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

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Running head: Dynamics of HIV Transmission in Yaoundé

Abstract

Background: Key populations (KP) including men who have sex with men (MSM), female sex workers (FSW), and their clients are disproportionately affected by HIV in Sub-Saharan Africa. We estimated the evolving impact of past interventions and contribution of unmet HIV prevention/treatment needs of KP and lower-risk groups to HIV transmission.

Setting: Yaoundé, Cameroon.

Methods: We parametrised and fitted a deterministic of HIV transmission model to Yaoundé-specific demographic, behavioural, HIV and intervention coverage data in a Bayesian framework. We estimated the fraction of incident HIV infections averted by condoms and antiretroviral therapy (ART) and the fraction of all infections over 10-year periods directly and indirectly attributable to unprotected sex within and between each risk group.

Results: Condom use and ART together may have averted 43% (95% uncertainty interval: 31-54) of incident infections over 1980-2018 and 72% (66-79) over 2009-2018. Most onward transmissions over 2009-2018 stemmed from unprotected sex between lower-risk individuals (47% (32-61)), clients (37% (23-51)), and MSM (35% (20-54)) with all their partners. The contribution of commercial sex decreased from 25% (8-49) over 1989-1998 to 8% (3-22) over 2009-2018, due to higher intervention coverage among FSW.

Conclusion: Condom use and recent ART scale-up mitigated the HIV epidemic in Yaoundé and changed the contribution of different partnerships to onward transmission over time. Findings highlight the importance of prioritizing HIV prevention and treatment for MSM and clients of FSW whose unmet needs now contribute most to onward transmission, while maintaining services which successfully reduced transmissions in the context of commercial sex.

Keywords: Mathematical model; HIV/AIDS, HIV incidence; Population attributable fraction; Condom use; Key populations

Introduction

Cameroon has one of the largest, albeit declining, HIV epidemics across West and Central Africa.[1] By 2018, HIV prevalence was 3.6% amongst 15-49 year-old adults, and there were an estimated 540,000 people living with HIV (PLHIV).[1] Modeled estimates of HIV incidence suggest the epidemic peaked in the late 1990s.[1]

In Cameroon, as elsewhere, key populations (KP) such as female sex workers (FSW), their clients, and men who have with men (MSM) experience a high burden of HIV.[2] Despite same-sex practices and sex work being criminalized, research and programs addressing HIV prevention among sex workers have been in place since the emergence of HIV in Cameroon.[3,4] HIV prevalence among FSW and MSM in Cameroon were 21% and 25% in 2016, respectively,[2] with higher (45.1%[2]) HIV prevalence estimates among MSM in Yaoundé (Cameroon's largest city).[5]

FSW have been an important focus for early HIV research and prevention efforts in Yaoundé[6-8] through the World Health Organisation/Global Programme on AIDS which was introduced in Cameroon in 1987.[9] However, FSW received less attention after 2000 as the prevalence increased among pregnant women[9]. For example, only 5% and 2% of all funds allocated to HIV prevention in 2013 were estimated to be spent on programmes on FSW/clients and MSM, respectively.[10]

Clients of FSW have received little attention despite early local studies suggesting an important role due to them acting as a bridge in sexual networks.[6] Little was known about clients' sexual practices and HIV prevalence until a 2017 survey in Yaoundé, which found that HIV prevalence among clients of FSW (3%) was around twice as high as among all males.[11]

Variability in scale-up, reach, and access to condom-based prevention and antiretroviral treatment (ART) has led to differential coverage by risk group. Interventions have increased over time and mainly focused on condom use and ART since male circumcision is ubiquitous in Cameroon.[12-14] Self-reported condom-use at last sex among KP increased to high levels since the 1990s (in 2016, 75% of MSM, and 90% of FSW with their clients[2]) but has remained relatively low among lower-risk populations (~25%).[13,15] In contrast, access to

ART became available in 2000,[16,17] with ART coverage among PLHIV reaching 52% in 2018.[1,18] Levels of viral suppression are highest in FSW and lowest in the male population.[2,11,19] Universal HIV testing and treatment was initiated in 2020.[20]

In other West and Central African countries, programs focused on the needs of FSW and their clients have been credited with reducing their HIV epidemics.[21-23] To date, there has been no assessment of the population-level impacts of the delivery of HIV services on the epidemic in Cameroon, and of the evolving contribution of KP to onward transmission, which is rarely estimated. Thus, we conducted a data-driven mathematical modeling study to 1) assess the potential population-level impact of condom-use and ART in risk groups on the HIV epidemic and, 2) assess the contribution of these groups or their partnerships, due to the remaining unmet HIV prevention and treatment needs, to onward HIV transmission over time, in Yaoundé, Cameroon.

Methods

Setting

Yaoundé has experienced one of the largest HIV epidemics in Cameroon. The estimated HIV prevalence among all 15-49 years old in the city reached a peak of 8.3% (95% confidence interval 6.7-10.1) in 2004[24] and declined to 4.4% (3.2-5.6) in 2017[19]. In 2016, HIV prevalence among FSW and MSM were 23.9% (20.4-27.8) and 45.1% (39.3-51.0),[2] respectively.

Mathematical model description

We adapted a published deterministic compartmental model of HIV transmission,[23] and calibrated it to reproduce Yaoundé-specific demographic (15-49 years), behavioural, HIV epidemiological and intervention data over 1980-2018. We modelled a growing population using local census estimates.[25]

Individuals enter the modelled population at age 15 and leave due to ageing (age 50), or via background- and HIV-related mortality. There are six risk groups: lower-risk females and males, FSW, clients of FSW (“clients”), younger (15-24 years) and older (25-49 years) MSM (Figure S1a,http://links.lww.com/QAI/B577). The proportion of MSM, FSW and clients is stable over time and fitted to empirical estimates, with FSW being defined as woman reporting commercial sex as their primary source of income.[2,12,13,24-28] In the model, HIV transmission occur within main, casual, and commercial partnerships between risk groups. MSM can have main and casual partnerships with any female, whereas only FSW and clients engage in commercial sex (Table S1, Figure S1a,http://links.lww.com/QAI/B577). Lower-risk females and males were defined as females and males not engaging in commercial sex nor sex between males (Table S1, Figure S1a,http://links.lww.com/QAI/B577).

Following infection, PLHIV progress through acute infection to untreated chronic infection (during which they experience HIV-related mortality) (Figure S1b,http://links.lww.com/QAI/B577). PLHIV initiate ART, with a fraction of treated PLHIV being virally suppressed and experiencing reduced HIV-related mortality and suppressed infectivity. Individuals may stop and re-start ART.

HIV transmission occurs through insertive/receptive vaginal/anal sex acts. The per-capita rate of acquiring HIV depends on the per-act HIV transmission probability by type of sex act, the annual number/types of new partners, number of sex acts involving and not involving condoms by partnership type (Table S2,http://links.lww.com/QAI/B577), sexual mixing between groups by partnership type, the HIV prevalence and probability of viral suppression among partners, and in the case of male partners, circumcision coverage. The per-act efficacy of condoms in reducing HIV acquisition/transmission was 71-98%,[29-31] while the per-partner efficacy of circumcision in reducing HIV acquisition was 38-68%.[14] Pre-Exposure Prophylaxis (PrEP) was not available in Cameroon in 2018 thus was not modelled.

Model parameterisation and fitting

We parametrised and fitted the model within a Bayesian framework using importance resampling method[32,33] to account for uncertainties in parameters and estimates of demographic, epidemiological and intervention fitting outcomes (listed in Tables S1-3,http://links.lww.com/QAI/B577 details in supplement).

Data sources

Several data sources informed these parameters and outcomes (Tables S1-3,http://links.lww.com/QAI/B577).

Data to inform the demography, sexual behaviour and HIV prevalence for the overall and lower-risk populations were sourced from the Census and United Nations Population Division, several Demographic Health Surveys (DHS) (1997, 2004, 2011, 2018)[13,24,28,34,35] and the 4-city study.[15,27,36] The sexual behaviours and levels of HIV intervention of KPs were based on local surveys spanning over 1990-2018.[2,4,11,26,27,37-44]

The size of each KP was determined based on existing studies in Yaoundé (mainly conducted after 2012),[2,12,13,24-28] which suggested that between 0.5-3.4% of 15-49 years old females were currently FSWs, and 0.5-2.3% and 2-20% (reflecting high heterogeneity in empirical estimates) of 15-49 years old males were MSM and clients of FSW, respectively (Figure S2,http://links.lww.com/QAI/B577).

The model reflected reported evolutions in condom-use over time among the different risk groups, and partnership types, the higher condom use among KPs – especially by FSW during commercial sex – compared to the rest of the population, and similar levels of condom use reported by MSM with male and female partners[2] (Figure 1, Table S2,http://links.lww.com/QAI/B577). National annual estimates of ART coverage over 2012-2017 were obtained from the Joint United Nations Programme on HIV and AIDS (UNAIDS)[1] which suggested an increase from 24% to 50% over the period. Around 80% of PLHIV on ART were virally suppressed in 2017.[19] The model reflected very high coverage (94-99%) of male circumcision.[12,13,24]

Biological parameters and intervention efficacy parameters related to condom-use, male circumcision, ART, and risk-group- specific level of viral suppression were sourced from published literature (Table S1,http://links.lww.com/QAI/B577).[31,45-50]

The model was fitted to 40 empirical fitting outcomes (Table S3,http://links.lww.com/QAI/B577) including: total population size (2015), HIV prevalence among all (15-49 years) females and males in Yaoundé (three time points[12,13,24]), HIV prevalence among FSW (five time points[2,6,27,42,51]), and recent HIV prevalence estimates among clients (one time point[11]) and MSM (two time points[2,52,53]). We screened-out simulations where ART coverage among PLHIV was inconsistent with sex-specific UNAIDS national estimates (Figure S3,http://links.lww.com/QAI/B577), and fitted the model to recent risk-group-specific estimates of viral suppression levels among PLHIV in Yaoundé[2,11,19] (Figure S4,http://links.lww.com/QAI/B577). A set of 1000 posterior fits was resampled (based on their individual log-likelihood[32,33]) from a pool of simulations consistent with each fitting outcomes. Additional available HIV prevalence data not used for model fitting were used for comparison.

Impact of condom use and ART

The fraction of incident HIV infections directly or indirectly averted by past interventions (condoms, ART, and both) over a period[t_0, t] (AF_{t_0-t}, equation 1), was derived by comparing the model cumulative number of incident HIV infections over[t_0, t] in the baseline scenario with interventions (CI_{t_0-t}) with that from a counterfactual scenario without the intervention (condoms and/or ART) in any of the risk group, or in a specific group over the same period, (CI_{t_0-t}).

Equation 1: $AF_{t_0-t} = CI_{t_0-t}$

The counterfactual scenarios assumed that the intervention had no efficacy in reducing HIV acquisition (condoms) and transmission (condoms and ART) and HIV-related mortality (ART) in relevant risk groups. The cumulative number of incident HIV infections and fraction of incident HIV infections averted were first calculated at the overall population level, then within each risk group, in order to identify which group most benefited from interventions.

We estimated four indicators to describe who acquired and transmitted infections the most (indicators 1,3) and the efficiency in acquisition and transmission (indicators 2,4).

Sources of HIV acquisition (indicator 1,2)

We first estimated the distribution or fraction of all incident HIV infections over 2009-2018 occurring in each risk group (indicator 1), as well as the annual HIV incidence rate (expressed as the number of incident infections per 100 susceptible person-years), in each group (indicator 2).

Sources of onward HIV transmission (indicators 3,4)

We derived the population attributable fraction (PAF_{t_0-t}, equation 2) as the fraction of all HIV infections directly or indirectly transmitted by specific partnership types between two specific groups over[t_0, t] (indicator 3). The PAF_{t_0-t} can also be interpreted as the sources of onward transmission.

Equation 2: $PAF_{t_0-t} = \frac{CI_{t_0-t}(risk) - CI_{t_0-t}(norisk)}{CI_{t_0-t}(risk)}$

Here, $CI_{t_0-t}(risk)$ and $CI_{t_0-t}(norisk)$ are the numbers of incident HIV infections in the presence and absence of transmission during sex between the relevant groups, respectively. The sum of the PAFs over mutually exclusive groups exceeds 100%[54] as it accounts for secondary transmissions which may overlap for different groups.

We derived the per-capita $HIVtransmissionrate_{t_0-t}$ (per 100 infected person-years, equation 3) from a specific risk group by dividing the total number of infections over[t_0, t] due to the specific group by the cumulative number of person-years lived in the infected group over the same period ($\int_{t_0}^{t} infected(risk)$)[55] (indicator 4).

Equation 3: $HIVtransmissionrate_{t_0-t} = 100 \times \frac{CI_{t_0-t}(risk) - CI_{t_0-t}(norisk)}{\int_{t_0}^{t} infected(risk)}$.

To identify where these direct and indirect transmissions occurred, HIV transmission rates were also calculated as the number of infections due to the specific risk group over$[t_0, t]$ occurring in another specific group.

AF_{t_0-t}, PAF_{t_0-t} and $HIVtransmissionrate_{t_0-t}$ were estimated over successive decades over 1989-2028. We report median estimates as well as 95% uncertainty interval (UI, 2.5th and 97.5th percentiles of the distribution) across the 1000 posterior fits. Uncertainties in PAF_{t_0-t} estimates are described in the supplementary.

Results

Model fitting and epidemic dynamics

Figures 1-2, S2-5,http://links.lww.com/QAI/B577 show that the baseline scenario reproduced available demographic data and time trends in HIV prevalence, and intervention coverage data across risk groups.

Impact of condom use and ART

Over 1980-2018, increases in condom-use and ART may have averted 43.4% (31.4-53.6) of incident HIV infections in the overall population, and 72.2% (65.6-78.5) over 2009-2018 (Figure 1g).

Condom-use alone potentially averted more than a third, 38.7% (26.7-49.9) of incident HIV infections over 1980-2018, and 58.1% (51.5-68.1) over 2009-2018, due to increasing levels of condom use (Figure 2a-c). Condom-use between clients and all their partners was estimated to have averted the largest fraction of overall infections, followed by condom use between MSM and all partners, and FSW and all partners, and between lower-risk groups with medians $AFs_{2009\text{-}2018}$ of 35.5%, 29.3%, 29.2%, 18.7%, respectively (Table 1).

In contrast, ART alone potentially averted 5.8% (3.9-9.1) of infections over 1980-2018, increasing to 32.1% (27.2-36.1) over 2009-2018 (Figure 2e-h, S3-4,http://links.lww.com/QAI/B577). ART use among MSM, FSW, clients, and lower-risk groups, respectively, averted 9.4%, 6.6%, 5.6%, and 17.4% of all HIV infections over 2009-2018.

Who benefited from HIV interventions

Over 2009-2018, infections averted from the combination of HIV interventions ($AF_{2009\text{-}2018}$) exceeded 71.2% in all groups except MSM. Impact was largest among clients ($AF_{2009\text{-}2018}$=81.6% (72.1-88.0)), mainly due to higher levels of interventions among FSW compared to other groups. It was lowest among younger ($AF_{2009\text{-}2018}$=54.3% (48.8-62.2)) and older ($AF_{2009\text{-}2018}$=42.3% (36.6-49.3)) MSM, despite similar ART coverage and higher condom use as in the lower-risk groups because of higher per-act HIV risk (Figure S6,http://links.lww.com/QAI/B577).

Sources of HIV acquisition (indicators 1-2)

Most HIV infections might have been acquired by lower-risk groups despite lower incidence rates (Figure S7,http://links.lww.com/QAI/B577). HIV incidence rates over 2009-2018 were almost 3-fold higher among KP than lower-risk groups; and among all females compared to all males. The highest HIV incidence rates were estimated among MSM (Figure S8, Table S4,http://links.lww.com/QAI/B577). The model suggested larger incidence declines among

KP compared to lower-risk groups. The proportions of PLHIV by risk group over time is shown in Table S5,http://links.lww.com/QAI/B577.

Contribution of risk groups to onward HIV transmission (indicator 3)

Over 2009-2018, the largest contributor to onward transmission was sex between lower-risk groups ($PAF_{2009\text{-}2018}$ = 46.6%), sex between clients (36.5%), MSM (35.1%) and FSW (13.6%) with all partners (Figure 3, Table 2).

The estimated contribution of KPs was higher at the early stage of the epidemic and declining over time thereafter. The largest estimated decline was for the PAF from sex between FSW and all their partners (from $PAF_{1989\text{-}1998}$=33.1% (13.0-57.6)) to $PAF_{2009\text{-}2018}$=13.6% (5.9-29.2)) largely because of past increases in condom-use during commercial sex. Conversely, the contribution of sex between lower-risk individuals slightly increased over time (from $PAF_{1989\text{-}1998}$=37.5% (23.3-55.6) to $PAF_{2009\text{-}2018}$=46.6% (32.0-61.4) over 2009-2018). The high PAF of MSM with all partners plateaued from the early 2000's ($PAF_{2009\text{-}2018}$=35.1% (20.1-54.0)).

Contribution of different partnership types within risk groups to onward transmission

Over 2009-2018, the PAF of sex between MSM and their female partners (27.5% (15.9-44.5)) was slightly higher than the PAF of sex between MSM and their male partners (23.2% (12.7-36.3)) although the difference was larger earlier in the epidemic (Table 2), with less than <2% of transmissions due to infections from female to MSM.

For FSW, commercial sex initially contributed more to HIV transmission than sex between FSW and their non-commercial sex partners, although this difference attenuated for the last two decades ($PAF_{2009\text{-}2018}$=8.3% and 9.0%, respectively), given the large increase in condom use during commercial sex. The large $PAF_{2009\text{-}2018}$ of sex between clients and all their partners over the past and next decade mainly stems from non-commercial sex rather than commercial sex, with more transmissions occurring from clients to their non-commercial partners ($PAF_{2009\text{-}2018}$=26.7%) than from non-commercial partners to clients ($PAF_{2009\text{-}2018}$=6.3%) across decades. Estimates of the $PAF_{2009\text{-}2018}$ of KP were most sensitive to uncertainties in their relative population size (Supplementary and Figures S9-S10,http://links.lww.com/QAI/B577).

Efficiency of transmission (indicator 4)

Despite the PAF of KPs declining over time, sex by KP living with HIV has consistently resulted in more direct and indirect transmissions per year living with the infection (>2-fold) than lower-risk individuals (Table S6,http://links.lww.com/QAI/B577). Nearly half of transmissions contributed by FSW over 2009-2018 were secondary infections acquired by lower-risk females (Table S7,http://links.lww.com/QAI/B577).

Discussion

Our study shows that condom use among KP and more recently ART scale-up, achieved a large impact on the HIV epidemic in Yaoundé. Past and current KP programmes have successfully reduced onward transmission in the context of commercial sex. As a result, most onward transmission is now due to unmet prevention/treatment needs of MSM, clients of FSW, and lower-risk groups.

We estimated that to date most of the prevention benefits were due to condom use, particularly among KPs partly because it was introduced and adopted earlier than ART. The magnitude of historical increases in condom use during commercial sex is consistent with estimates from Benin[21], and Côte d'Ivoire.[22] ART population-level impact recently increased, mainly due to increased coverage in lower-risk population, and this estimated impact is similar to findings from other Western/Central African countries.[22,23] However, our findings suggest that further scale-up would be needed to achieve the UNAIDS target of reducing HIV incidence to below 1 infection per 1000 susceptible-year[56] before 2030 (Figure S5,http://links.lww.com/QAI/B577). Improvements are expected because Cameroon has made ART universally available since 2020,[20] despite possible disruptions in HIV prevention due to COVID-19.

FSW and their clients benefitted the most from past interventions, and despite relatively high condom use, MSM benefited the least. These findings reflect the need for different levels of intervention coverage to address differential vulnerabilities across groups. The reason why the contribution of unmet needs of MSM remain high is a higher per-act transmission probability of anal intercourse compared to vaginal intercourse – which means higher coverage of condom use or other public health (e.g. PrEP) and human rights interventions are needed to avert transmission. Our findings on the PAF of sex between men resemble that of Dakar, Senegal (42% over 1995-2005), and are higher than those reported in other settings (around 5-10%)[22,23,57,58] where HIV prevalence among MSM is lower. Our estimate of the HIV incidence among MSM over the 2009-2018 (8.6 (7.0-9.9) infections per 100 susceptible person-year) is consistent with estimates from empirical studies conducted in Sub-Saharan Africa over the same time period,[59,60] but our predicted HIV incidence markedly decreases to 2.2 infections over 2019-2028 due to reported increases in coverage of interventions among MSM in Yaoundé compared to other settings. Additional empirical studies, using a highstandard sampling design would improve our understanding of these time dynamics and better inform the overall contribution of MSM to the HIV epidemic in Yaoundé.

We found that clients of FSW may play an important role in current onward transmission. The reasons for these are: a) clients comprise a large fraction of the male population; b) complex sexual networks that link commercial sex and casual sex wherein clients have a higher number of casual sex partners than non-client males and thus an added layer of vulnerability beyond just their role in commercial sex networks; c) existing and disproportionate prevention gaps among clients. Few studies have previously reported on the role of clients in HIV epidemics in Sub-Saharan Africa. In Côte d'Ivoire,[22] partnerships between clients and non-FSW over 2005-2015 contributed to 44% of overall transmissions[22] (34% over 2009-2018 in our study). Taken together, our findings suggest an important benefit of implementing HIV prevention and treatment services to reach clients of FSW, which has unfortunately been found extremely challenging and, to our knowledge, never been deployed at a large-scale.[61-63]. Although these efforts would align well with the call to reach men in HIV prevention efforts, and given the challenges in recruiting and sustaining intervention in clients of FSWs, further modelling impact and cost-effectiveness of implementing different prevention interventions, including new promising tools (e.g. HIV self-testing, oral or long-acting injectable PrEP) in different risk populations, may be required. Lower-risk males were assumed to be able to form non-commercial sexual relationships with FSW (at a twice lower rate than clients), and thus the 'lower-risk males' included non-client partners of FSW.

We examined various indicators in our analyses of the contribution of specific partnerships and unmet needs of specific risk groups to the overall HIV epidemic. A key finding is that the per-capita contributions of KP remain high which are a better marker of disproportionate risk because they account for population size as well as differential risks of per-act transmissions. We found that it could be most efficient to prioritize partnerships at disproportionate risk of onward transmission – for example between MSM or clients and their female partners with interventions such as PrEP, increased condom and/or lubricant use, and early and effective ART.

Our results highlight the importance of examining past impact to understand current contribution. All published modelling studies estimated a decline in the contribution of commercial sex (or FSW) to HIV epidemics in Western/Central Africa,[21-23,64,65] with extremely high contributions in the early days of the epidemic. Our results ($PAF_{2009-2018}$=8.3% (3.3-21.9) for the PAF of commercial sex) are in line with estimates for the past decade, between 5% and 19%.[21-23] The reason that unmet needs of FSW play a smaller role in the current epidemic is because of the gains achieved thus far. The significance of this finding is that FSW programmes should be continued in order to keep the HIV epidemic under control, especially in Cameroon where FSWs still experience high levels of stigma and violence, which increases their ability to acquire and transmit HIV.[66]

Our study has several strengths. It was based on a comprehensive search of the published and grey literature complemented with new data for KPs, including data on clients of FSW and size of KPs, which was specific to Yaoundé. We also had access to recent estimates of intervention coverage among KP based on testing of viral load suppression, improving our estimates over time. Our model was fitted into a Bayesian framework which accounted for uncertainties in parameters and outcomes. Our analysis relies on advanced epidemic indicators, such as the "per-capita" transmission rates which have been shown to be useful in furthering epidemic appraisal.

Our study also has limitations and highlighted important data gaps such as city-specific data on clients before 2017 in Yaoundé. Indirect information was traditionally obtained via studies among truck drivers on Cameroonian main roads. However, these are imperfect proxy population for FSW clients in Yaoundé due to the geographical location of the truck stops (outside the city of Yaoundé) and the specific socioeconomic status of this population among all FSW clients,[51,67,68] and our model was in good agreement with national estimates among clients in the DHS. We predicted high HIV prevalence among MSM before the first empirical survey in 2011,[26] before the reduction in their risk following intervention uptake, but no data were available to validate model predictions. As a result, historical estimates of the contribution of MSM to the HIV epidemic in Yaoundé should be interpreted with caution, whereas our recent estimates are less uncertain since they rely on two consistent local surveys.[2,26] We identified the size of KP as the main factor of uncertainty around estimates of the contribution of KPs to the HIV epidemic. However, KPs size estimate were based on the best data available and the substantial variability across studies was taken into account in the analysis and reflected in the UI of the model estimates (from 2% of clients among males[27] to >20%[28]). Our estimate of the contribution of MSM to overall transmission which are based on the best available data may nevertheless be under or over-estimated due to data limitation. First, the data used to derive our wide prior range (0.5% to 2.3%) of MSM population size estimates may still be an underestimate stemming from measurement bias in a context where sex between men is criminalized. Our results suggested a near 2-fold variation of PAF estimates if MSM pop size varied 2-fold. Second, although our model tried to capture uncertainty by using a Bayesian fitting method, reporting of behavioural data by any population is always subject to desirability bias, whereas assessing the levels and coverage of HIV interventions can also be influenced by selection and reporting biases. These issues were addressed by accounting for the full uncertainty in empirical estimates of levels of condom use and viral suppression in all populations, and by assuming an over reporting of condom-use consistency (up to 25% relative) for all sex acts, which should have sensibly reduced the effects of these different potential biases. Vertical HIV transmission was not considered in the model based on decreasing rates of vertical transmission over time in Cameroon, alongside low probability of survival into adolescence among infants living with HIV due to limited HIV treatment coverage over the period of time considered,[69] and is unlikely to have influenced PAF estimates. Our model did not represented the population aged 50 years or older, due to large data gaps regarding this age group, but UNAIDS has estimated that only around 5% of new HIV infections in Cameroon occur in this population, thus we assumed that this simplification did not significantly alter our estimates.[1]

In conclusion, our study shows that despite the HIV epidemic in Yaoundé being characterised as "generalised" (with overall HIV prevalence >1%), unmet prevention and treatment needs among KP still contribute to a substantial proportion of transmitted infections. In particular, since women are the ones who acquire most infections, addressing the treatment needs of clients and MSM, who have substantial non-commercial sex or sex with women, would be an efficient and significantly impact the HIV epidemic in Yaoundé, as they contribute the majority of transmissions but represent a minority of the overall population.

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Figure Captions

Figure 1. 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;http://links.lww.com/QAI/B577 Proportion of PLHIV who are virally suppressed for d) MSM, e) FSW, and f) lower-risk populations. The model is also fitted to UNAIDS estimates of the ART coverage at the national level[1] (Figure S4,http://links.lww.com/QAI/B577). Dashed lined represent UNAIDS 90-90-90 targets (73% virally suppressed among PLHIV). Dots represent data and 95% confidence interval. Line and shaded areas represent median model predictions and 95% uncertainty intervals. In (g) Estimated proportions (AF) of HIV infections in the total population averted by the use of condoms alone, ART alone, and due to condoms and ART together over successive 10-year time-periods. Boxplots represent median (middle line), interquartile range (25 and 75% percentiles and 95%UI (whiskers).

Figure 2. 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 in Yaoundé, Cameroon. Red squares and interval represent empirical estimates use for model fitting (Table S2,http://links.lww.com/QAI/B577), while blue shade represent model 95% uncertainty interval. Grey squares and intervals reflect estimates only used for comparison[7,13,19,24,35].

Figure 3. Model predictions of the contribution of different partnerships to incident HIV infections not covered by interventions over the last three decades in Yaoundé. Boxplots represent median, interquartile range and 95%UI.

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

Manuscript Tables

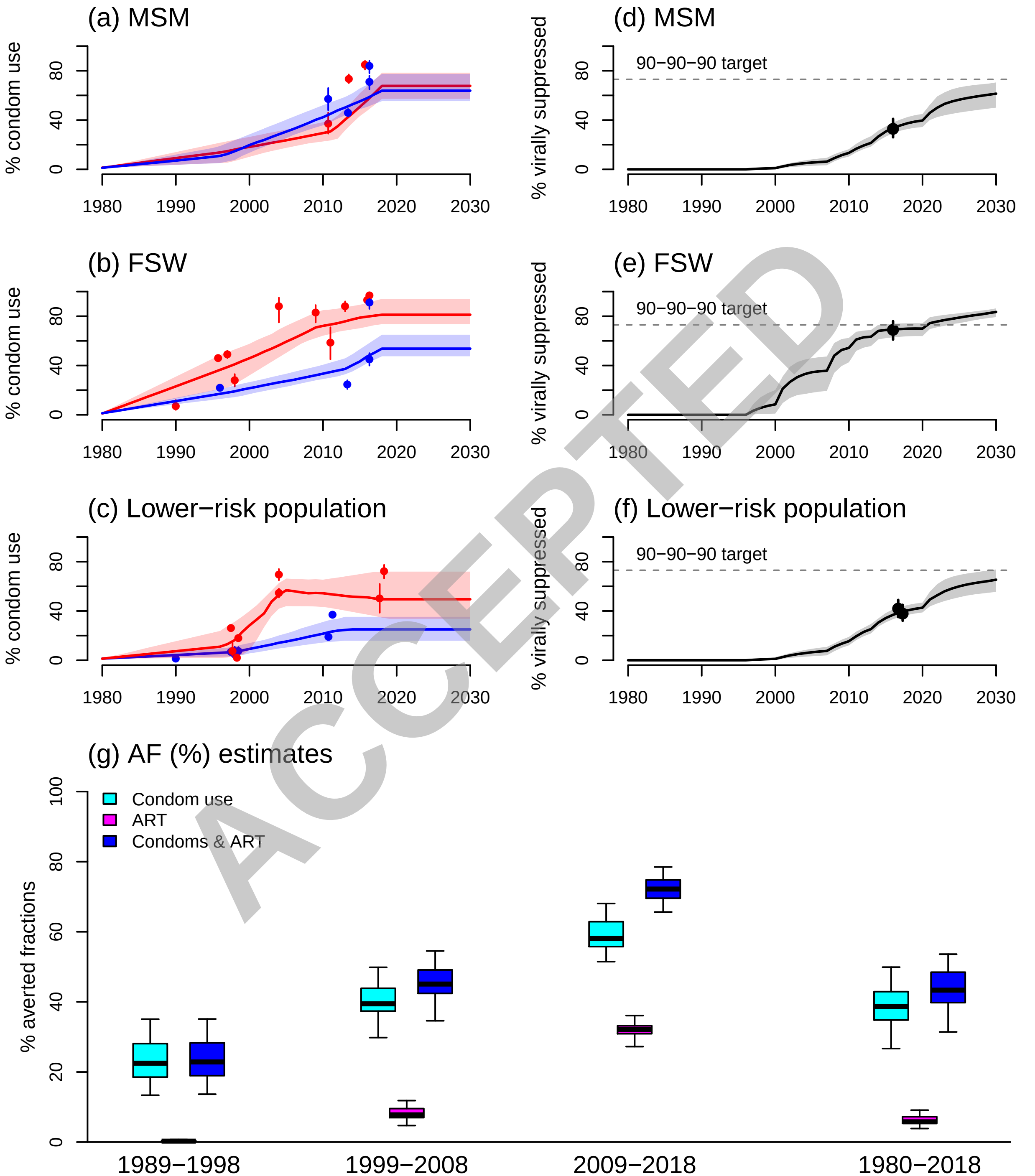
Table 1. Model estimates of the fraction of HIV infections in the overall population averted (2009-2018) due to increases in condom use alone or to ART alone in specific risk groups, and their intervention coverage in 2018.

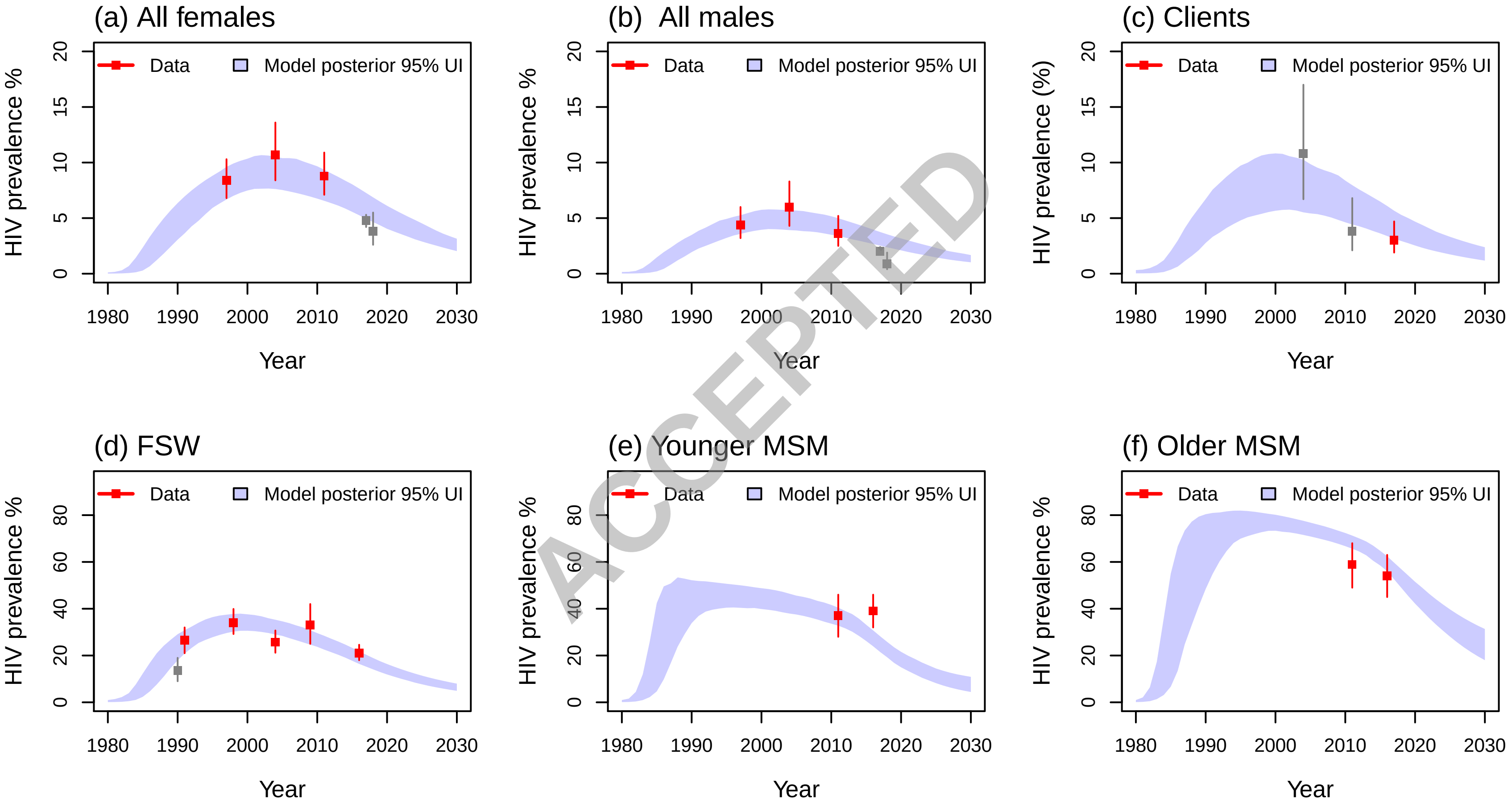
Risk group with all their partners	Condom use		ART	
	Consistency of use %	Averted fractions %	Coverage %	Averted fractions %
All	As below	58.1% (51.5-68.1)	As below	32.1% (27.2-36.1)
MSM	65.7% (57.7-77.5)	29.3% (18.7-40.5)	46.8% (41.0-51.8)	9.4% (5.3-14.4)
FSW	72.9% (64.8-82.5)	29.2% (10.7-50.3)	87.3% (81.0-91.8)	6.6% (2.4-13.4)
Clients	41.6% (29.5-54.1)	35.5% (19.1-55.5)	44.0% (38.3-49.9)	5.6% (3.1-8.2)
Lower-risk (male + females)	29.1% (20.1-39.5)	18.7% (8.6-31.2)	50.5% (46.3-56.0)	17.4% (11.5-22.4)

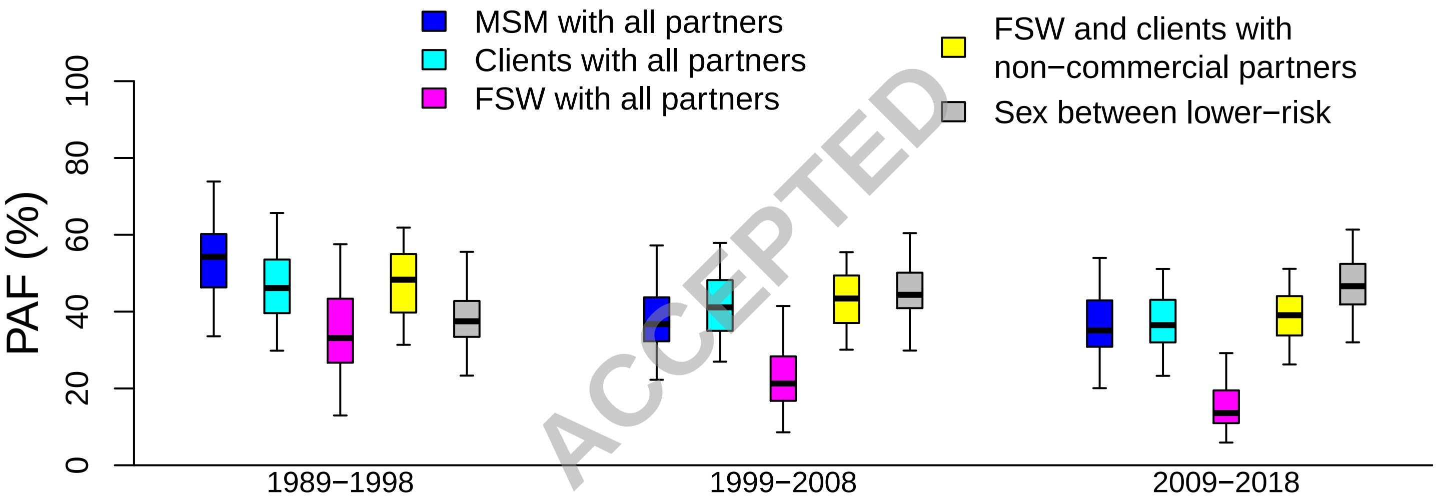
To estimate the fraction averted, the base-scenario was compared against a counterfactual where condom-use (or ART coverage) in the risk group(s) of interest was set to zero between 2009 and 2018.

Table 2. Model estimates of the proportion of incident HIV infections occurring in Yaoundé during a period that were transmitted by different partnership types (Population Attributable Fractions, PAF).

Partnership	**1989-1998**	**1999-2008**	**2009-2018**
1 - MSM ↔ all partners	**54.3% (33.6-73.9)**	**36.7% (22.2-57.2)**	**35.1% (20.1-54.0)**
• MSM ↔ MSM	35.1% (21.3-47.5)	23.2% (13.4-35.6)	23.2% (12.7-36.3)
• MSM ↔ female partners	47.2% (28.7-65.7)	29.7% (18.1-49.5)	27.5% (15.9-44.5)
• MSM → female partners	47.1% (28.6-65.6)	29.5% (18.0-49.3)	27.2% (15.6-44.2)
• MSM ← female partners	1.1% (0.4-2.0)	0.9% (0.4-1.5)	1.0% (0.4-1.8)
2 - Clients ↔ all partners	**46.1% (29.8-65.7)**	**41.1% (27.0-57.9)**	**36.5% (23.3-51.1)**
• Client ↔ commercial sex partners	24.6% (8.4-48.8)	14.2% (5.2-32.9)	8.3% (3.3-21.9)
• Clients → commercial partners	14.6% (3.4-36.7)	8.0% (2.4-22.4)	5.0% (1.7-15.0)
• Clients ← commercial partners	20.2% (6.5-41.9)	10.6% (3.6-25.8)	5.5% (2.0-14.9)
• Clients ↔ non-commercial sex partners	38.6% (25.7-57.5)	36.9% (24.0-52.4)	34.2% (21.5-48.0)
• Clients → non-commercial partners	31.5% (18.8-48.6)	29.9% (18.4-43.8)	26.7% (16.2-39.9)
• Clients ← non-commercial partners	12.2% (4.6-24.5)	7.8% (3.1-15.9)	6.3% (2.6-13.9)
3 - FSW ↔ all partners	**33.1% (13.0-57.6)**	**21.3% (8.6-41.4)**	**13.6% (5.9-29.2)**
• FSW ↔ commercial partners	24.6% (8.4-48.8)	14.2% (5.2-32.9)	8.3% (3.3-21.9)
• FSW ↔ non-commercial sex partners	20.2% (7.2-33.8)	13.0% (4.8-23.8)	9.0% (3.6-18.3)
4 - FSW & clients ↔ non-commercial partners	**48.3% (31.4-61.9)**	**43.4% (30.1-55.5)**	**39.1% (26.3-51.1)**
5 – Sex between lower risk individuals	**37.5% (23.3-55.6)**	**44.4% (29.9-60.4)**	**46.6% (32.0-61.4)**


(a) MSM
% condom use
(b) FSW
(c) Lower−risk population
(d) MSM
% virally suppressed
90−90−90 target
(e) FSW
(f) Lower−risk population
(g) AF (%) estimates
% averted fractions
Condom use
ART
Condoms & ART
1989−1998
1999−2008
2009−2018
1980−2018


(a) All females
Data
Model posterior 95% UI
HIV prevalence %
Year
(b) All males
(c) Clients
HIV prevalence (%)
(d) FSW
(e) Younger MSM
(f) Older MSM
ACCEPTED


MSM with all partners
Clients with all partners
FSW with all partners
FSW and clients with non−commercial partners
Sex between lower−risk
PAF (%)
0
20
40
60
80
100
1989−1998
1999−2008
2009−2018