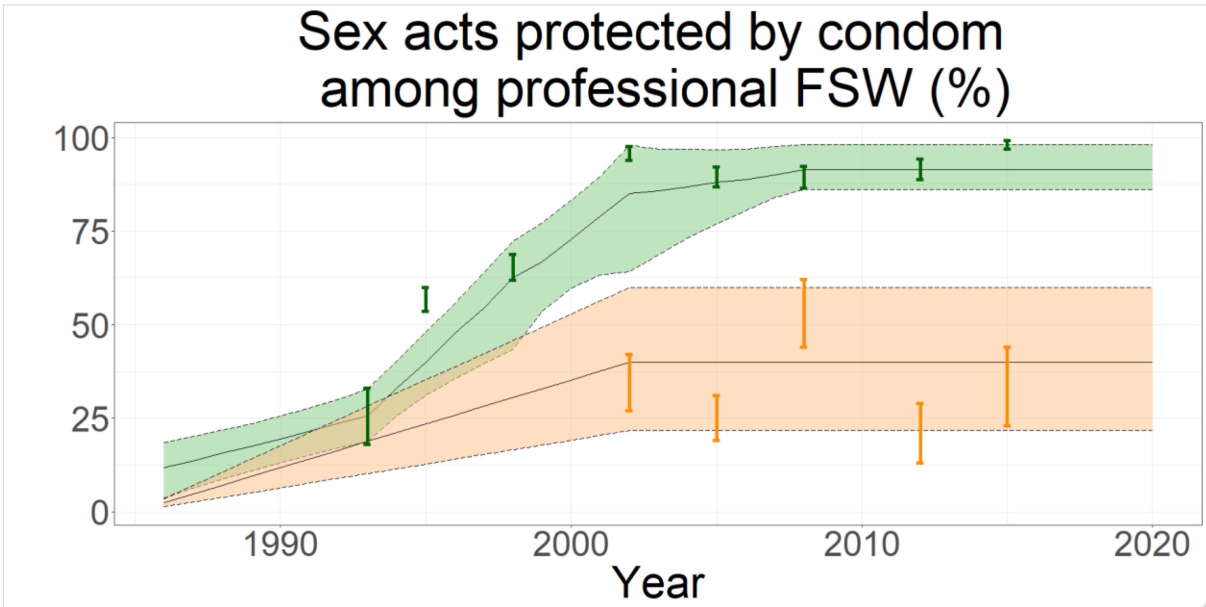


Figure S16. Posterior percent of commercial and non-commercial partnerships (shown in green and orange respectively) protected by condoms between professional FSW and clients from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) base-case scenario, compared to available historical behavioural data in bars.

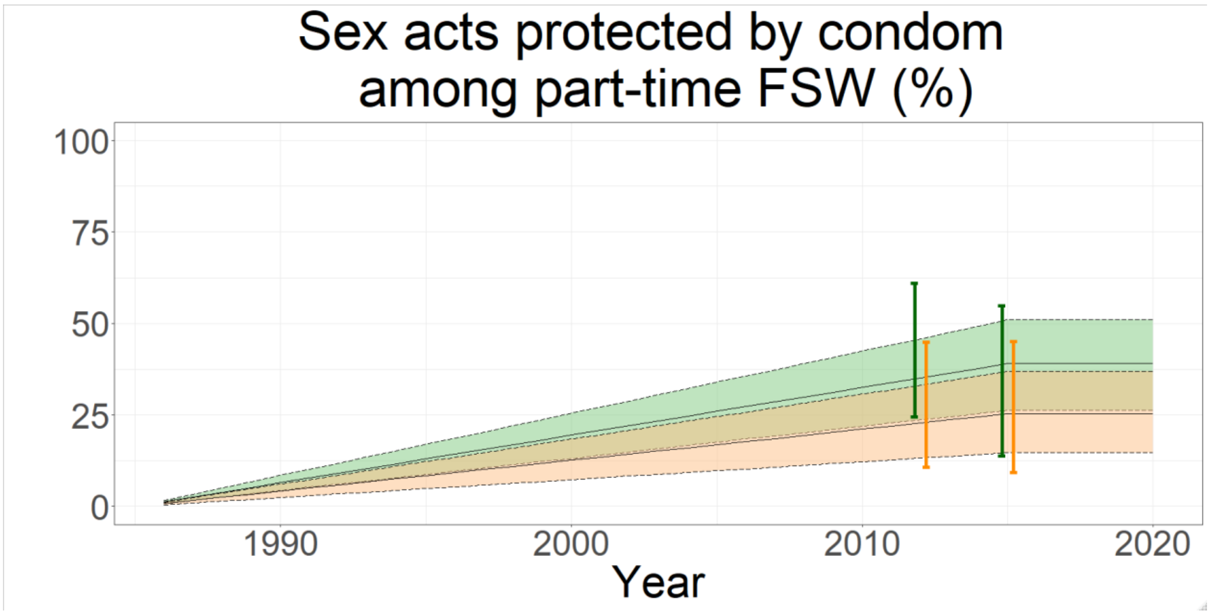


Figure S17. Posterior percent of commercial and non-commercial partnerships (shown in green and orange respectively) protected by condoms between part-time FSW and clients from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded regions) of base-case scenario, compared to available historical behavioural data in bars.

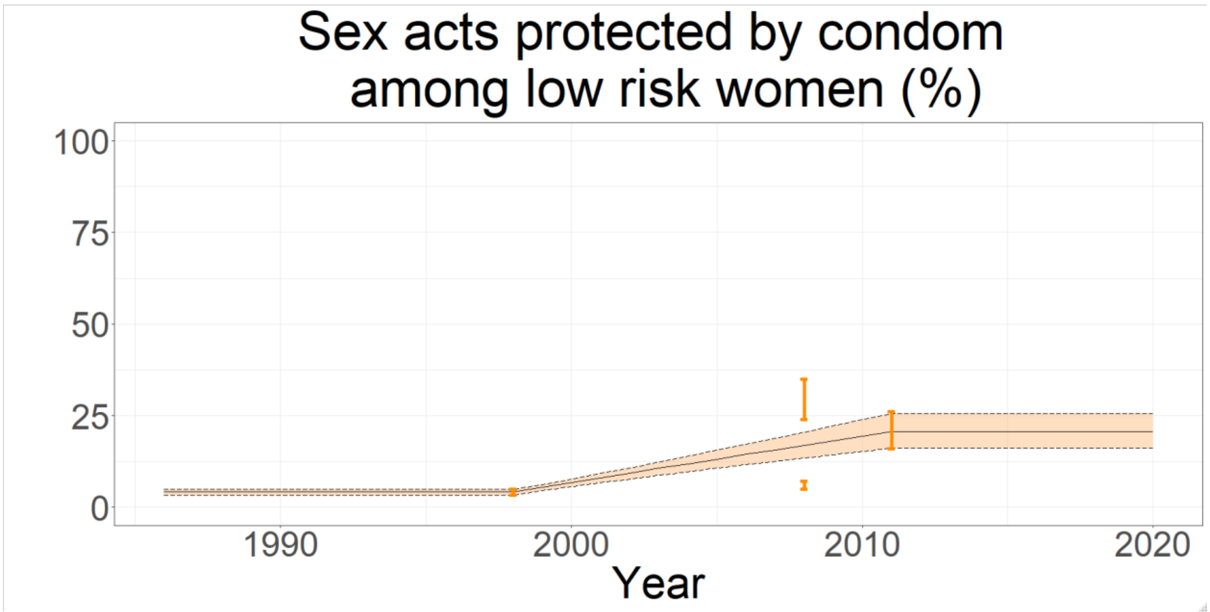


Figure S18. Posterior percent of non-commercial partnerships between low-risk women and their partners (clients and low-risk men) protected by condoms from the 111 posterior parameter sets, showing median (solid line) and 95% UI across all fits (shaded region) of base-case scenario, compared to available historical behavioural data in orange bars.

Table S10: Scenarios of potential disruptions

Table S10: Scenarios and population-level impact of potential disruptions to HIV prevention/treatment and changes in sexual behaviours applied over 6 months in our main analysis, and 3, 12 months in our sensitivity analysis

Scenario	Assumed effect of COVID-19 and responses to COVID-19	Justification, source, and plausibility of scenarios in the two cities	Estimated impact on new HIV infections or HIV-related deaths in the two cities over 1 year
Main five scenarios			
⇓ New ART initiation - all (1)	No new ART initiations for anybody	Strong hypothetical assumption reflecting ART supply issues or reduced outreach.[119-122] . Early data from Cameroon suggests a 32% decrease in ART initiations over January-June 2020 compared to January-June 2019.[123]	Modest impact even when assuming no new ART initiations over a 6-month period, with a 5% increase in annual new HIV infections and 3% increase in HIV-related deaths.
⇓ VLS - all (2)	Level of viral suppression is reduced by a fixed fraction (10%, 25%, 50%) for everybody	The pandemic reduces access to ART clinics/viral load monitoring/adherence support,[124-126] ART supply issues.[119-121] In a global online survey among LGBT+, 26% of PLHIV reported having experienced interrupted or restricted access to refills of ART medication. Out of this group, over half (55%) had a month's stock supply or less of ART available.[125] In a global survey among MSM, 45% (n=1254) of PLHIV reported being unable to refill their HIV medicine prescription remotely.[127] Cameroon's ministry of health data shows a 10% decrease in the proportion of PLHIV on ART who are virally suppressed in June 2020 compared to December 2019 (80% vs 88%).[128]	Substantial impact on both new infections and mortality when the reduction exceeds 10% over a 6-month period. A 25% reduction over 6 months is associated with a 9% and 6% increase in new HIV infections and HIV deaths in Yaoundé, respectively, vs 8% and 12% in Cotonou.
⇓ Condom use any partners – all (3)	Condom use during all sex acts reduced by a fixed fraction (10%, 25%, 50%) for everybody	Reduced outreach and potential disruption in condom provision.[125,129,130] In a global online survey among LGBT+, 12% of the sample reported no or uncertain access to condoms[125]. No data was available for sub-Saharan Africa. Large reductions in all condom use by lower-risk populations are not anticipated in the two cities as condom provision seems to have been maintained.	Significant impact (>5%) on new HIV infections could be caused by reductions of condom use of over 10% over 6 months. A 25% reduction in all condom use over 6 months would be associated with a ~10% increase in new HIV infections and HIV deaths in both cities. No significant impact on HIV mortality.

⇓ Casual partnerships – all (4)	Number of casual partnerships are reduced by a fixed fraction (10%, 25%, 50%) for everybody	Reductions in casual (or non-commercial) partners are reported in studies in the US, UK, and Australia.[124,129,131,132] For example, a study among MSM in in Australia suggested a 84% relative reduction in proportion of MSM reporting sex with casual partners compared to before COVID-19.[132] Decrease in casual sex was mentioned in newspaper articles in Central and West Africa.[133], but no data is currently available for Africa.	Reductions in casual sex were associated with very modest decreases in new HIV infections (<5%), unless the reductions were large (>25%) and/or over more than 6 months.
⇓ Commercial partnerships – FSW and clients (5)	Number of commercial partnerships are reduced by a fixed fraction (10%, 25%, 50%) for FSW and clients	Reductions documented among male sex workers in the US,[134] and mentioned in newspaper articles in Central and West Africa,[135] since bars and nightclubs were shut during the evenings in many African countries. Reductions not precisely documented in Africa, although in a recent survey in Cotonou, 88% of surveyed FSW reported that clients were "rare" in hotspots. [136]	Little impact on new HIV infections in Yaoundé (~2% decrease in new HIV infections when assuming a 50% reduction in commercial partnerships over 6 months), however more significant impact in Cotonou (7% decrease in new HIV infections in the same scenario)
Additional condom scenarios – Both settings			
⇓ Commercial condom use – FSW and clients (3a)	Condom use during commercial sex acts decreases by a fixed fraction (10%, 25%, 50%) for FSW and clients	Subset of scenario (3). UNAIDS has reported interruptions to condom supplies among FSW owing to the pandemic[137]. In Cotonou, 21% of FSW have reported a decrease in the distribution of free condoms over September/October 2020. [136] Decreases in condom use during commercial sex could also result from the economic impact of the COVID-19 pandemic, since condomless sex with a client is more lucrative than sex with condoms.	Significant impact (>5%) on new HIV infections in both cities, especially among their key populations, when the reduction exceeds 5%. A 25% reduction in commercial condom use is associated with an overall 8% decrease in new HIV infections in Cotonou, but 31% among FSW. These estimates are 2% and 12% in Yaoundé, respectively.
⇓ Non-commercial condom use – all (3b)	Condom use during non-commercial sex acts decreases by a fixed fraction (10%, 25%, 50%)	Subset of scenario (3)	Significant impact (>5%) on new HIV infections in Yaoundé. A 25% reduction in non-commercial condom use is associated with a 9% decrease in new HIV infections in Yaoundé (2% in Cotonou).
Setting specific scenarios – setting specific			

⇓ HIV testing – all (6)	HIV testing reduced by a fixed fraction (10%, 25%, 50%, 100%)	Not modelled in Yaoundé. Several studies have reported decreases in HIV testing.[125,129,130,138] As an example, around 20% of sample in two studies among MSM in the US and LGBT+ globally reported less or no access to HIV testing[125,129] during the pandemic. Also, only 30% of a sample of MSM reached through a rapid global online survey reported being able to access onsite HIV testing.[130] Difficulties in accessing HIV self-tests have also been reported. For example, in a recent survey, 56% of a sample of 9335 MSM reported potential interruptions to HIV self-testing.[127] Early data from Cameroon suggests a 30% decrease in the number of people tested for HIV over January-June 2020 compared to January-June 2020. [123]	Little impact on new HIV infections in Cotonou (<4%), even when all testing is suspended.
⇓ MSM partnerships – MSM (7)	Number of partnerships between males are reduced by a fixed fraction (10%, 25%, 50%) for MSM	Not modelled in Cotonou. See scenario (4) for justifications, most of empirical data having been collected among MSM. No available data in Africa.	Modest overall impact on new HIV infections in Yaoundé: a 5% decrease when MSM partnerships are reduced by 50% over 6 months, but the impact would be much more significant among MSM (~33% decrease in that scenario)
⇓ All condom use by MSM, FSW and clients at same level as among lower-risk populations – MSM, FSW and clients (8)	Condom use during all sex acts of MSM, FSW and clients to the same levels as condom use among lower-risk population	Not modelled in Cotonou. This hypothetical scenario reflects the expected effects of the absence of HIV prevention programs among key populations.	Important impact, with a 14% increase in new HIV infections overall, and 44%, 29%, and 20% increases among FSW, their clients, and MSM, respectively
⇓ Part-time sex work (9)	Assuming a concomitant increase in commercial sex by clients with full-time FSW (9a), or the client demand for sex work is maintained and transferred to full-time FSW (9b)	Not modelled in Yaoundé. This scenario reflects possible adverse effects of closing bars and nightclubs in the evenings in Cotonou.	Negligible overall impact (<1% change in new HIV infections)
Risk-group specific scenarios			
⇓ new ART initiation and	No new ART initiations and 50% reduction in viral suppression for the	Subset of scenario (1+2)	

VLS – specific groups	following risk groups: FSW and/or clients (Cotonou, Yaoundé) and/or MSM (Yaoundé only), non FSW/clients (Cotonou, Yaoundé), non –FSW/clients/ MSM (Yaoundé only)	
⇓ condom use	50% reduction in condom use in all sex acts decreases for the following partnerships • FSW and/or clients (Cotonou, Yaoundé), and/or MSM (Yaoundé only) with all partners • Between FSW and clients and MSM (Yaoundé only) • Non-FSW and non-clients and/or non-MSM (Yaoundé only) with all partners • Between non-FSW and non-clients and/or non-MSM (Yaoundé only)	Subset of scenario (3)

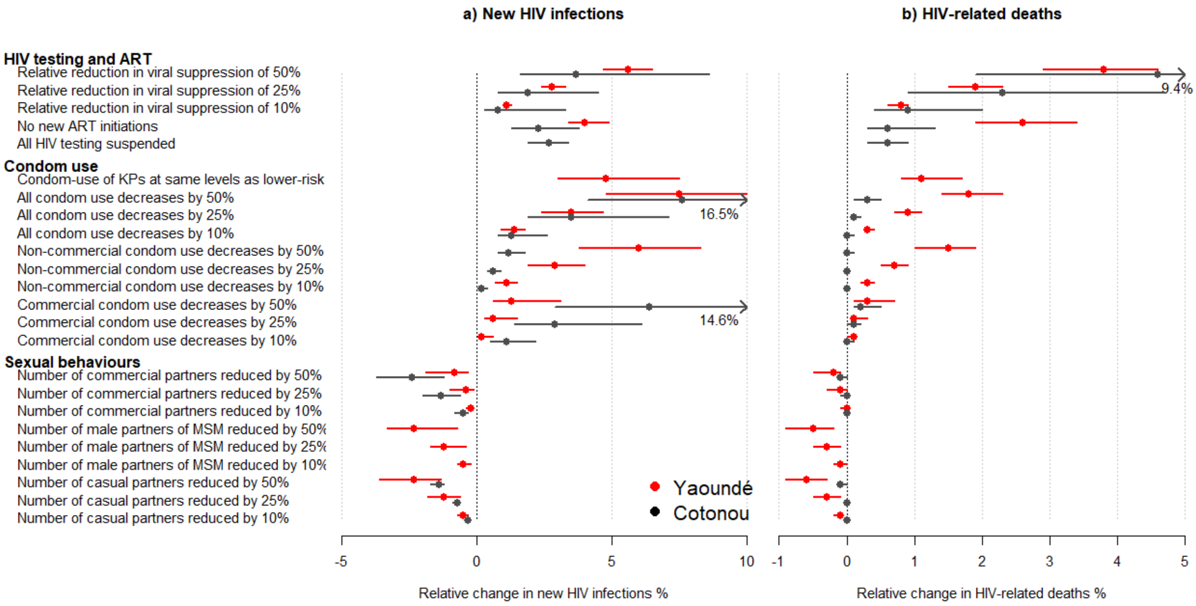


Figure S19: First set of scenarios. Relative change in cumulative number of HIV infections (a) and HIV-related deaths (b) over 5 years under individual scenarios assuming 6-months disruptions, compared to base-case in Yaoundé (red) and Cotonou (black). Dots represent median estimates across model predictions, whereas lines represent 95%UI (2.5th and 97.5th percentile of the estimates).

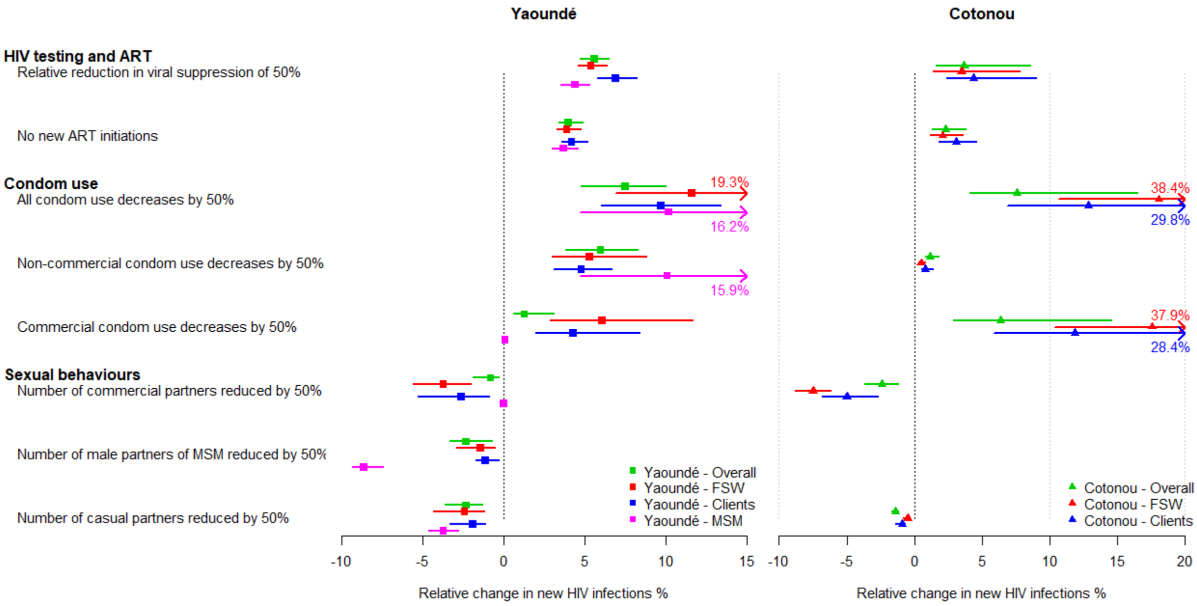


Figure S20: Relative change in cumulative number of new HIV infections in Yaoundé (squares) and Cotonou (triangles) over 5 years under individual scenarios assuming 6-months disruptions, calculated overall (green dots and lines), among MSM (pink dots and lines), FSW (red dots and lines), and their clients (blue dots and lines). Dots represent median point-estimates across model predictions, whereas lines represent 95%UI (2.5th and 97.5th percentile of the estimates).

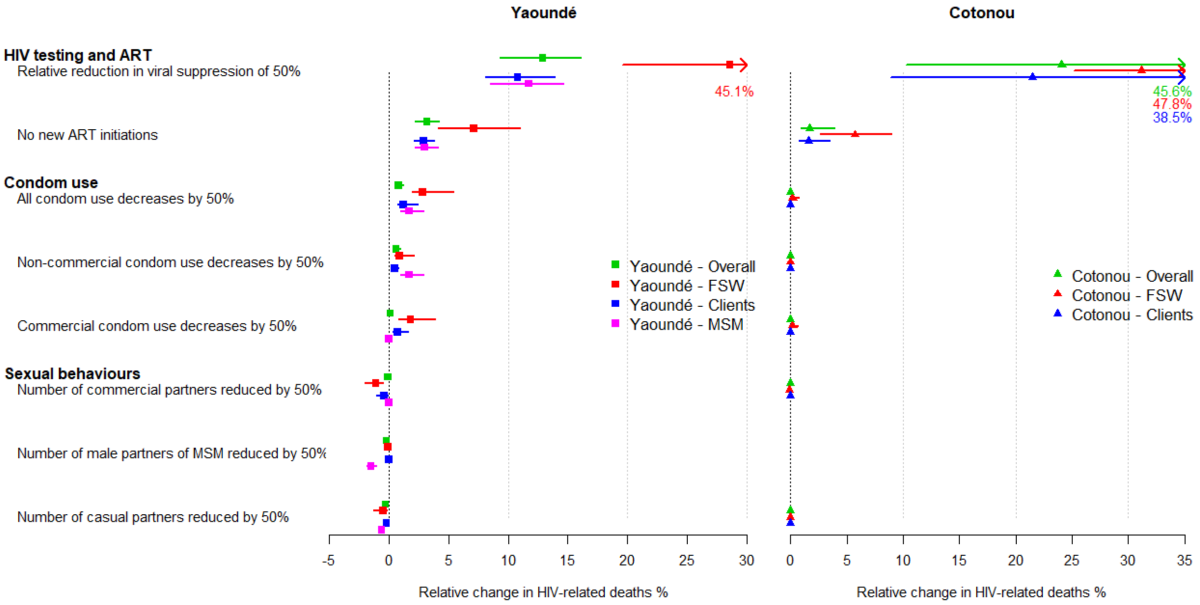


Figure S21: Relative change in cumulative number of HIV-related deaths in Yaoundé (squares) and Cotonou (triangles) over 1 year under individual scenarios assuming 6-months disruptions, calculated overall (green dots and lines), among MSM (pink dots and lines), FSW (red dots and lines), and their clients (blue dots and lines). Dots represent median point-estimates across model predictions, whereas lines represent 95%UI (2.5th and 97.5th percentile of the estimates).

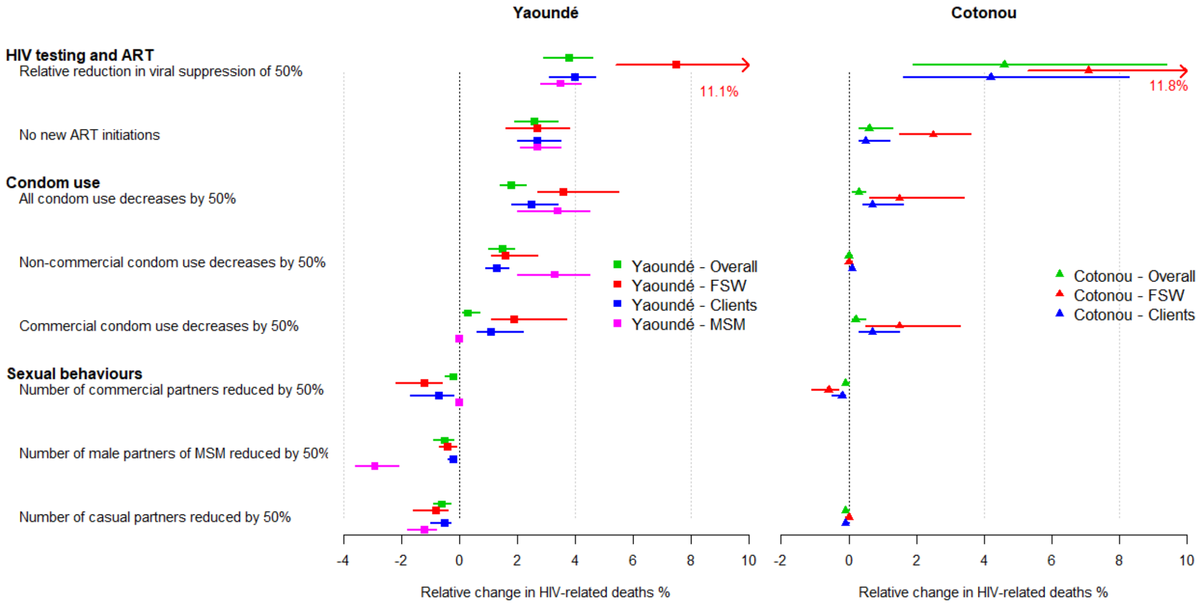


Figure S22: Relative change in cumulative number of HIV-related deaths in Yaoundé (squares) and Cotonou (triangles) over 5 years under individual scenarios assuming 6-months disruptions, calculated overall (green dots and lines), among MSM (pink dots and lines), FSW (red dots and lines), and their clients (blue dots and lines). Dots represent median point-estimates across model predictions, whereas lines represent 95%UI (2.5th and 97.5th percentile of the estimates).

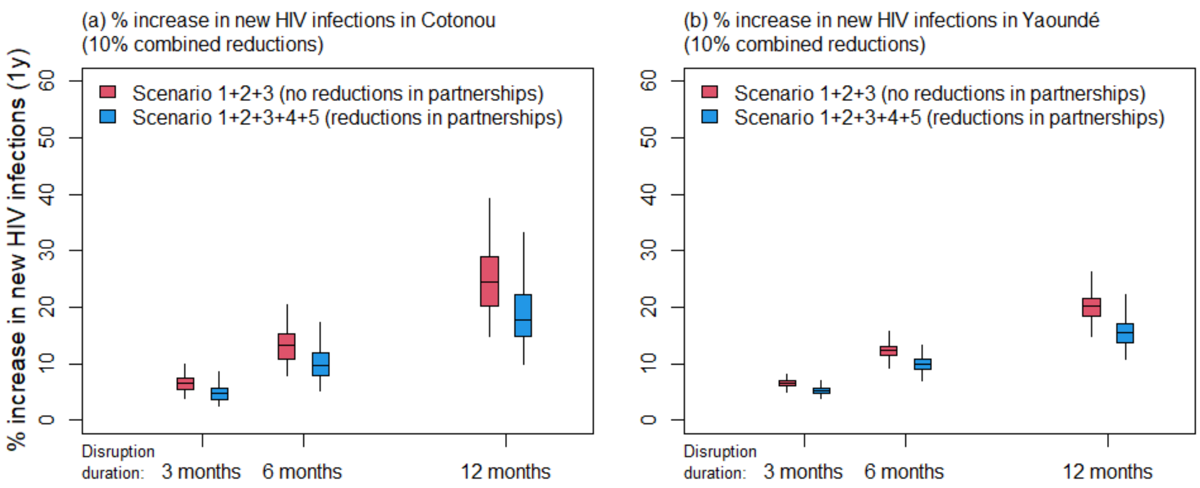
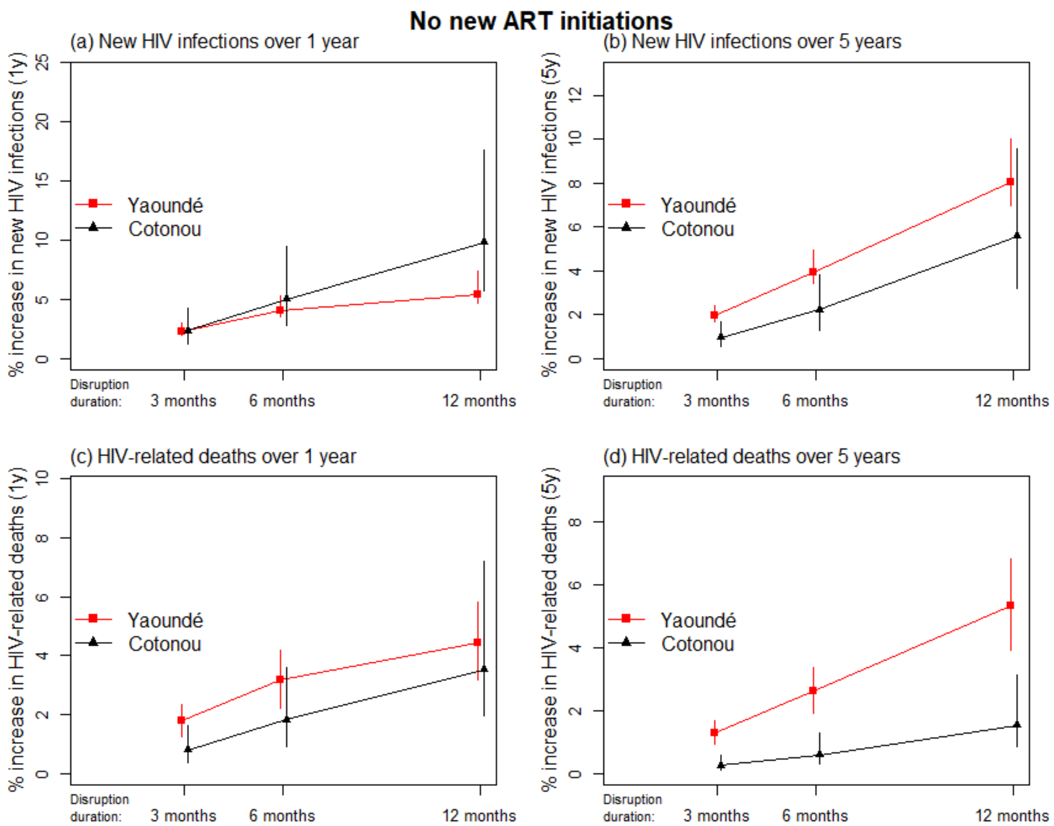
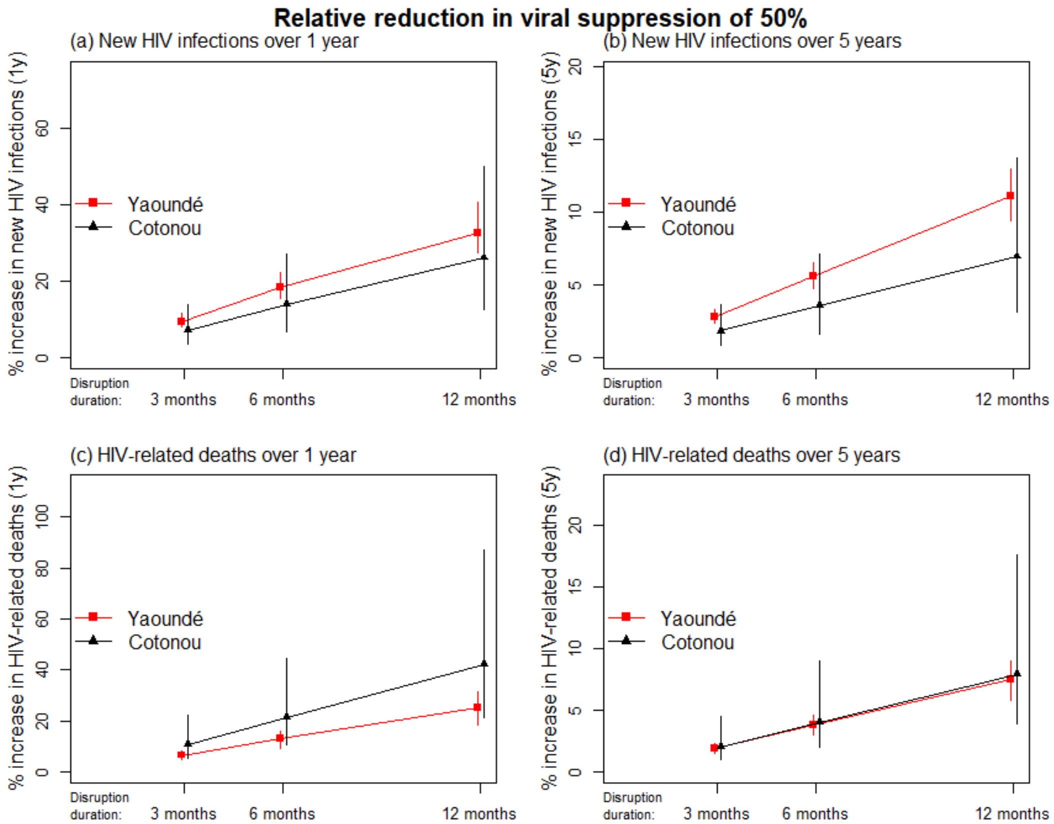
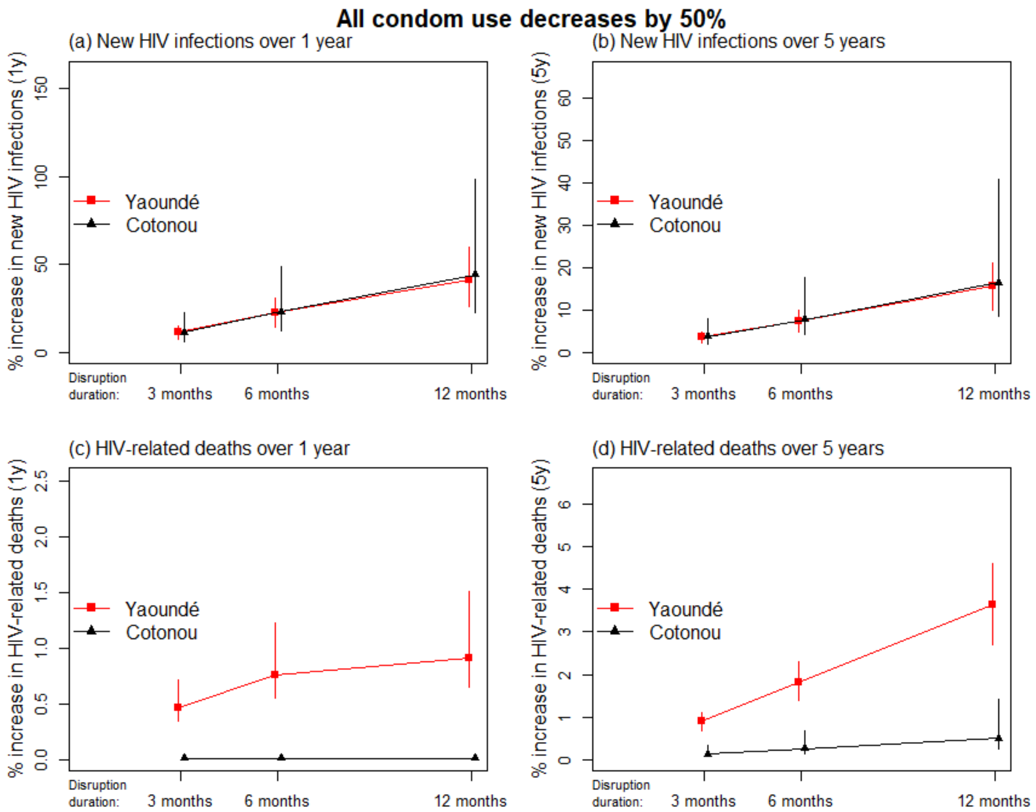


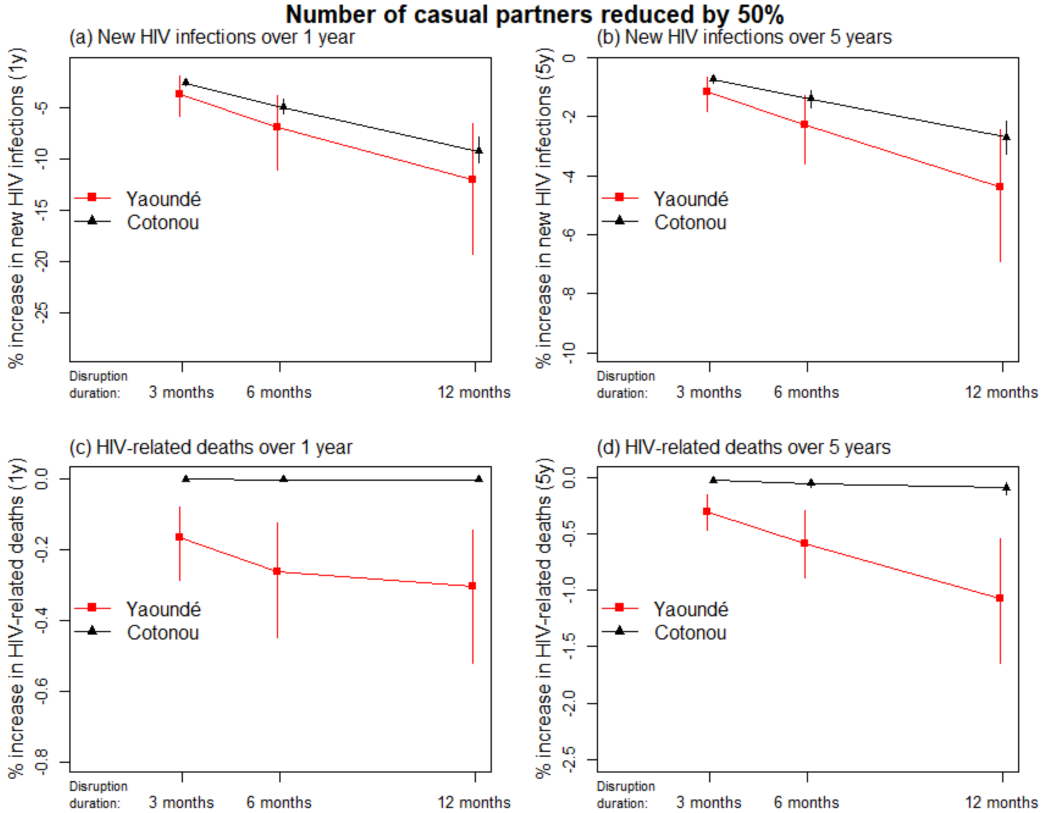
Figure S23: Relative change in cumulative number of new HIV infections in a) Cotonou, and, b) Yaoundé over 1 year under combined scenarios assuming no ART initiations, 10% reduction in viral load suppression and condom use (red boxes), as well as 10% reduction in numbers of casual and commercial partnerships (dark blue boxes) over 3/6/12 months.



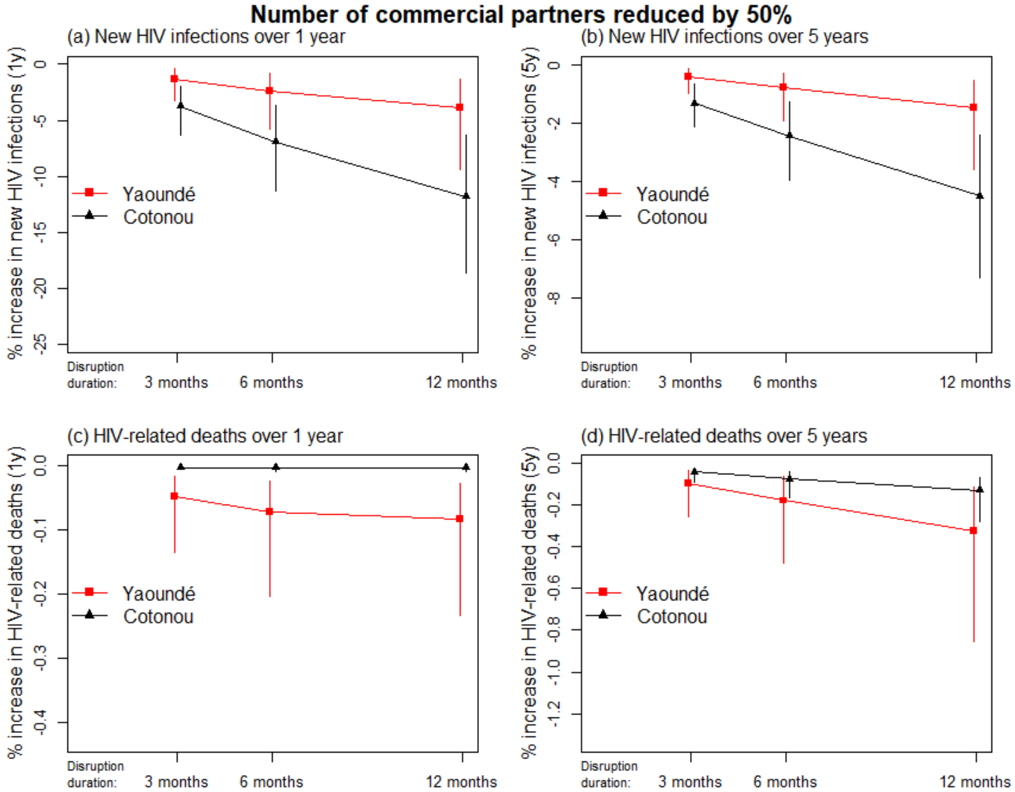

Relative reduction in viral suppression of 50%
(a) New HIV infections over 1 year
% increase in new HIV infections (1y)
0
20
40
60
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(b) New HIV infections over 5 years
% increase in new HIV infections (5y)
0
5
10
15
20
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(c) HIV-related deaths over 1 year
% increase in HIV-related deaths (1y)
0
20
40
60
80
100
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(d) HIV-related deaths over 5 years
% increase in HIV-related deaths (5y)
0
5
10
15
20
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months


All condom use decreases by 50%
(a) New HIV infections over 1 year
% increase in new HIV infections (1y)
0
50
100
150
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(b) New HIV infections over 5 years
% increase in new HIV infections (5y)
0
10
20
30
40
50
60
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(c) HIV-related deaths over 1 year
% increase in HIV-related deaths (1y)
0.0
0.5
1.0
1.5
2.0
2.5
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months
(d) HIV-related deaths over 5 years
% increase in HIV-related deaths (5y)
0
1
2
3
4
5
6
Yaoundé
Cotonou
Disruption duration:
3 months
6 months
12 months

Number of casual partners reduced by 50%



Number of commercial partners reduced by 50%



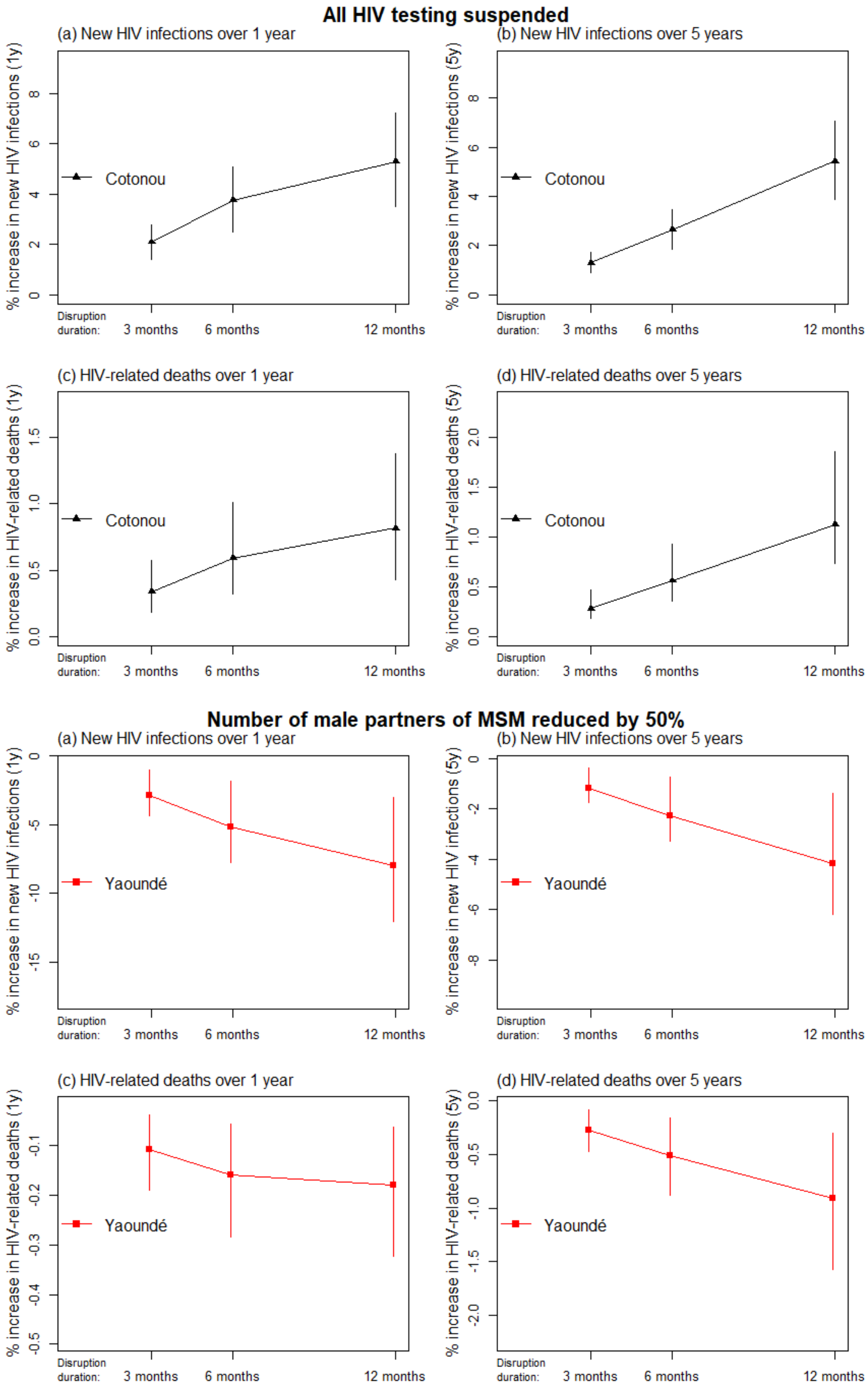


Figure S24: Relative change in cumulative overall number of new HIV infections calculated over a) 1 year, b) 5 years, and HIV-related deaths over c) 1 year, and d) 5 years under individual scenarios assuming 6-months disruptions, compared to base-case in Yaoundé (red squares) and Cotonou (dark triangles). Error bars represent 95%UI across model predictions.

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