Quantifying the evolving contribution of HIV interventions and key populations to the HIV epidemic in Yaoundé, Cameroon. Supplementary material.

Model overview (adapted from the supplementary material for Mukandavire et al. JIAS 2018 [1])

We adapted[1] 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 $i = 1,2 \ldots 6$. 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,[2] 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.

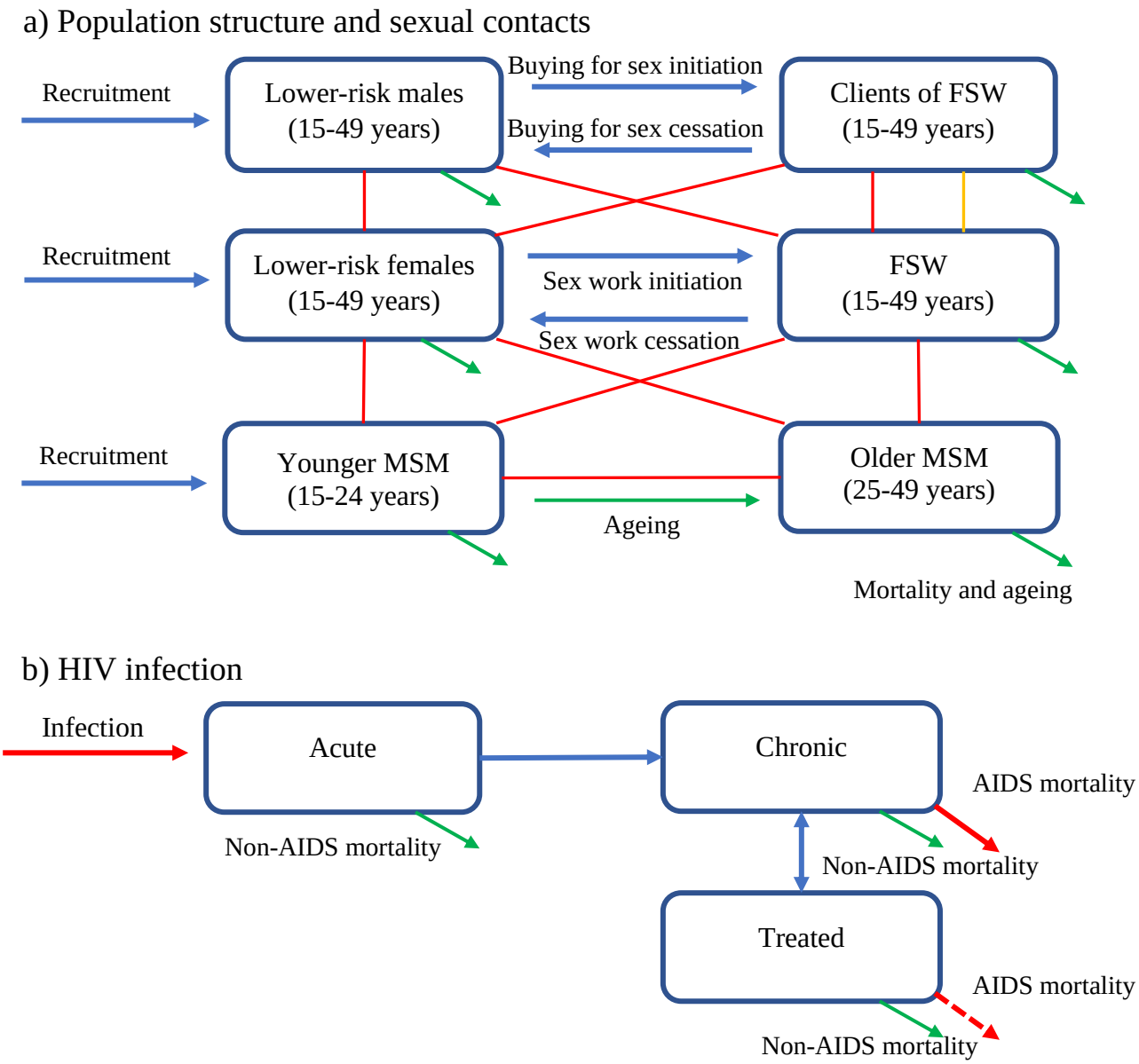


Figure S1. a) Modelled population structure, population flows (blue arrows), mortality and ageing (green arrows) and sexual partnerships (main/casual: red lines, commercial: orange lines) between the different risk groups. b) Natural history of HIV infection. The model assumes that a proportion α_t of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

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 (v), or if on HIV treatment but not virally suppressed $(1-\alpha_j)T_j$, such that $B_j = (vE_j + I_j + (1-\alpha_j)T_j)/N_j$, 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:

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

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

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

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

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

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 $\rho_{5*}^k$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

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

Model parameterisation and fitting

The model was coded in C programming language, numerically solved using a Runge-Kutta four method,[3] and fitted using the importance resampling method[4,5] 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).

Model parameters (Tables S1, S2)

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

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)).[6-8] 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,[9-12] whereas only one recent (2017) estimate was available for clients[13] 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[14,15].

Sexual behaviours

Several Demographic Health Surveys (DHS) (1997, 2004, 2011, 2018)[16-20] and the 4-city household based study[21-23] 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.[16,17,23,24] The annual number of sex acts of the lower-risk groups $\Psi_{i=1-2}$ was taken from the 4-cities study weekly estimates[25], 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[18]. Clients of FSW in the 2017 "Modes of transmission" study[13] 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,[9] except for commercial partners, where a wider range was selected from all available estimates for Yaoundé.[9,21,26-28] 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.[9] 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)[21] and the sex acts between MSM and their main or casual female partners (in the 2016 IBBS).[9] 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).[29]

Interventions: Male circumcision

Over 90% of males are circumcised in Cameroon[16,17,24] (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.[30]

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[31] (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.[9] 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%,[32-34] 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.[35] 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.[36] 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,[2] 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.[37] Viral suppression was assumed to fully prevent HIV transmission to partners.[38] 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).[39-41] We assumed a relatively high drop-out rate σ of 10% given these relatively low retention estimates of the first year of initiation.

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,[9] 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 [6,9,28] (Figure S2b). The fraction of male clients among all males was defined based on several studies conducted in Yaoundé which reported heterogeneous estimates [16-18,21,24] (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,[16,17,42,43] and cross-validated with the household surveys Cameroon Population-based HIV Impact Assessment (CAMPHIA) [2] and DHS[20] 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 [9,10,21,26,42,44-46] (Figure 1d). The model was also fitted to a recent estimate of the HIV prevalence among male clients of FSW conducted in Yaoundé,[13] 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[9,47,48] (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[49] (Figure S3). Finally, the coverage of viral suppression among all females and all males living with HIV was compared to recent national CAMPHIA estimates,[2] whereas the coverage among each key population was compared to recent local estimates in 2016 for MSM and FSW,[9] and 2017 for clients of FSW[13] (Figure S4).

Epidemic dynamics

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).

Uncertainty analyses

We used Spearman's rank correlation to assess the influence of uncertainty in key model parameters or outcomes on the $PAFs_{2009\text{-}2018}$ estimates. This informed key data gaps driving the uncertainty in our estimates.

Estimates of the $PAF_{2009\text{-}2018}$ of KP were most sensitive to uncertainties in the population size of MSM, FSW, and of clients, followed by number of commercial and non-commercial sex acts of clients, as well as the HIV prevalence in the client group (Figures S9-S10). For example, the $PAF_{2009\text{-}2018}$ of MSM with all partnerships ranged from 20% if MSM represents less than 1% of the male population and almost 50% if the size of MSM group was doubled. Other key sources of uncertainty across PAFs of KP were the, which are not known precisely (Figure S10).

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 [7] (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 [8] 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 [9-12] Clients: interquartile range of the time since first commercial sex in the 2017 MOT survey [13]
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 [14,15].
Sexual activity of lower risk groups				
Annual number of new main partnerships	n_{1-2}^m	0.4-0.7	0.3-0.5	Calculated from reported lifetime number of partners in the DHS and 4 cities study [16,17,23,24]

Total annual number of sex acts	Ψ_{1-2}	52-104	52-104	Based on 4-cities study weekly estimates [25]. 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[18]
Annual number of new casual partnerships	n_{1-2}^{c}	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[18]
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 [13] and DHS and 4-cities study estimates for lower-risk populations
Sexual activity of FSW				
Annual number of new main partnerships	n_4^m	--	0.6 - 0.7	2016 IBBS in Yaoundé [9]
Annual number of sex acts with main partners	${\Psi_4}^{m}$	--	135 – 192	2016 IBBS in Yaoundé [9]
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 [9], 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[9].
Annual number of sex acts with casual partners	$\Psi_4{}^c$	--	83 – 125	2016 IBBS in Yaoundé[9]
Annual number of clients of FSW[b]	$n_4{}^{co}$	NA	104-1200	Wide range based on multiple surveys in Yaoundé[9,21,26-28]. 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 [9]
Total annual number of sex acts with main partner	$\Psi_{5*}{}^m$, $\Psi_5{}^m$	101-135	78-104	2016 IBBS [9]
Annual number of new casual partnerships	n_{5*}^c , n_5^c	11-18	4-6	2016 IBBS [9]
Total annual number of sex acts with casual partner	$\Psi_{5*}{}^c$, $\Psi_5{}^c$	57-114	23-47	2016 IBBS [9]
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 [9]: 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%		[21]
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)[29]
Fraction of sex acts between MSM and their main female partners that are anal†		--	15-18%	2016 IBBS [9], 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 [9], 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 [50], 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 [50] 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[51]
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	[50]
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% --	[16,17,24]
Per-partner efficacy of male circumcision in reducing HIV acquisition risk among males	ϑ	38-66% --	[30]
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%	[32-34]
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)[2]
Efficacy of viral suppression in reducing HIV transmissibility per sex act†		100%	[38]

Relative risk of HIV-related mortality when virally suppressed compared to not virally suppressed	φ	0.16-0.42	From [37] (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 [39-41].

[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)[21], and was selected as a lower bound.

Table S2: 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[19], reported as "current use" of condoms as mean of contraception.
1998	6.8% (4.7-9.8)	5-11%	DHS[18], reported by females
1998	7.6% (5.0-11.0)	5-11%	DHS[18], reported by males
2011	19% (18-20)	19-37%	DHS[16], reported by females
2011	37% (36-38)	19-37%	DHS[16], reported by males
Between lower-risk individuals in a casual partnership			
1990	1%	1-5%	DHS[19], reported as "current use" of condoms as mean of contraception.
1998	2.2% (1.0-4.7)	1-30%	DHS[18], reported by females
1998	7.6% (3.8-14.8)	1-30%	DHS[18], reported by males
1998	26%	1-30%	4-cities study [22,57], reported by females
1998	18%	1-30%	4-cities study [22,57], reported males
2004	54.7% (51-58)	51-74%	DHS[17,58], reported by females
2004	69.6% (65-74)	51-74%	DHS[17,58], reported by males
2018	50.3% (38.6-61.9)	39-77%	DHS[20], reported by females
2018	72.3% (66.4-77.4)	39-77%	DHS[20], reported by males
Between FSW and their main partners			
1996	22% (20-24)	15-28%	From[11]. Expanded uncertainty around estimate for sex with non-clients.
2013	24.5% (21-28)	21-28%	Interpreted from[28,59] (reported as levels of consistent condom use)
2016	45% (40-50)	40-50%	From[9]
Between FSW and their casual partners			
1996	22% (20-24)	15-28%	From[11]. Expanded uncertainty around estimate for sex with non-clients.
2016	91% (86-94)	86-94%	From[9]
Between FSW and their clients			
1990	7% (4-12)	Used for cross-validation	From[12]. 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[44]
1997	49% (46-52)	20-55%	From[60]
1998	28% (23-33)		4-cities study[21]
2004	88% (75-95)	Used for cross-validation	Reported by male clients[17]
2011	58% (45-71)		Reported by male clients[16]
2009	83% (75-89)	75-89%	From[10,26]
2013	84-92%	Used as cross-validation	Interpreted from[28,59] (reported as levels of consistent condom use)
2016	93% (90-95)	90-98%	From[9], for regular clients
2016	97% (95-98)		From[9], for casual clients
Between MSM and their male partners			
2011	33% (28-37)	28-37%	From[15]
2013	70-77%	Used as cross-validation	Interpreted from [28,59]
2016	73% (68-77)	68-78% (main)	From[9], for main male partners
2016	85% (81-88)	81-88% (casual)	From[9], for casual male partners
Between MSM and their female partners			
2011	50% (43-57)	43-57%	From[15]
2013	43-49%	Used as cross-validation	Interpreted from[28,59] (reported as levels of consistent condom use)
2016	71% (65-76)	65-76% (main)	From[9], for main male partners
2016	84% (78-88)	78-88% (casual)	From[9], for casual male partners

Table S3: 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	[9]
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[6,9,28]
Fraction of male clients among all males				
1985[a] and 2016	NA	N.A.	2-20%	[c]Adapted from several studies conducted in Yaoundé[16-18,21,24]
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[9,28]
HIV prevalence among all females				
1997	8.4% (n=942)	6.8-10.3%	4.4-13.2%	[24] (4-cities study)
2004	10.7% (n=538)	8.4-13.6%	5.0-25.5%	[17] (DHS) table 16.4
2011	8.8% (n=847)	7.1-10.9%	4.6-14.1%	[16] (DHS) table 15.4
HIV prevalence among all males				
1997	4.4% (n=811)	3.2-6.0%	1.4-8.4%	[42,43] (4 cities study)
2004	6.0% (n=550)	4.3-8.3%	1.8-11.8%	[17] (DHS) table 16.4
2011	3.6% (n=778)	2.5-5.2%	0.9-7.6%	[16] (DHS) table 15.4
HIV prevalence among female sex workers				
1991	26.6% (n=262)	21-32%	12.6-40.1%	[44]
1998	34.0% (n=320)	29.2-39.9%	22-48.8%	[21] (4-cities study)
2004	25.7% (n=325)	21.2-30.7%	14.5-38.2%	[46] (Grand South region)
2009	33.3% (n=114)	25.3-42.4%	13-55.5%	[26]
2016	21.1% (n=574)	18-24.6%	13.4-28.9%	[9]
HIV prevalence among clients of sex workers				
2017	3.0% (n=596)	1.9-4.7%	0.3-7.3%	[13]
HIV prevalence among 15-24 years old MSM				
2011	36.5% (n=104)	27.9-46.1%	14.5-50.5%	[47,48]
2016	39.2% (n=186)	32.5-46.4%	21.5-49.5%	[9]
HIV prevalence among 25-49 years old MSM				
2011	58.8% (n=102)	49.1-67.9%	34.0-72.5%	[47,48]
2016	54.1% (n=120)	45.2-62.8%	31.5-67.5%	[9]

ART coverage among all females living with HIV[e]				
2012	26.0% (n=50)	NA	16-40%	UNAIDS national estimates [49]
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 [49]
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%	[2]
Viral suppression coverage among all males living with HIV				
2017	38%[f]	29-48%	15.5-63%	[2]
Viral suppression coverage among clients of FSW living with HIV				
2017	35% (n=17)	17-58%	0-93%	[13]
Viral suppression coverage among FSW living with HIV				
2016	69% (n=133)	61-76%	49-86.5%	[9]
Viral suppression coverage among MSM living with HIV				
2016	33% (n=138)	26-41%	15.5-53%	[9]

[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 [9]: 1.27% (0.99 - 1.65), 2013 R2P [28]: 1.88% (1.15-2.61), 2015. WorldBank [6]: 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 [18].

[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[9]: 0.71% (0.59 - 0.86), 2013 R2P[28]: 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

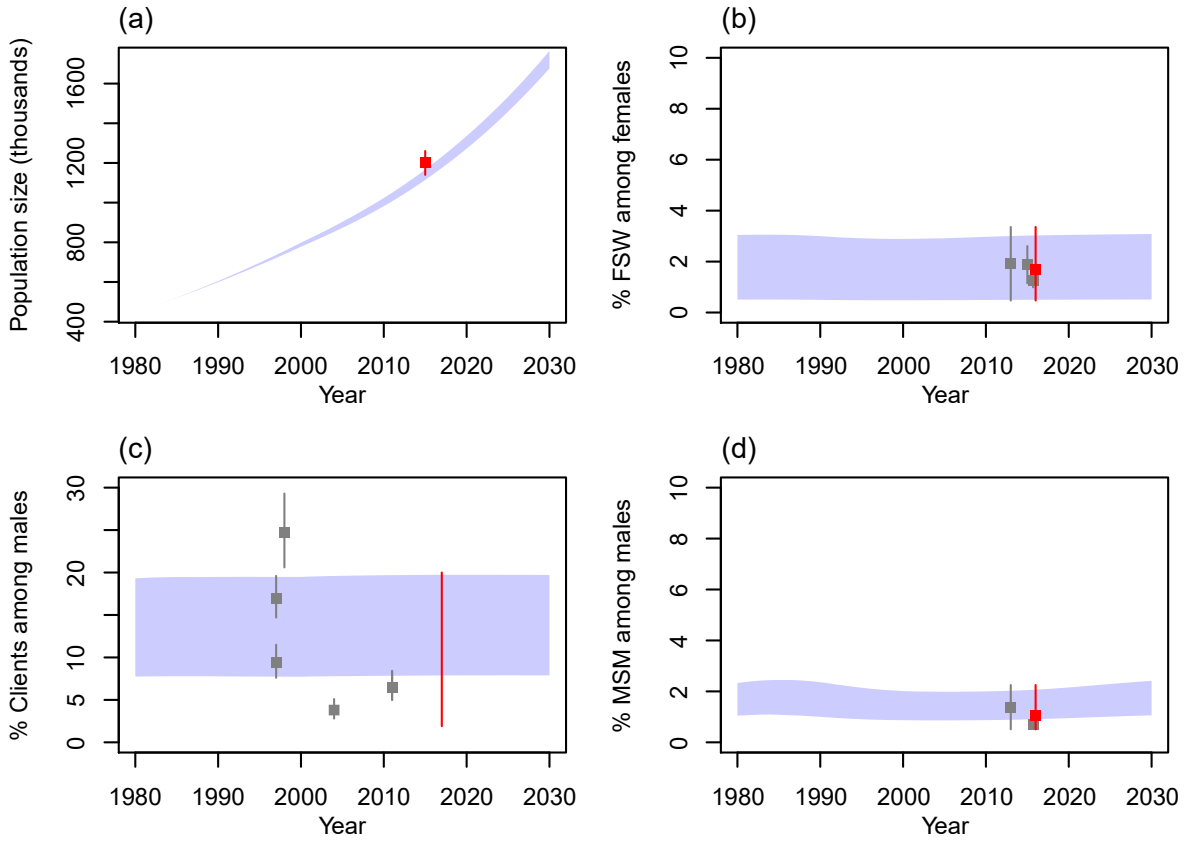


Figure S2. Model fits to sociodemographic outcomes in Yaoundé, Cameroon: a) total 15-49 year-old population size, fractions of b) FSWs among all females, c) Clients among all males, d) MSM among all males. Blue shades represent model outcomes 95%UI. Red dots and intervals are outcomes used for fitting 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.

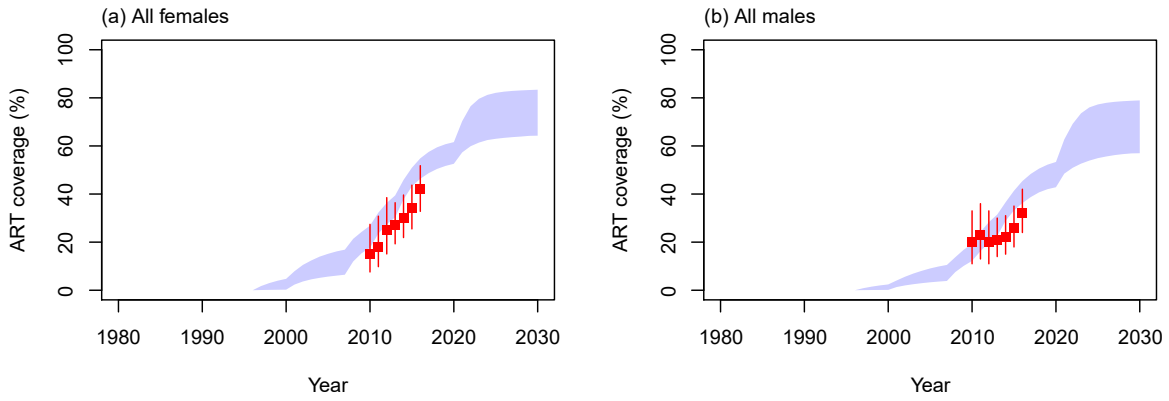


Figure S3. Empirical (UNAIDS national estimates for Cameroon) and posterior simulated ART coverage among all HIV+ a) females and b) males over time. Blue shades represent model outcomes 95%UI, while red dots and intervals represent UNAIDS estimates.

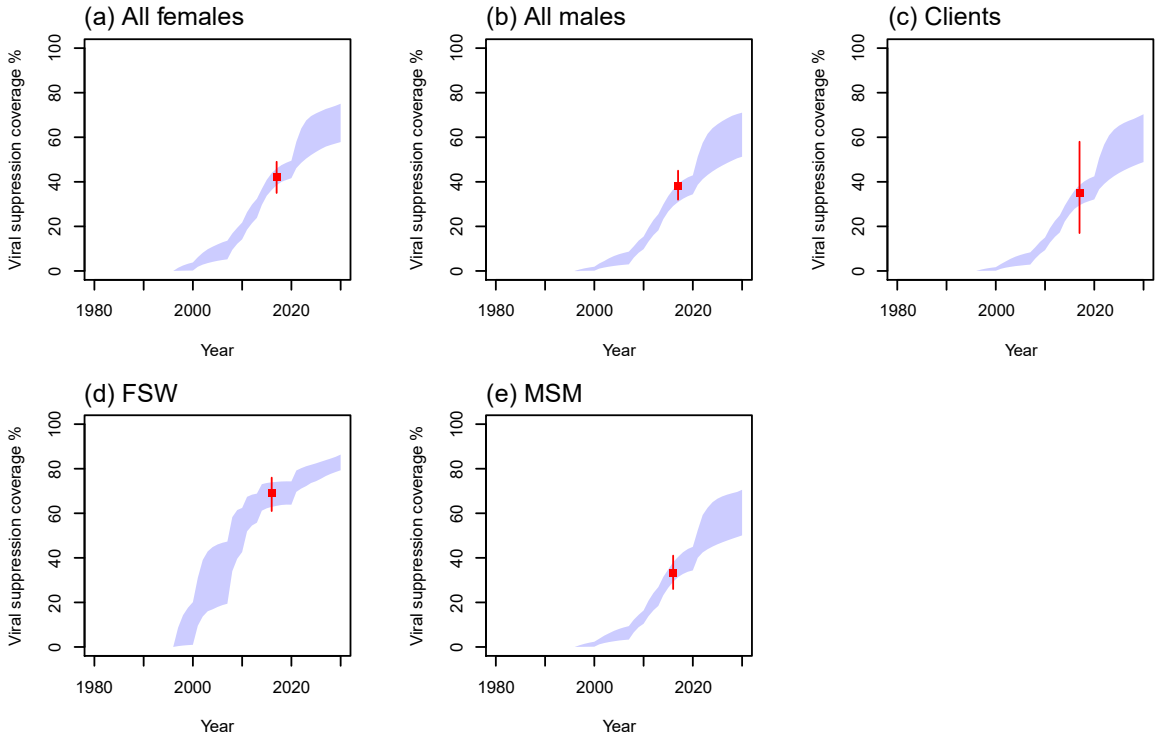


Figure S4. Empirical and simulated levels of viral suppression coverages among a) all females, b) all males, c) FSW, d) clients of FSW, e) all MSM, living with HIV in Yaoundé, Cameroon. Blue shades represent model outcomes 95%UI, while red dots and intervals represent empirical estimates from CAMPHIA for all females and males[2], MOT survey among clients[13], IBBS 2016 among FSW and MSM[9].

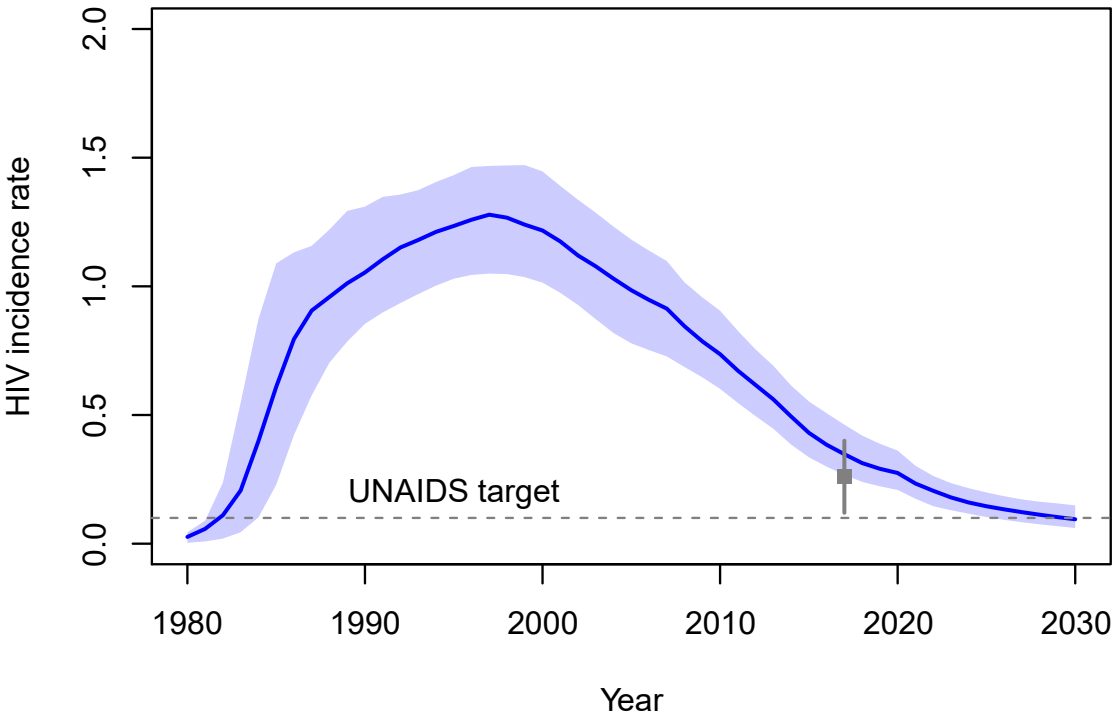


Figure S5: Model estimates of overall HIV incidence rate (indicator 2, calculated per 100 susceptible person-year) in Yaoundé. Lines and shades represent median and 95%UI, respectively. Grey square and interval represent the national estimate and 95%CI from the CAMPHIA study[2]. Dashed line represent the UNAIDS target of 0.1 new infection per 100 person-years [61].

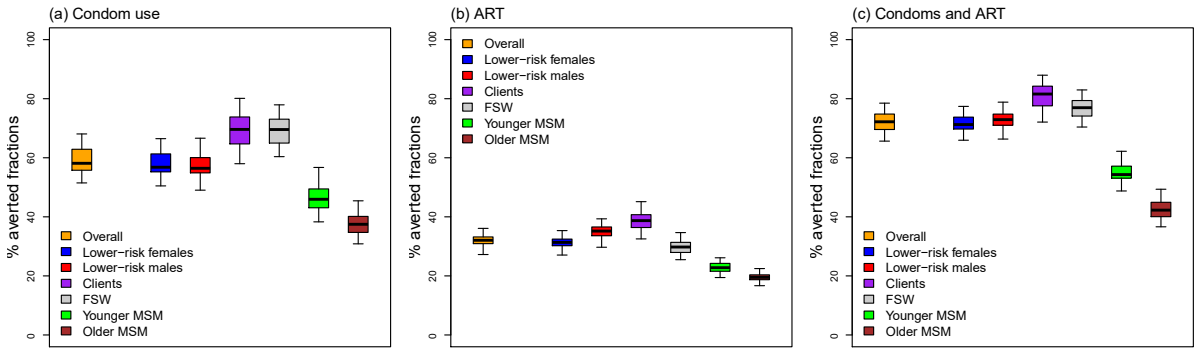


Figure S6. Estimated proportions of infections averted over 2009-2018 by the overall use of a) condoms, b) ART, c) both condoms and ART, overall and across the different modelled population groups in Yaoundé, Cameroon.

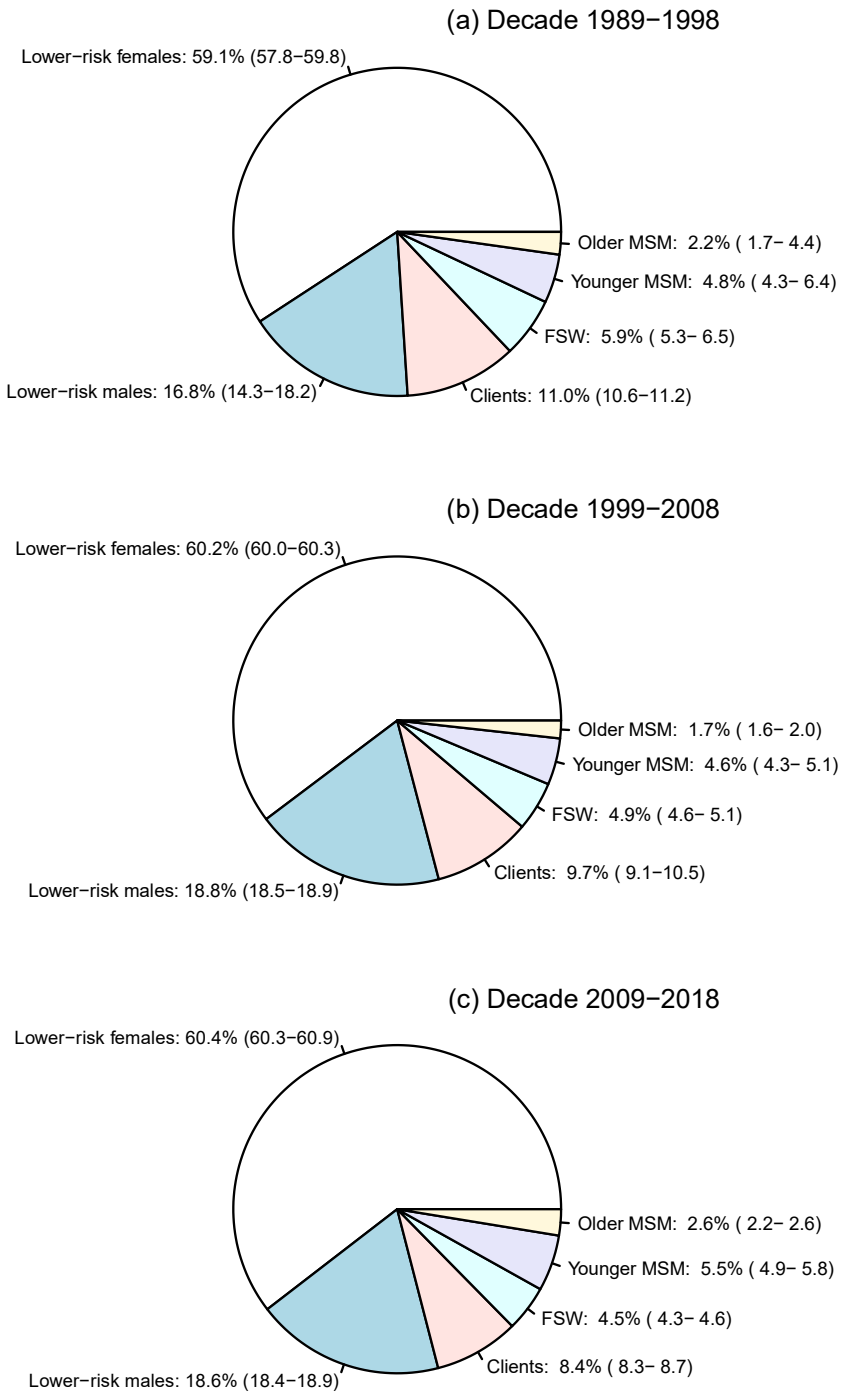


Figure S7: Median (with 95%UI) model estimates of the fraction of all incident HIV infections estimated to have occurred among the different modelled population groups in Yaoundé over the decades a) 1989-1998, b) 1999-2008, c) 2009-2018 (indicator 1).

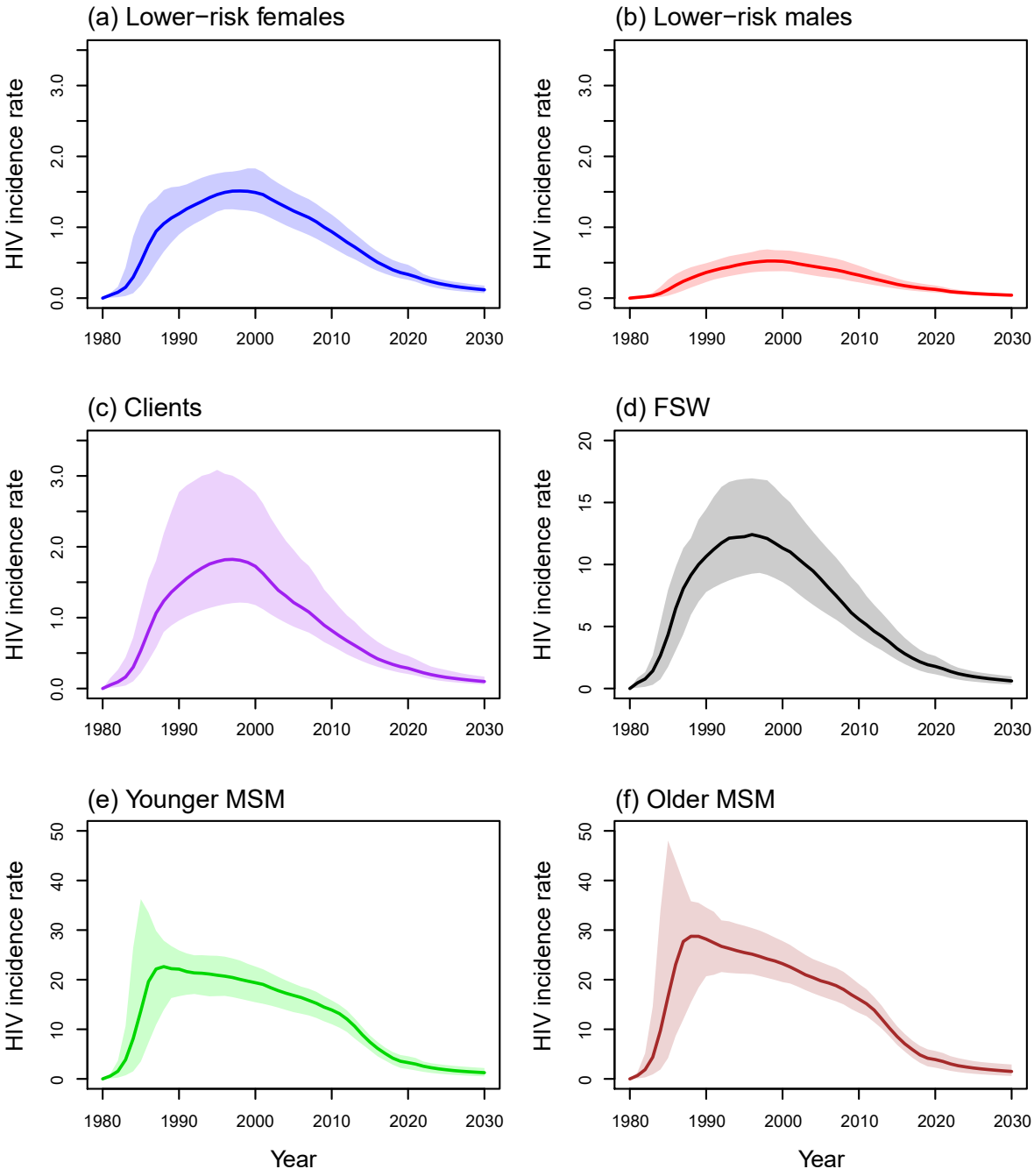


Figure S8: Model estimates of HIV incidence rate per 100 susceptible person-years estimated to have occurred among a) 15-49 years old lower-risk females, b) 15-49 years old lower risk males, c) 15-49 years old clients, d) 15-49 years old FSW, e) 15-24 years old and f) 25-49 years old MSM in Yaoundé over time. Lines represent median estimates, whereas shades represent 95%UI.

Table S4: Model estimates of HIV incidence rates per 100 susceptible person-year to all risk groups, calculated over successive decades in Yaoundé, Cameroon (median and 95%UI of indicator 2).

	1989-1998	1999-2008	2009-2018	2019-2028
Overall	1.20 (1.01-1.40)	1.03 (0.85-1.23)	0.50 (0.40-0.63)	0.17 (0.12-0.22)
All lower-risk	1.01 (0.82-1.20)	0.88 (0.67-1.08)	0.44 (0.32-0.56)	0.15 (0.10-0.19)
All key-populations	3.34 (2.34-6.00)	2.52 (1.86-4.25)	1.20 (0.86-1.99)	0.42 (0.27-0.69)
All females	1.55 (1.31-1.89)	1.39 (1.12-1.64)	0.67 (0.51-0.84)	0.23 (0.16-0.29)
All males	0.82 (0.67-0.99)	0.68 (0.55-0.86)	0.34 (0.27-0.42)	0.12 (0.08-0.16)
Lower-risk females	1.46 (1.20-1.76)	1.28 (1.03-1.56)	0.63 (0.48-0.81)	0.21 (0.15-0.28)
Lower-risk males	0.47 (0.34-0.63)	0.45 (0.32-0.61)	0.21 (0.15-0.31)	0.074 (0.045-0.11)
Clients	1.76 (1.16-2.99)	1.30 (0.93-2.06)	0.54 (0.38-0.83)	0.18 (0.12-0.28)
FSW	11.95 (8.83-16.37)	9.40 (6.70-12.53)	3.59 (2.58-5.25)	1.12 (0.65-1.55)
Younger MSM	21.15 (16.63-25.29)	17.48 (13.98-20.03)	8.35 (6.56-9.80)	2.11 (1.09-3.05)
Older MSM	24.73 (19.58-29.62)	20.80 (17.65-24.79)	9.46 (7.76-11.79)	2.50 (1.24-4.11)
FSW and clients	2.51 (1.54-4.70)	1.84 (1.21-3.23)	0.72 (0.53-1.32)	0.25 (0.16-0.47)
All MSM	22.33 (18.58-25.57)	18.34 (15.79-20.50)	8.59 (7.04-9.90)	2.30 (1.15-3.47)

Table S5: Distribution of PLHIV in each modelled risk group, calculated over successive decades and over the epidemic course (2009-2018), and distribution of the overall population in each modelled risk group (median and 95%UI).

	Proportion among PLHIV				Proportion among the overall population
Risk group	1989-1998	1999-2008	2009-2018	2019-2028	2009-2018
All lower-risk	76.5% (67.8-83.3)	81.8% (74.9-86.9)	83.1% (77.1-87.7)	83.8% (77.9-88.3)	90.7% (88.4-94.5)
All key-populations	23.5% (16.7-32.2)	18.2% (13.1-25.1)	16.9% (12.3-22.9)	16.2% (11.7-22.1)	9.5% (5.6-11.8)
Total	100%	100%	100%	100%	100%
All females	64.3% (59.2-68.4)	65.1% (60.7-68.6)	65.5% (61.4-69.1)	66.0% (61.8-69.7)	50.1% (49.9-50.3)
All males	35.7% (31.6-40.8)	34.9% (31.4-39.3)	34.5% (30.9-38.6)	34.0% (30.3-38.2)	49.9% (49.7-50.1)
Total	100%	100%	100%	100%	100%
Lower-risk females	59.8% (52.4-65.5)	62.0% (56.2-66.3)	62.8% (57.5-66.4)	63.7% (58.5-67.1)	49.3% (48.5-49.8)
Lower-risk males	16.5% (13.3-21.5)	19.8% (16.4-24.7)	20.3% (16.5-25.0)	20.1% (16.5-24.6)	41.2% (39.3-45.1)
Clients	8.6% (4.9-13.6)	8.3% (4.6-12.1)	7.4% (4.1-10.7)	6.8% (3.9-10.1)	8.0% (3.9- 9.8)
FSW	4.2% (1.4-9.1)	3.4% (1.1-7.0)	3.0% (1.0-6.2)	2.7% (0.9-5.4)	0.7% (0.3-1.5)
Younger MSM	4.7% (2.7-5.6)	3.0% (1.6-3.8)	2.8% (1.5-3.8)	2.2% (1.2-3.3)	0.5% (0.3-0.6)
Older MSM	6.3% (3.6-7.7)	3.8% (2.2-5.0)	4.1% (2.2-5.5)	4.9% (2.5-6.7)	0.4% (0.2-0.5)
Total	100%	100%	100%	100%	100%
FSW and clients	13.0% (8.1-21.8)	11.5% (7.7-18.7)	10.1% (6.9-16.1)	9.4% (6.2-13.9)	8.7% (4.6-10.9)
All MSM	11.0% (6.2-13.2)	6.9% (3.7-8.8)	6.9% (3.7-9.2)	7.2% (3.7-10.0)	0.9% (0.5-1.1)

Table S6: Estimated HIV transmission rates per 100 infected person-years to all partnerships, calculated over successive decades in Yaoundé, Cameroon (median and 95%UI of indicator 4).

	1989-1998	1999-2008	2009-2018	2019-2028
Lower-risk females	17.0 (12.2-23.3)	10.8 (7.6-14.4)	6.4 (4.4-8.7)	4.0 (2.6-5.4)
Lower-risk males	37.0 (23.8-50.3)	23.8 (15.6-31.4)	15.6 (10.0-20.0)	9.7 (6.0-13.4)
Clients	100.6 (68.4-150.1)	60.4 (40.7-90.7)	36.4 (24.3-54.3)	23.4 (14.6-36.0)
FSW	152.1 (89.8-265.1)	74.8 (41.5-123.2)	30.6 (14.5-53.5)	17.1 (6.2-31.6)
Younger MSM	162.3 (121.9-212.6)	104.5 (81.0-134.6)	68.6 (51.8-91.5)	48.4 (26.9-75.2)
Older MSM	158.5 (113.7-231.9)	98.3 (76.0-148.8)	56.5 (44.6-84.7)	30.3 (18.5-51.6)

Table S7: Estimated HIV transmission rates per 100 infected person-years originating from each modelled population group (rows), calculated among each group and all groups combined (columns) over 2009-2018 in Yaoundé, Cameroon (median and 95%UI).

	All groups	Lower-risk females	Lower-risk males	Clients	FSW	Younger MSM	Older MSM
Lower-risk females	6.4 (4.4-8.7)	2.9 (1.7-4.3)	2.4 (1.6-3.2)	1.0 (0.5-1.4)	0.2 (0.08-0.4)	0.03 (0.01-0.05)	0.01 (0.01-0.02)
Lower-risk males	15.6 (10.0-20.0)	12.2 (7.6-15.3)	1.9 (1.0-3.2)	0.8 (0.4-1.2)	0.4 (0.1-0.8)	0.02 (0.01-0.04)	0.01 (0.0-0.02)
Clients	36.4 (24.3-54.3)	26.2 (16.0-37.7	4.8 (2.9-8.2)	2.6 (1.3-4.8)	2.9 (1.2-8.0)	0.07 (0.03-0.1)	0.03 (0.01-0.05)
FSW	30.6 (14.5-53.5)	14.6 (7.0-28.4)	6.7 (4.1-12.0)	7.7 (2.4-14.2)	1.3 (0.4-3.5)	0.1 (0.05-0.5)	0.05 (0.02-0.2)
Younger MSM	68.6 (51.8-91.5)	39.9 (29.0-59.6	6.8 (4.2-10.6)	3.3 (1.5-5.0)	2.1 (0.9-6.1)	9.5 (7.6-10.8)	4.3 (3.7-5.4)
Older MSM	56.5 (44.6-84.7)	33.1 (24.0-56.3	5.8 (3.8-9.4)	2.8 (1.3-4.4)	1.9 (0.7-5.3)	8.5 (7.5-9.4)	3.3 (2.9-4.1)

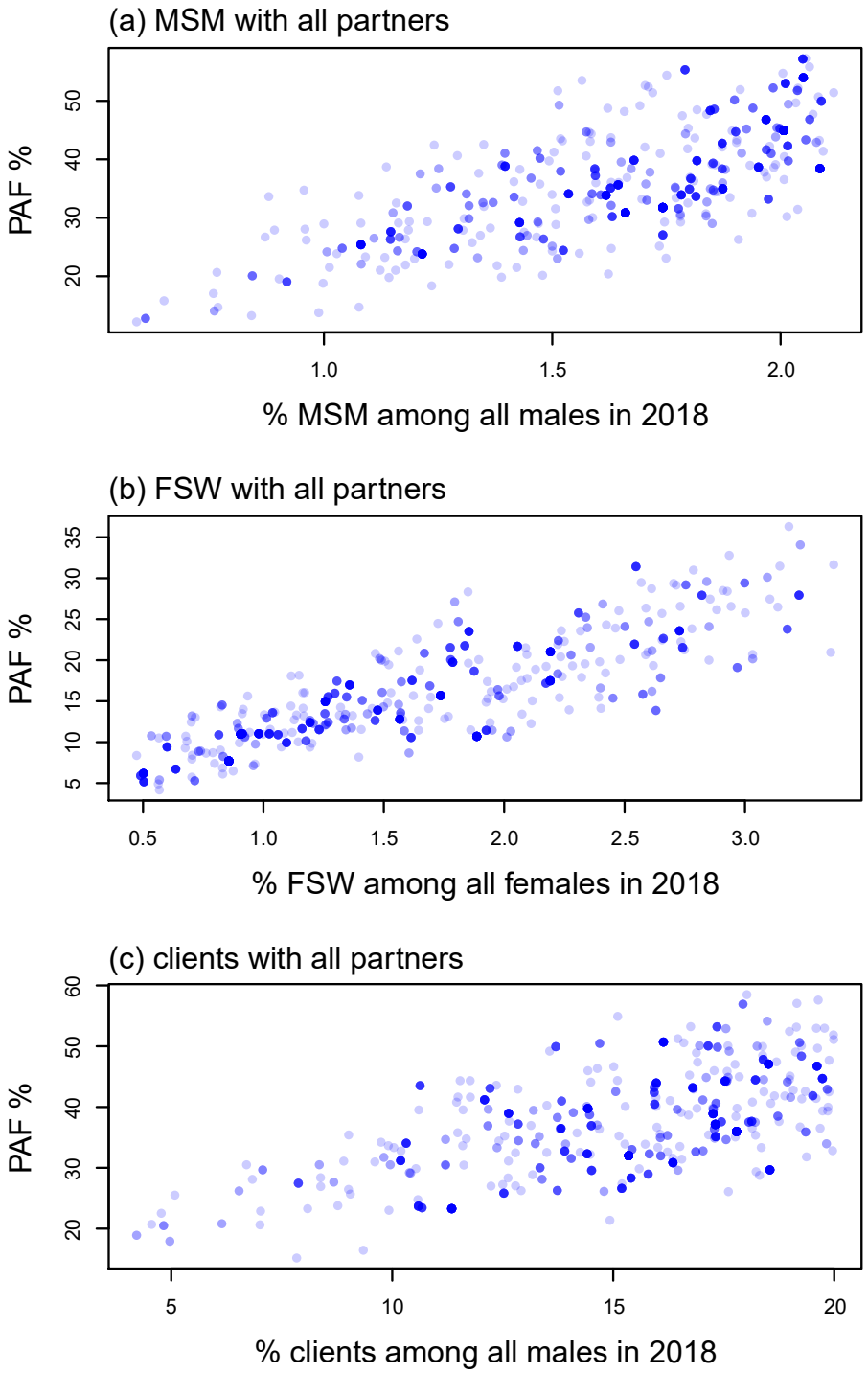
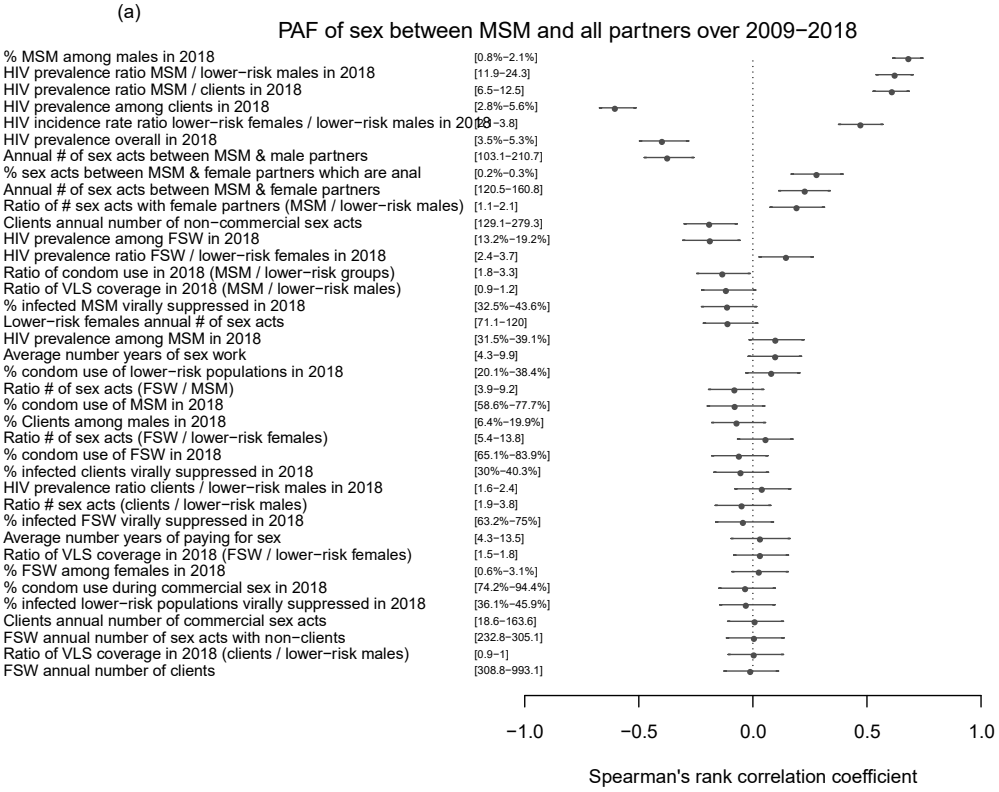
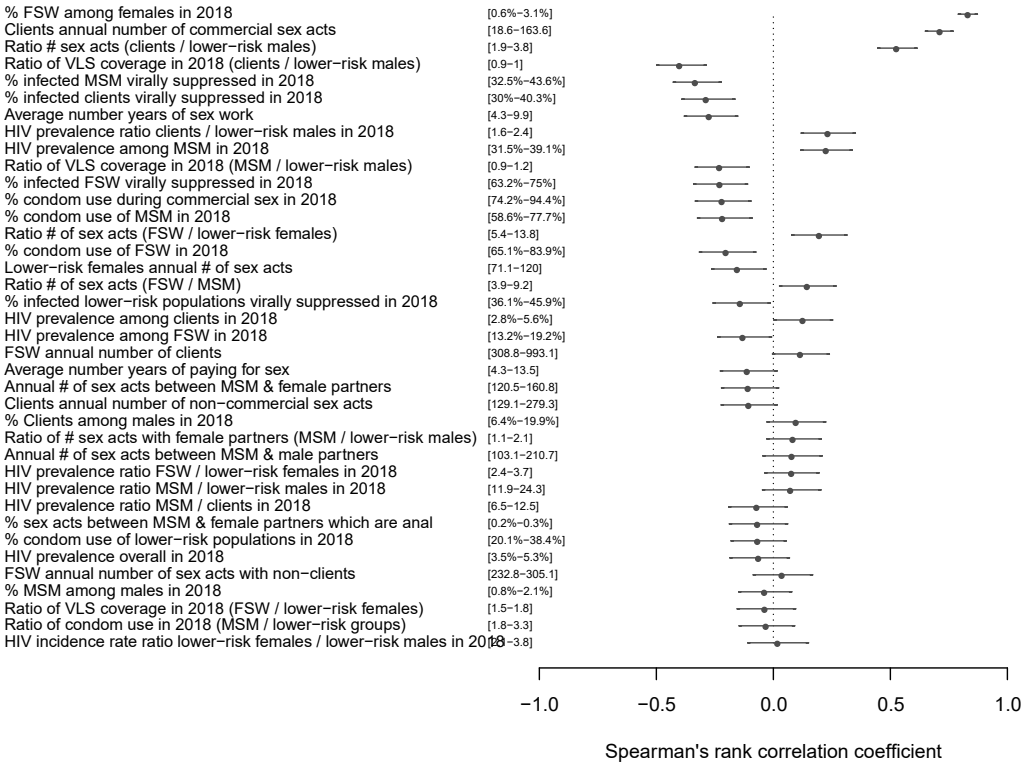


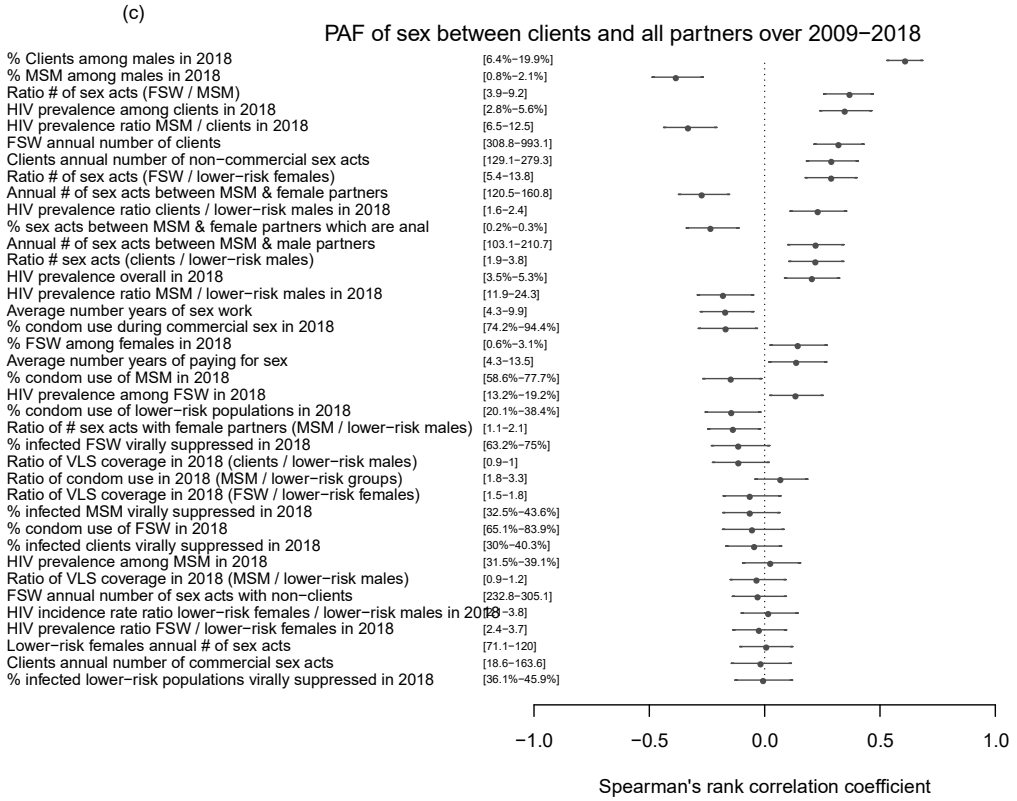
Figure S9: PAF estimates stratified by KP sizes: Relationship between a) MSM group size in 2018 and $PAF_{2009\text{-}2018}$ of MSM with all partners over 2009-2018, b) FSW group size in 2018 and $PAF_{2009\text{-}2018}$ of FSW with all partners, c) client group size in 2018 and $PAF_{2009\text{-}2018}$ of clients with all partners. Darker blue dots correspond to outcomes of simulations which have been resampled multiple times during the fitting process.

(a)


PAF of sex between MSM and all partners over 2009−2018
% MSM among males in 2018 [0.8%−2.1%]
HIV prevalence ratio MSM / lower−risk males in 2018 [11.9−24.3]
HIV prevalence ratio MSM / clients in 2018 [6.5−12.5]
HIV prevalence among clients in 2018 [2.8%−5.6%]
HIV incidence rate ratio lower−risk females / lower−risk males in 2018 [1.8−3.8]
HIV prevalence overall in 2018 [3.5%−5.3%]
Annual # of sex acts between MSM & male partners [103.1−210.7]
% sex acts between MSM & female partners which are anal [0.2%−0.3%]
Annual # of sex acts between MSM & female partners [120.5−160.8]
Ratio of # sex acts with female partners (MSM / lower−risk males) [1.1−2.1]
Clients annual number of non−commercial sex acts [129.1−279.3]
HIV prevalence among FSW in 2018 [13.2%−19.2%]
HIV prevalence ratio FSW / lower−risk females in 2018 [2.4−3.7]
Ratio of condom use in 2018 (MSM / lower−risk groups) [1.8−3.3]
Ratio of VLS coverage in 2018 (MSM / lower−risk males) [0.9−1.2]
% infected MSM virally suppressed in 2018 [32.5%−43.6%]
Lower−risk females annual # of sex acts [71.1−120]
HIV prevalence among MSM in 2018 [31.5%−39.1%]
Average number years of sex work [4.3−9.9]
% condom use of lower−risk populations in 2018 [20.1%−38.4%]
Ratio # of sex acts (FSW / MSM) [3.9−9.2]
% condom use of MSM in 2018 [58.6%−77.7%]
% Clients among males in 2018 [6.4%−19.9%]
Ratio # of sex acts (FSW / lower−risk females) [5.4−13.8]
% condom use of FSW in 2018 [65.1%−83.9%]
% infected clients virally suppressed in 2018 [30%−40.3%]
HIV prevalence ratio clients / lower−risk males in 2018 [1.6−2.4]
Ratio # sex acts (clients / lower−risk males) [1.9−3.8]
% infected FSW virally suppressed in 2018 [63.2%−75%]
Average number years of paying for sex [4.3−13.5]
Ratio of VLS coverage in 2018 (FSW / lower−risk females) [1.5−1.8]
% FSW among females in 2018 [0.6%−3.1%]
% condom use during commercial sex in 2018 [74.2%−94.4%]
% infected lower−risk populations virally suppressed in 2018 [36.1%−45.9%]
Clients annual number of commercial sex acts [18.6−163.6]
FSW annual number of sex acts with non−clients [232.8−305.1]
Ratio of VLS coverage in 2018 (clients / lower−risk males) [0.9−1]
FSW annual number of clients [308.8−993.1]
−1.0
−0.5
0.0
0.5
1.0
Spearman's rank correlation coefficient

(b)


PAF of sex between FSW and all partners over 2009−2018
% FSW among females in 2018 [0.6%−3.1%]
Clients annual number of commercial sex acts [18.6−163.6]
Ratio # sex acts (clients / lower−risk males) [1.9−3.8]
Ratio of VLS coverage in 2018 (clients / lower−risk males) [0.9−1]
% infected MSM virally suppressed in 2018 [32.5%−43.6%]
% infected clients virally suppressed in 2018 [30%−40.3%]
Average number years of sex work [4.3−9.9]
HIV prevalence ratio clients / lower−risk males in 2018 [1.6−2.4]
HIV prevalence among MSM in 2018 [31.5%−39.1%]
Ratio of VLS coverage in 2018 (MSM / lower−risk males) [0.9−1.2]
% infected FSW virally suppressed in 2018 [63.2%−75%]
% condom use during commercial sex in 2018 [74.2%−94.4%]
% condom use of MSM in 2018 [58.6%−77.7%]
Ratio # of sex acts (FSW / lower−risk females) [5.4−13.8]
% condom use of FSW in 2018 [65.1%−83.9%]
Lower−risk females annual # of sex acts [71.1−120]
Ratio # of sex acts (FSW / MSM) [3.9−9.2]
% infected lower−risk populations virally suppressed in 2018 [36.1%−45.9%]
HIV prevalence among clients in 2018 [2.8%−5.6%]
HIV prevalence among FSW in 2018 [13.2%−19.2%]
FSW annual number of clients [308.8−993.1]
Average number years of paying for sex [4.3−13.5]
Annual # of sex acts between MSM & female partners [120.5−160.8]
Clients annual number of non−commercial sex acts [129.1−279.3]
% Clients among males in 2018 [6.4%−19.9%]
Ratio of # sex acts with female partners (MSM / lower−risk males) [1.1−2.1]
Annual # of sex acts between MSM & male partners [103.1−210.7]
HIV prevalence ratio FSW / lower−risk females in 2018 [2.4−3.7]
HIV prevalence ratio MSM / lower−risk males in 2018 [11.9−24.3]
HIV prevalence ratio MSM / clients in 2018 [6.5−12.5]
% sex acts between MSM & female partners which are anal [0.2%−0.3%]
% condom use of lower−risk populations in 2018 [20.1%−38.4%]
HIV prevalence overall in 2018 [3.5%−5.3%]
FSW annual number of sex acts with non−clients [232.8−305.1]
% MSM among males in 2018 [0.8%−2.1%]
Ratio of VLS coverage in 2018 (FSW / lower−risk females) [1.5−1.8]
Ratio of condom use in 2018 (MSM / lower−risk groups) [1.8−3.3]
HIV incidence rate ratio lower−risk females / lower−risk males in 2018 [1.8−3.8]
−1.0
−0.5
0.0
0.5
1.0
Spearman's rank correlation coefficient



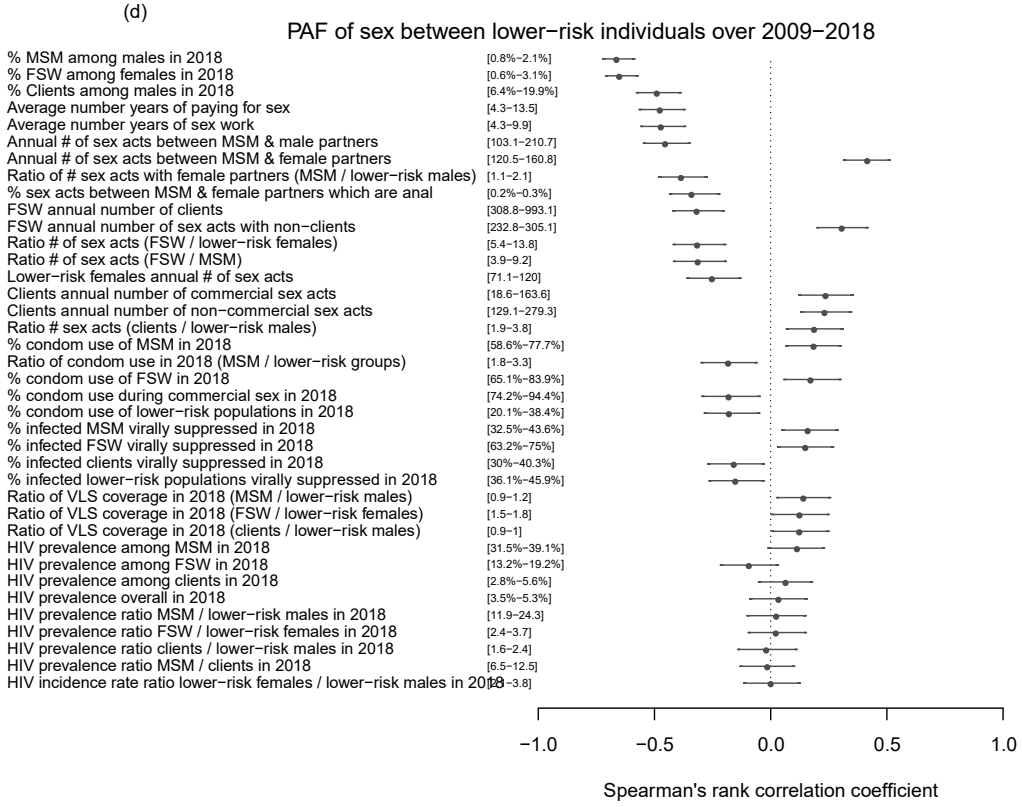


Figure S10: Univariate correlations between key model parameters and outcomes and PAF of a) sex between: MSM with all partners, b) FSW with all partners, c) clients with all

partners, d) lower-risk individuals, calculated over 2009-2018. Numbers and percentages into square brackets represent 95%UI of posterior distribution.

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