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Anal intercourse among female sex workers in Côte d'Ivoire: prevalence, determinants, and model-based estimates of the population-level impact on HIV transmission

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ABSTRACT

Current evidence suggests that anal intercourse (AI) during sex work is common in sub-Saharan Africa, but few studies investigated the contribution of heterosexual AI to HIV epidemics. Using a respondent-driven sampling survey of female sex workers (FSW) in Abidjan (2014), we estimated AI prevalence and frequency. Poisson regressions were used to identify AI determinants. About 20% of FSW (N=466) engaged in AI during a normal week (95% confidence intervals: 15-26%). Women who performed AI were generally younger, had been selling sex for longer, were born in Côte d'Ivoire, reported higher sex-work income, more frequent sex in public places, and violence from clients than women not reporting AI. Condom use was lower, condom breakage/slippage more frequent, and use of water-based lubricants was less frequently reported for AI than for vaginal intercourse (VI). Using a dynamic transmission model, we estimated that 22% (95% credible intervals: 11-37%) of new HIV infections could have been averted among FSW during 2000-2015 if AI had been substituted for VI acts. Despite representing a small fraction of all sex acts, AI is an underestimated source of HIV transmission. Increasing availability/uptake of condoms, lubricants, and pre-exposure prophylaxis for women engaging in AI could help mitigate HIV risk.

Keywords: Anal sex; Ivory Coast, Female sex worker; HIV/AIDS; Mathematical model; Respondent-driven sampling; West Africa

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Female sex workers (FSW) share a disproportionately high burden of HIV worldwide (1). This results from an intertwined sets of behavioral, biological, and socio-structural factors that enhance their vulnerability to HIV acquisition (2). Although sex work intersects with injecting drug use in some settings, the primary mode of HIV acquisition and transmission for FSW is thought to be vaginal intercourse (VI). Insertive, and receptive anal intercourse (AI) in particular, carry a well-recognized heightened risk of HIV transmission as compared to VI (3, 4), which does not substantially differ between male-female and male-male contacts (5, 6). Paradoxically, the role of heterosexual AI in HIV epidemics seems to have been minimized in prevention, assuming that AI contributes little to HIV transmission despite growing evidence that this behavior is quite common among heterosexual men and women of all ages (7-9). An emerging body of work also suggests that AI during sex work is ubiquitous and reported by FSW across sub-Saharan Africa, with lifetime prevalence estimates of AI ranging from 6-41% (10).

Collecting reliable information on AI prevalence, its frequency, and its determinants are key to design more effective HIV prevention efforts. Targeted interventions among high-risk populations, such as FSW performing receptive AI, could be an effective way to further curb HIV transmission (11). Specifically, evidence suggests that condom use during AI is lower and breakage more frequent than during VI (3, 12-14). Studies have also associated substance abuse, sexual violence, and coercion to AI practices (10, 15-17). These factors could further enhance HIV transmission during AI and understanding these vulnerability patterns remains important to prevention efforts.

Even though sex work is a recognized risk factor for HIV, the specific population-level impact of heterosexual AI on HIV transmission, and particularly during sex work, has rarely been studied. Recent studies show that that the contribution of sex work to overall HIV transmission in

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Côte d'Ivoire is important (18, 19). Yet, the specific impact of receptive and insertive AI performed by FSW and clients, respectively, on population-level HIV transmission remains unknown. Even if only a small proportion of individuals practice AI during commercial sex, this impact could also extend beyond FSW-clients partnerships through further sexual mixing of clients with women not engaging in sex work.

With the ultimate goal of improving prevention strategies towards FSW, this paper addresses two separate objectives. First, a respondent-driven sampling (RDS) survey conducted among FSW in Côte d'Ivoire was analyzed to estimate AI prevalence, its frequency, and to identify the determinants of this practice. Second, the population-level impact of AI during sex work on HIV transmission was estimated for Côte d'Ivoire using a dynamic transmission model. This will enable us to assess the contribution of AI to the HIV epidemic and help inform prevention activities.

METHODS

Study design and population

A cross-sectional RDS survey was conducted among FSW in Abidjan (Côte d'Ivoire) during March-July 2014. The survey collected information on HIV prevalence, sexual behaviors, reproductive health, and engagement in HIV prevention and treatment services. The study design and recruitment procedure have been described elsewhere (20, 21). Briefly, RDS is a network-based technique used to sample hard-to-reach populations (22). The technique starts with a convenience sample of 'seeds' who then further recruit members of this population using a chain-referral procedure (23). Five seeds were selected in Abidjan and each participant could recruit a maximum of three FSW until the target sample size, based on convergence of HIV prevalence, was met (N=466). Eligibility criteria for participation were being assigned female at birth, being

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over 18 years of age, reporting more than half of income from sex work, and having resided in Abidjan for the past three months.

Structured questionnaires were administered face-to-face by trained interviewers in French or English. With respect to sexual behaviors, participants were asked during a "normal week" how many sexual partners they usually have (including clients and non-paying partners), the number of VI and AI acts performed, and frequency of condom use in the last year for VI and AI. Women were then asked the number of new clients, regular clients, and non-paying partners with whom they had VI and AI during the last month. From this set of questions, we estimated AI prevalence and frequency during a "normal week", and AI prevalence during last month. AI prevalence during last year was indirectly derived from the question about condom use during AI over the last 12 months. If women had not practiced AI during the last year, this was recorded in the questionnaire using the 'not applicable' response option. Self-reports of clinical sexually transmitted infection (STI) diagnosis in the last 12 months were also collected.

Upon completion of the questionnaire, a trained nurse provided HIV counselling and testing. HIV status was determined using a testing algorithm composed of three rapid tests (Determine, HIV 1/2 STAT-PAK®, and Genie® III) (20).

Statistical analyses

Descriptive statistics are presented both as crude and adjusted estimates based on RDS sampling weights (i.e., RDS-II) (24). Confidence intervals were calculated for crude and adjusted estimates by clustering the standard errors at the recruiter level.

To examine determinants of AI, univariate and multivariable Poisson regression models were used to estimate prevalence ratios. Weekly prevalence of AI was chosen as the outcome because it had no missing value and was directly measured in the questionnaire (AI during last

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year was indirectly ascertained). Potential determinants of AI that had few missing values and were accurately measured, and for which an association with AI was previously reported or was deemed plausible were considered. These include: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, education level, country of birth, marital status, religion, having sex with clients in public places, sharing of earnings with someone providing a service for sex work, drug consumption in last year, excessive alcohol drinking, clients using violence/force in last year to have certain types of sexual intercourse, knowledge that AI carries the highest HIV risk, and consistent condom use for VI during last year. Clustering of participants by recruiter was taken into account using Generalized Estimating Equations and an exchangeable correlation structure (25). Continuous independent variables were entered in the model using natural cubic splines with two degrees of freedom (26). Observations with missing values for the covariates were removed from the analyses (n=5).

The association between AI exposure and HIV prevalence or STI was also examined for different exposure definitions. Given the lack of balance between covariates between those reporting and not reporting AI, nearest neighbor matching on the Mahalanobis distance was applied (27). We matched on covariates based on our a priori knowledge of potential confounders. These include: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, consistent condom use during the last year for VI, country of birth, marital status, performing sex work in public places, and excessive alcohol consumption. Results from both un-matched and matched Poisson regressions are presented. All statistical analyses were performed using the R statistical software (28) and relevant analytic packages (29-32).

Modeling population-level impact of anal intercourse on HIV transmission

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An age-stratified dynamic model of HIV transmission was developed for Côte d'Ivoire and calibrated to local epidemiological and programmatic data (33, 34). The model represents an open population of sexually active individuals stratified by age (15-19, 20-24, 25-49, and 50-59 years). Behavioral heterogeneity is incorporated in the model through the following mutually-exclusive groups: low-risk females, high-risk females (>1 partner year^{-1}), FSW not practicing AI, FSW practicing AI, low-risk males, high-risk males (>2 partners year^{-1}), clients of FSW, bisexual men who have sex with men (MSM), and exclusive MSM.

In this model, the force of HIV infection depends on: number and type of sexual partners and associated HIV prevalence, infectiousness (which varies by disease stage, ART treatment status, and viral suppression), sexual mixing between age and risk groups, the fraction of condom-protected sexual acts, and the uninfected partner's susceptibility. For the latter, we assumed that young women have higher risk of HIV acquisition (35, 36) and that insertive/receptive AI also increases susceptibility. Specifically, receptive AI increased risk of HIV transmission by a factor varying between 2 and 20 as compared to receptive VI, and insertive AI by a factor of 2 as compared to insertive VI (4). Based on the proportion of FSW reporting AI during the last year in the RDS survey, women entering the sex trade are assumed to either engage in AI at a certain frequency or not until they retire from sex work (recruitment in/out of sex work is independent of age).

The model was parameterized following a comprehensive review of the scientific and grey literature. Because we modeled HIV transmission in Côte d'Ivoire from the 1970s onwards, other FSW surveys were also used to parametrize and calibrate the model. The full list of model parameters can be found in appendix (Tables S1-S7). Uncertainty associated with the model's parameters was captured through the elicitation of prior distributions. The model was then

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calibrated to HIV prevalence and coverage of antiretroviral therapy (Table S8) using a Bayesian framework with Incremental Mixture Importance Sampling (37). Further information on sexual mixing patterns (Text S1), the model's equations (Texts S2-S3), the estimation of historical trends in condom use, HIV testing, and ART coverage (Text S4), and selected model fits are presented as supplementary material (Figures S3-S4).

The contribution of AI performed by FSW with their partners on HIV transmission was estimated using the Population Attributable Fraction (PAF) calculated over the 2000-2015 period. The PAF is the proportion of cumulative number of new HIV infections occurring over a certain time period that would not have been acquired had the risk factor (i.e., the excess risk of AI versus VI) been removed. This was achieved by setting the relative risk of insertive/receptive AI versus VI to one. In other words, we assumed that AI acts were substituted with VI acts. Two scenarios were investigated: first the impact of AI alone was considered; second, the PAF also took into account the lower condom use during AI by increasing condom use to the same fraction as for VI.

Ethics

All women were informed about the study procedures and provided written informed consent before the interview. The study was approved following ethical review by the *Comité national d'éthique et de la recherche* in Côte d'Ivoire, the *Johns Hopkins School of Public Health Institutional Review Board* in the United States of America, and the *Imperial College Research Ethics Committee* in the United Kingdom.

RESULTS

The five seeds recruited 593 women of which 466 met the eligibility criteria and consented participation. The average age of participants was 27 years old (ranging between 18

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and 57 years old). The majority of FSW were born in Côte d'Ivoire, had some secondary education, and had been selling sex for an average of 6 years (Table 1).

RDS-adjusted estimates of prevalence and frequency of anal intercourse

About 20% of FSW reported performing AI during a normal week (95% confidence intervals [CI]: 15-26%; Table 1). This increased slightly to 24% (95%CI: 18-30%) if the recall period extends to the last month and 24% (95%CI 18-30%) over the last 12 months, suggesting relative consistency of AI practice over the course of a year. Among all FSW, the average frequency of AI was 1.9 (95%CI: 0.8-2.9) acts per week compared to 32 (95%CI: 28-37) VI acts per week, resulting in 4% (95%CI: 2-6%) of all sex acts being AI. If restricted to FSW reporting AI on a weekly basis, the fraction of all sex acts that are AI reaches 21% (95%CI: 15-28%). Knowledge that AI carries the highest sexual HIV risk was only 6% (95%CI: 4-9%).

Among FSW who engaged in AI during last year, 82% (95%CI: 70-90%) reported often or always using a condom during VI, compared to 59% (95%CI: 46-71%) during AI (28% never used a condom during AI; 95%CI: 18-41%). Condom breakage/slippage during the last month was more frequently reported by women having engaged in AI in the last month: 38% (95%CI: 25-53%) for those reporting AI compared to 21% (95%CI: 15-29%) for those not reporting it. This could be due to the fact that use of appropriate water-based lubricants are less frequently reported for AI (9%; 95%CI: 5-17%) than for VI (27%; 95%CI: 21-33%). In Abidjan, the average price for VI protected by a condom was $8 USD (95%CI: $7-10) compared to an average price almost three times higher without condom ($25; 95%CI: $19-30). Condom-protected AI was about twice as expensive as condom-protected VI ($20 USD; 95%CI: $14-26). Condomless AI was the priciest ($27; 95%CI: $19-36).

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AI was commonly and similarly reported with all partner types: AI prevalence during last month was 13% (95%CI: 9-18%) with new clients, 13% (95%CI: 10-18%) with regular clients, and 14% (95%CI: 10-19%) with non-paying partners (Table 2). Consistent condom use for VI, however, varied markedly by partner type and was much lower during AI for both new and regular clients, and similarly low with non-paying partners (Table 2).

Determinants of anal intercourse during normal week

In univariate analyses, most variables were associated with weekly AI prevalence (Table 3). After adjustment for potential confounders, results from the multivariable regression show that AI declines with age but increases with time since first paid sex. There was also a positive association between reports of weekly AI and income from sex work. Women born outside of Côte d'Ivoire were 80% less likely to report AI than those born in the country (Prevalence Ratio [PR]=0.20; 95%CI: 0.05-0.86). Women who have sex with clients in public spaces (PR=2.20; 95%CI: 1.50-3.24) and women reporting sexual violence from clients (PR=1.75; 95%CI: 1.20-2.56) were more likely to report AI than those who did not report such experiences.

Association between anal intercourse, HIV, and STI

Women who reported performing AI during a normal week were less likely to test positive for HIV (5.7% HIV positive; 95%CI: 1.9-16.0%) than those that do not perform AI (12.6% HIV positive; 95%CI: 8.4-18.0%). However, when using exposure to AI over longer recall periods, the estimates became closer to the null value (Table 4). After matching on potential confounders to minimize imbalances, exposure to AI reported over the past month or last year was positively associated, albeit not significantly, with testing HIV positive. AI was not associated with reports of having been diagnosed with an STI but all the effect size measures had large confidence intervals.

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Population-level impact of AI performed by female sex worker on HIV transmission

Selected model parameters, their prior distribution, and the posterior distributions are summarized in Table 5. The posterior median size of the FSW population was 1.6% (Credible Interval [CrI]: 1.1-2.2%) of the female population aged 15-59 years old. The posterior fraction of FSW engaging in AI and the proportion of AI sex acts for this group had medians of 25% (95%CrI: 20-29%) and 21% (95%CrI: 15-26%), respectively. Finally, the posterior median of the relative risk of receptive AI, versus receptive VI, was 6.3 (95%CrI: 3.0-11.1) (it was fixed at 2 for insertive AI).

The fraction of new HIV infections due to AI among FSW over 2000-2015 was estimated at 22% (95%CrI: 11-37%) if we assumed that condom use remains unchanged for these AI acts (Figure 1). Among clients, this PAF was estimated at 9% (95%CrI: 4-16%) for the same period. Overall, if all AI acts performed by FSW were replaced by VI acts, a total of 4% (95%CrI: 2-9%) of new HIV infections would have been averted at the population level over the 2000-2015 period (Figure 1). Because condom use is lower for AI than for VI, PAF can also be computed by replacing all AI acts with VI acts and protecting them with condom at the same rate as for VI acts. Doing so, the PAF estimates are slightly higher with 26% (95%CrI: 13-41%) of new HIV infections averted among FSW, 11% (95%CrI: 6-20%) among CFSW, and 6% (95%CrI: 3-11%) in the whole population.

DISCUSSION

As many as a fifth of FSW in Abidjan reported practicing AI on a weekly basis and about a fourth did so during the last year. FSW reported practicing AI with all partner types in relatively equal proportions. Among those practicing AI, anal sex accounted for about 21% of their weekly sex acts. This meant that about 22% of new HIV infections in FSW may be due to

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AI and could have been averted if VI had been practiced instead. At the population-level, even if FSW constitute 1.6% (95%CrI: 1.1-2.2%) of the female population and only 3-7% of all sex acts performed by FSW are AI, we estimated that AI practiced during sex work could account for 4% (95%CrI: 2-9%) of all new HIV infections during 2000-2015. This estimate does not consider women not engaging in sex work that do engage in AI and should be considered conservative.

The prevalence of AI observed here are consistent with those from other studies of FSW in sub-Saharan Africa (10). We found that women born outside of Côte d'Ivoire were less likely to report AI than those born in the country but religion was not associated. Our results also suggest that young women, those having sex in public spaces, and those who have been selling sex for longer were the most likely to practice AI - highlighting a heightened pattern of vulnerability. Sexual violence and coercion have often been associated with AI (10, 15, 17, 38) and FSW reporting sexual violence by clients in Abidjan were 75% more likely to have engaged in AI. If AI is performed in a context of sexual violence, the HIV risk posed by this practice could be higher since traumatic abrasions of the rectal mucosa can facilitate transmission (10, 39). On the other hand, AI was also reported by women who had higher weekly income and the price charged for AI was more than twice that of VI. Given such financial incentives, AI may not always be performed in a coercive context. Reflecting low awareness of HIV risk associated with AI, condom use was low with 28% of women never using condom during AI.

In this cross-sectional sample of FSW, we did not find any consistent associations between AI reports and HIV prevalence. First, AI practice was measured over short time-periods and our exposure measurements may not reflect this behavior at the time of HIV infection. Second, the lack of association could be due to unmeasured confounders. Third, there were strong covariate imbalances between women engaging in AI and those who did not. Matching was used

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to alleviate this issue but the resulting matched sample sizes for these analyses were small, leading to wide confidence intervals. Findings from cross-sectional studies on the association between AI and HIV prevalence were also found to be inconsistent in a recent review (10). Prospective studies of the effect of sexual risk behaviors on HIV incidence are more appropriate to determine causality and there is indeed strong empirical evidence that AI enhances HIV risk (6). A recent meta-analysis of per-act probabilities of HIV transmission for unprotected receptive AI found them to be substantially higher than those of male-to-female VI (6).

Our results need to be interpreted in light of a number of limitations. First, estimating AI prevalence among FSW is challenging for several reasons: the practice can be stigmatized, is often taboo, and the AI questions can be misunderstood. This can affect the accuracy of self-reports and AI can potentially be underestimated due to social desirability bias (6). Further, AI could be underreported in face-to-face interviews such as the one conducted in this study (10). Second, these challenges are further compounded by difficulties related to selecting representative samples of FSW, which are hard-to-reach and marginalized populations. This, along with the characteristics of the different survey instruments, could explain why FSW in our sample generally report higher number of sexual acts than previous studies in Côte d'Ivoire (40-42). Third, the dynamic model used to assess the population-level impact of AI on HIV transmission assumed that AI behaviors are constant over time and do not change as long as the women are involved in sex work. Given the cross-sectional nature of this survey, disentangling cohort and period effects on AI prevalence would have been challenging, however. A sensitivity analysis, examining the influence of different parameters on the PAF estimates nevertheless showed that the most important source of parameter uncertainty was not AI prevalence, frequency, or condom use during AI but the relative risk of receptive AI versus receptive VI

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(Figure S5). Finally, our results do not account for other modes of HIV transmission such as through blood exposures. This is unlikely to affect our PAF estimates, however, since injecting drug use is uncommon in Abidjan (43) and unsafe medical injections are nowadays believed to account for a small proportion of incident HIV infections in sub-Saharan Africa (44-47). However, this assumption has been challenged in the past (48-50) and necessitates ongoing surveillance to assess prevalence of unsafe injections and ultimate parenteral HIV acquisition risk in Côte d'Ivoire.

The study's strengths include the detailed characterization of AI practice and quantification of the population-level of AI during sex work on HIV transmission. The high PAF observed for AI among FSW suggest potential opportunities for further targeted interventions. Specifically, this study highlighted that both condom use during AI and knowledge of HIV risk associated with AI among FSW in Côte d'Ivoire are low.

In conclusion, AI is commonly practiced among FSW and their partners in Côte d'Ivoire. Despite consisting of only a small fraction of total sex acts performed by FSW, AI is an important and underappreciated factor for HIV acquisition and transmission in this group. More attention should be paid to this risk factor in product development and prevention. Transmission risk associated with AI could be mitigated through increased condom use and promotion of appropriate water-based lubricants to reduce condom breakage during AI. Given both the important financial incentives associated with condomless AI and the context of violence/coercion associated with this practice, this could prove challenging, however. In such instances, the use of pre-exposure prophylaxis for women engaging in AI could be considered.

AUTHOR CONTRIBUTION

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DD, KA, SB developed the questionnaire and oversaw data collection. MCB and MMG formulated the research questions and designed the study. JFV, MCB, and MMG developed the mathematical model. JFV and MMG implemented the coding. MA, MMG and SD gathered programmatic and epidemiological data to inform model parameters. MMG fitted the model, performed the statistical analyses, and interpreted the results. MMG wrote the paper while DD, KA, JFV, MA, MCB, SB, and SD critically reviewed it. All authors have read and approved the final version of the paper.

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Table 1: Characteristics of surveyed female sex workers in Abidjan, Côte d'Ivoire in 2014 (n=466, unless stated otherwise).

Characteristics	Crude Estimates (95%CI)	RDS-Adjusted Estimates (95%CI)
Socio-demographic characteristics		
Age (years)	28 (27-28)	27 (26-28)
Country of birth		
Côte d'Ivoire	76% (70-81%)	80% (74-86%)
Nigeria	23% (18-29%)	18% (13-25%)
Other	2% (1-3%)	1% (1-3%)
Education		
No school / Outside System / Other	18% (15-22%)	20% (15-27%)
Some or completed primary	33% (29-38%)	39% (32-45%)
Incomplete secondary	43% (38-48%)	37% (30-43%)
Completed secondary or higher	6% (5-9%)	5% (3-8%)
Currently married	7% (4-10%)	7% (4-12%)
Religion (1 missing value)		
Muslim	13% (10-17%)	13% (8-19%)
Christian	77% (72-81%)	78% (70-83%)
Other	10% (8-14%)	10% (7-14%)
Sex work characteristics		
Age at first paid sex (years)	22 (21-22)	20 (19-21)
Time since first paid sex (years)	6 (5-7)	7 (6-8)
Has sex with clients in public places	18% (15-22%)	19% (14-25%)
Number of sexual partners per normal week*	31 (27-34)	32 (27-36)
Number of VI/AI sex acts per week†		
Frequency of VI per normal week	32 (29-35)	32 (28-37)
Frequency of AI per normal week	1 (1-2)	2 (1-3)
Prevalence of AI†		
During a normal week	19% (15-23%)	20% (15-26%)
During last month (14 missing values)	21% (18-26%)	24% (18-30%)
During last year§	22% (18-26%)	24% (18-30%)
Proportion of weekly sex acts that are AI	3% (2-4%)	4% (2-6%)
Proportion of weekly sex acts that are AI among FSW that report weekly AI (N=86)	17% (14-21%)	21% (15-28%)
Knowledge that AI carries the highest HIV risk (1 missing value)	5% (4-8%)	6% (4-9%)
Condom use over last year†		
VI: Never used for VI	0% (0-2%)	0% (0-1%)
Almost never used for VI	1% (0-2%)	1% (0-5%)
Sometimes used for VI	8% (6-11%)	10% (6-14%)
Often used for VI	52% (47-56%)	57% (50-63%)
Always used for VI	39% (34-44%)	33% (27-39%)
AI: Never used for AI (N=100; 1 missing value)	32% (24-42%)	28% (18-41%)
Almost never used for AI	1% (0-7%)	1% (0-5%)
Sometimes used for AI	17% (11-26%)	12% (7-22%)
Often used for AI	21% (14-30%)	30% (18-45%)
Always used for AI	29% (22-38%)	29% (19-42%)
Average price charged per act (USD)‡		
VI with condom (N=464; 1 missing value)	$8 ($7-9)	$8 ($7-10)
VI without condom (N=178; 2 missing values)	$28 ($23-33)	$25 ($19-30)
AI with condom (N=73; 1 missing value)	$25 ($17-33)	$20 ($14-26)
AI without condom (N=53; 1 missing value)	$33 ($22-43)	$27 ($19-36)

AI=anal intercourse; VI=vaginal intercourse; 95%CI=95% Confidence Interval.

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*Includes new clients, regular clients, and non-paying partners with whom vaginal, anal, or oral intercourse was performed.
†With any partner types.
‡Exchange rate 1 CFA = 0.002 USD
§One women who did not report AI during last year but who did so during a normal week was recoded as having performed AI during last year since the question about AI during normal week was directly asked.

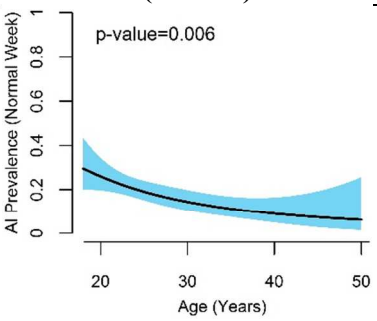
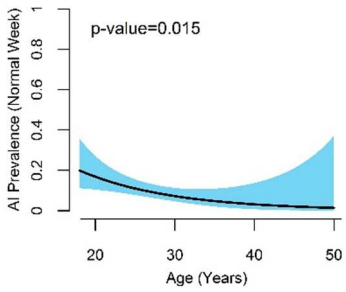
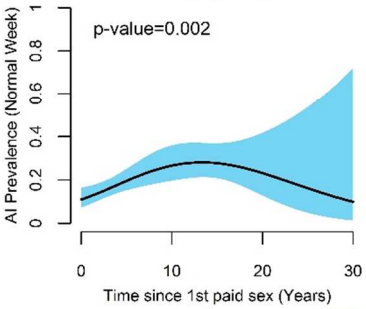
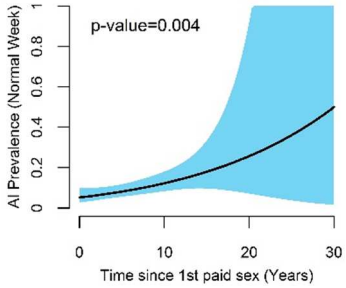
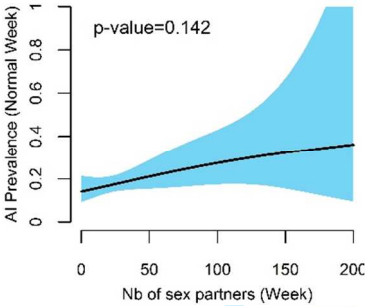
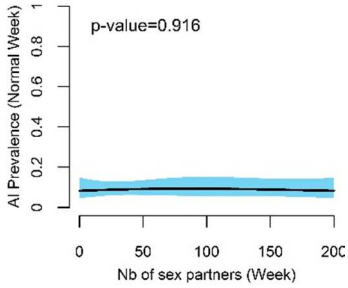
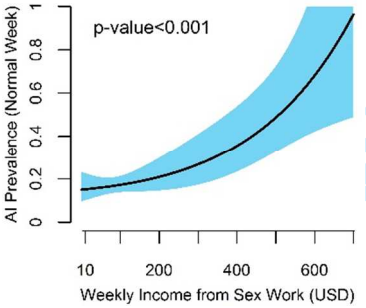
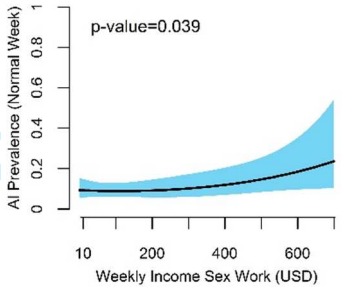
Table 2: Prevalence and frequency of vaginal/anal intercourse and consistent condom use during last month among Abidjan's female sex workers by partner type.

Characteristics	Crude Estimates (95%CI)	RDS-Adjusted Estimates (95%CI)
With new clients (N=463)		
Fraction reporting AI (5 missing value)	12% (9-15%)	13% (9-18%)
Consistent condom use for VI (7 missing values)	77% (73-81%)	75% (68-80%)
Consistent condom use for AI (N=55; 0 missing value)	49% (36-62%)	47% (30-65%)
Condom use at last VI or AI (6 missing values)	87% (84-90%)	89% (85-93%)
With regular clients (N=461)		
Fraction reporting AI (1 missing value)	14% (11-18%)	13% (10-18%)
Consistent condom use for VI (3 missing values)	67% (62-72%)	64% (57-70%)
Consistent condom use for AI (N=65; 0 missing value)	37% (27-49%)	36% (22-53%)
Condom use at last VI or AI (1 missing values)	82% (78-85%)	80% (73-85%)
With non-paying partners (N=451)		
Fraction reporting AI (5 missing values)	11% (9-14%)	14% (10-19%)
Consistent condom use for VI (36 missing values)	5% (4-8%)	4% (2-7%)
Consistent condom use for AI (N=50; 1 missing value)	8% (3-20%)	5% (1-17%)
Condom use at last VI or AI (1 missing value)	13% (10-17%)	13% (9-18%)

AI=anal intercourse; VI=vaginal intercourse; 95%CI=95% Confidence Interval.

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Table 3: Determinants of anal intercourse (during normal week) among female sex workers in Abidjan, Côte d'Ivoire in 2014 (n=461). (Poisson regression models with robust/clustered standard errors.)

Characteristics	PR (95%CI)*	aPR (95%CI)*
Age†		
Time since first paid sex†		
Weekly number of sex partners†		
Weekly income from sex work†		
Education		
No education	Referent	Referent
Some/completed primary	1.34 (0.77-2.35)	0.96 (0.57-1.60)
Secondary or higher	0.79 (0.45-1.38)	0.89 (0.54-1.49)
Foreign-born	**0.08 (0.02-0.30)**	**0.20 (0.05-0.86)**
Currently married (vs. not/formerly married)	0.15 (0.02-1.18)	0.20 (0.03-1.24)
Religion		
Muslim	Referent	Referent
Christian	1.04 (0.53-2.05)	1.17 (0.61-2.25)
Other	1.60 (0.70-3.64)	1.23 (0.58-2.61)
Has sex with clients in public places	**3.90 (2.76-5.52)**	**2.20 (1.50-3.24)**

Share earnings with someone who provides a service for sex work	**1.63 (1.10-2.42)**	0.97 (0.63-1.51)
Consumed drugs in last year	**2.38 (1.51-3.76)**	1.19 (0.74-1.92)
Consumed >6 alcoholic drinks in one occasion every week	**2.12 (1.43-3.14)**	0.96 (0.63-1.46)
Clients used violence/force to have certain types of sexual intercourse (last year)	**2.66 (1.82-3.90)**	**1.75 (1.20-2.56)**
Knows that AI carries the highest HIV risk	**1.51 (0.76-3.02)**	1.07 (0.61-1.89)
Consistently used a condom for VI during last year	**0.32 (0.18-0.56)**	0.61 (0.35-1.06)

PR=Prevalence Ratio; aPR=adjusted Prevalence Ratio; 95%CI=95% Confidence Interval.
Multivariable results are mutually adjusted for all variables listed in the table. A complete case analysis was used and 5 observations with missing values were removed.
*Estimates are adjusted for clustering of standard errors by recruiter (RDS-weights were not incorporated).
†Natural cubic spline with 2 degrees of freedom (95%CI represented by the shaded area; p-value based on Wald statistics).

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Table 4: Association between exposure to anal intercourse and HIV prevalence and reports of having diagnosed with a sexually transmitted infection (STI) in the last 12 months in a cross-sectional sample of female sex workers of Abidjan, Côte d'Ivoire. Poisson regression model with robust/clustered standard errors are used.

Anal Intercourse	Un-Matched Regressions		Matched Regressions†	
	Univariate PR (95%CI)	Multivariable* aPR (95%CI)	Matched AI/no AI	aPR (95%CI)
Outcome: HIV prevalence				
AI during normal week (n=451)	0.38 (0.14-1.01)	**0.46 (0.23-0.95)**	85 / 63	0.41 (0.13-1.25)
AI during last month (n=438)	0.51 (0.22-1.18)	0.79 (0.42-1.48)	94 / 69	1.18 (0.48-2.89)
AI during last year (n=451)	0.67 (0.33-1.35)	0.77 (0.42-1.41)	100 / 75	1.08 (0.43-2.70)
Outcome: Diagnosed by a doctor/health worker in the last 12 months with a STI				
AI during normal week (n=462)	1.28 (0.82-2.02)	0.93 (0.58-1.49)	84 / 63	1.07 (0.58-1.95)
AI during last month (n=448)	1.10 (0.69-1.76)	0.79 (0.48-1.29)	95 / 68	0.97 (0.52-1.79)
AI during last year (n=462)	1.09 (0.70-1.72)	0.85 (0.54-1.34)	99 / 75	0.99 (0.54-1.81)

PR=Prevalence Ratio; aPR=adjusted Prevalence Ratio; 95%CI=95% Confidence Interval; STI=sexually transmitted infection (includes: syphilis, gonorrhea, chlamydia, herpes, human papillomavirus, hepatitis B, hepatitis C, and other).

Estimates are adjusted for clustering of standard errors by recruiter identification (RDS-weights were not incorporated).

*Multivariable models are adjusted for the following covariates: age (natural spline with 2 degrees of freedom (dof)), time since first paid sex (natural spline 2 dof), weekly number of sexual partners (natural spline 2 dof), weekly income from sex work (natural spline with 2 dof), consistent condom use during last year for VI, country of birth (Côte d'Ivoire vs other), marital status (married vs other), having sex with clients in public spaces, and having consumed more than 6 alcoholic drinks in one occasion every week or more often.

†Women reporting AI were matched using a nearest neighbor matching algorithm based on minimizing the Mahalanobis distance to the following covariates: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, consistent condom use during last year for VI, country of birth, marital status, having sex with clients in public places, and having consumed more than 6 alcoholic drinks in one occasion every week or more often.

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Table 5: List of main parameters used in the mathematical model, elicited prior distributions, and posterior distributions following model calibration to epidemiological and intervention coverage data.

Parameters	Prior distribution	Posterior median with 95% CrI	Reference for priors
Demographics			
Proportion of FSW among females (%)*	*U*(0.8-1.7%)**U*(1.0-1.7)	1.6% (1.1-2.2%)	(51-56)
Proportion of CFSW among men (%)†	<20%	15% (10-19%)	
Turnover rate from FSW to non-FSW females ($year^{-1}$)	*U*(0.05, 0.20)	0.11 (0.07-0.18)	Assumption
Behavioral parameters			
FSW partner change rate ($year^{-1}$)	*U*(216, 360)	284 (225-348)	(40, 42, 57, 58)
CFSW partner change rate ($year^{-1}$)	*U*(23, 37)	31 (24-36)	(59)
CFSW partner change rate with women not working the sex trade ($year^{-1}$)	*U*(1.0, 6.8)	5.4 (3.6-6.5)	(56, 60, 61)
Number of sex acts per client-FSW partnership ($partnership^{-1}$ $year^{-1}$)	*U*(1, 4)	2.5 (1.7-3.4)	(61)
HIV transmission probability			
Female-to-male transmission probability (act^{-1})	*U*(0.013%, 0.141%)	0.089% (0.056-0.128%)	(5)
Male-to-female transmission probability (act^{-1})	*U*(0.060%, 0.109%)	0.089% (0.063-0.106%)	(5)
Changes in HIV transmission probability			
RR of HIV acquisition for women 15-24 years old as compared to those aged ≥25 years (act^{-1})	*U*(1.25, 2.5)	2.0 (1.5-2.5)	(35, 36)
RR of HIV transmission during acute infection (act^{-1})	*T*(9.2, 4.5, 18.8)	8.6 (5.6-12.6)	(5)
RR of HIV transmission for individuals on ART (detectable viral load) (act^{-1})	*T*(0.5, 0.3, 0.8)	0.5 (0.4-0.7)	Assumption
RR of HIV transmission for individuals on ART (virally suppressed) (act^{-1})	*T*(0.04, 0.01, 0.27)	0.12 (0.03-0.22)	(62)
RR of HIV transmission when sex act is protected by a condom (act^{-1})	*U*(0.75, 0.94)	0.83 (0.77-0.91)	Based on (63)
Condom use			
Proportion of protected sex acts by FSW with clients (selected years)	1991 = *U*(57%,68%)	62% (58-67%)	(40)
	2014 = *U*(85%,93%)	88% (86-92%)	(20, 57)
AI parameters			
Proportion of FSW that engage in AI (%)	*U*(18.3-29.9%)	25% (20-29%)	Our analysis
Proportion of sex acts that are anal for FSW that engage in AI (%)	*U*(14.8-27.6%)	21% (15-26%)	Our analysis
RR of HIV acquisition of receptive AI as compared to receptive VI (act^{-1})	*T*(10, 2, 20)	6.3 (3.0-11.1)	(4)
RR of HIV acquisition of insertive AI as compared to insertive VI (act^{-1})	2	2	(4)
Relative reduction in the proportion of protected sex acts AI versus VI§	*T*(0.75, 0.61, 0.92)	0.75 (0.66-0.85)	Our analysis

AI=anal intercourse; CFSW=clients of female sex worker; FSW=female sex workers; MSM=men who have sex with men; RR=relative risk; VI=vaginal intercourse; *T*(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); *U*(a,b)=Uniform distribution (a=minimum, b=maximum).

*The prior for the size of the FSW was parameterized by multiplying the size of the MSM population by a uniform prior for the ratio of FSW to MSM in order to keep the size of the former larger than the latter.

†The proportion of clients of FSW was indirectly estimated using the multiplier method, balancing the partner change rate reported by FSW and by clients of FSW. The proportion of clients of FSW was constrained to be smaller than 20%.

§In order to predict condom use at last AI/VI act, we modeled the relationships between condom use at last VI and the frequency of condom use during last year (ordinal responses). We then predict condom use at last sex for AI and VI separately based on the ordinal frequency responses and calculated their ratio.

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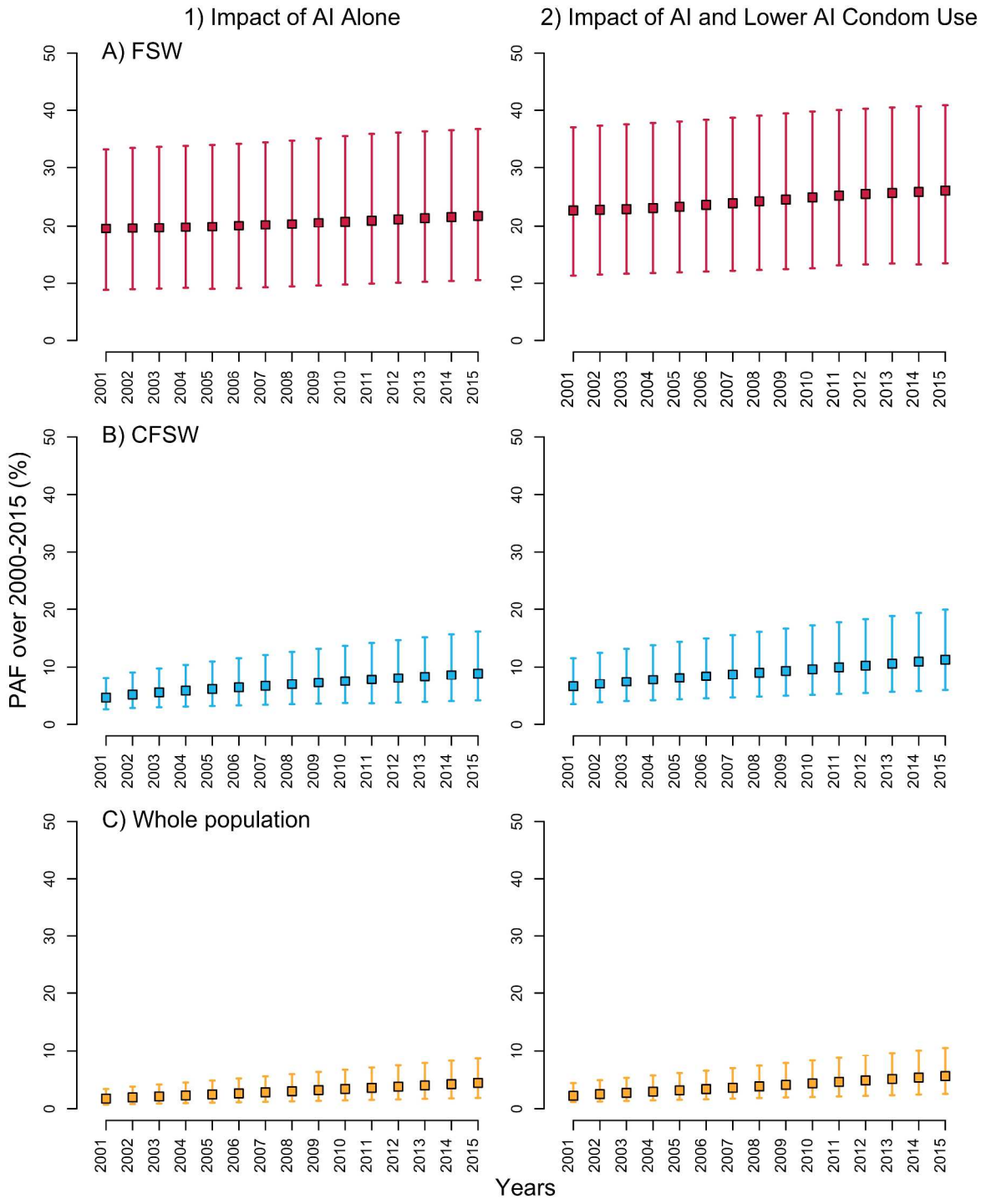


Figure 1: Population Attributable Fraction (PAF) of AI performed during sex work in Côte d'Ivoire for two scenarios: 1) we assumed that anal intercourse (AI) acts performed between female sex workers (FSW) and their clients (CFSW) were substituted by vaginal intercourse (VI) acts leaving condom use as for AI for these VI acts; 2) we assumed that AI acts were substituted with VI acts and that the proportion of sex acts protected by a condom was the same as for VI, (i.e., higher than in the previous scenario. PAF are calculated among A) FSW, B) CFSW, and C) the whole population. Median and 95% credible intervals are presented.

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SUPPLEMENTAL FIGURES, TABLES, AND TEXTS

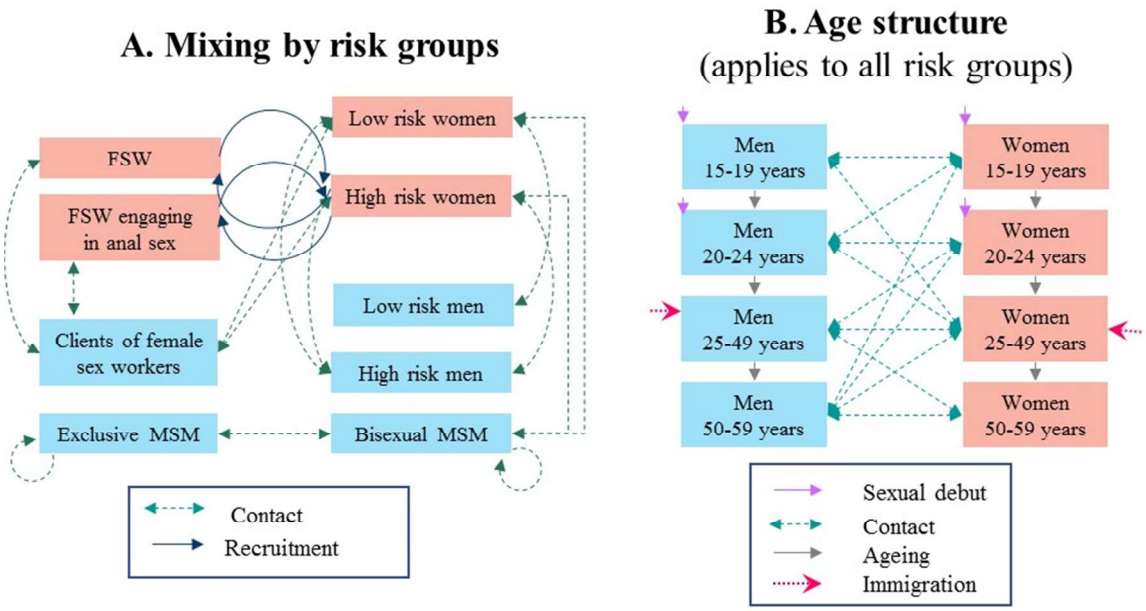


Figure S1: Representation of the different risk (A) and age (B) groups, as well as their contact pattern. Female sex workers (FSW) only have sexual contact with their clients but can retire from sex work, in which case FSW integrates the group of high-risk women. Clients of FSW (CFSW) have sexual contacts with both low- and high-risk women. Women in the low- and high-risk group have sexual contact with all members of the opposite sex with the exception of exclusive men who have sex with men (MSM). Exclusive MSM have sexual contacts with both exclusive MSM and bisexual MSM. With regards to age, sexual debut is either at 15 or 20 years of age for both men and women. Immigration is allowed in the 25-49 year's age group. All age groups have sexual contacts with other age group, except for women in the 50-59 age group that do not have sexual contact with men younger than 25 years old. This mixing by age was informed by data from Demographic and Health Survey (DHS). DHS data was also used to inform mixing between low- and high-risk groups of men and women.

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In the remaining of this appendix, risk groups are indexed from 1 to 9 by subscript k (low-risk women k=1; high-risk women k=2; FSW k=3,4 (k=4 denotes those engaging in anal intercourse); low-risk men k=5, high-risk men k=6, CFSW k=7, bisexual MSM k=8; exclusive MSM k=9) and age group from 1 to 4 by subscript i (15-19 years old: i=1; 20-24 years old: i=2; 25-49 years old: i=3; 50-59 years old: i=4).

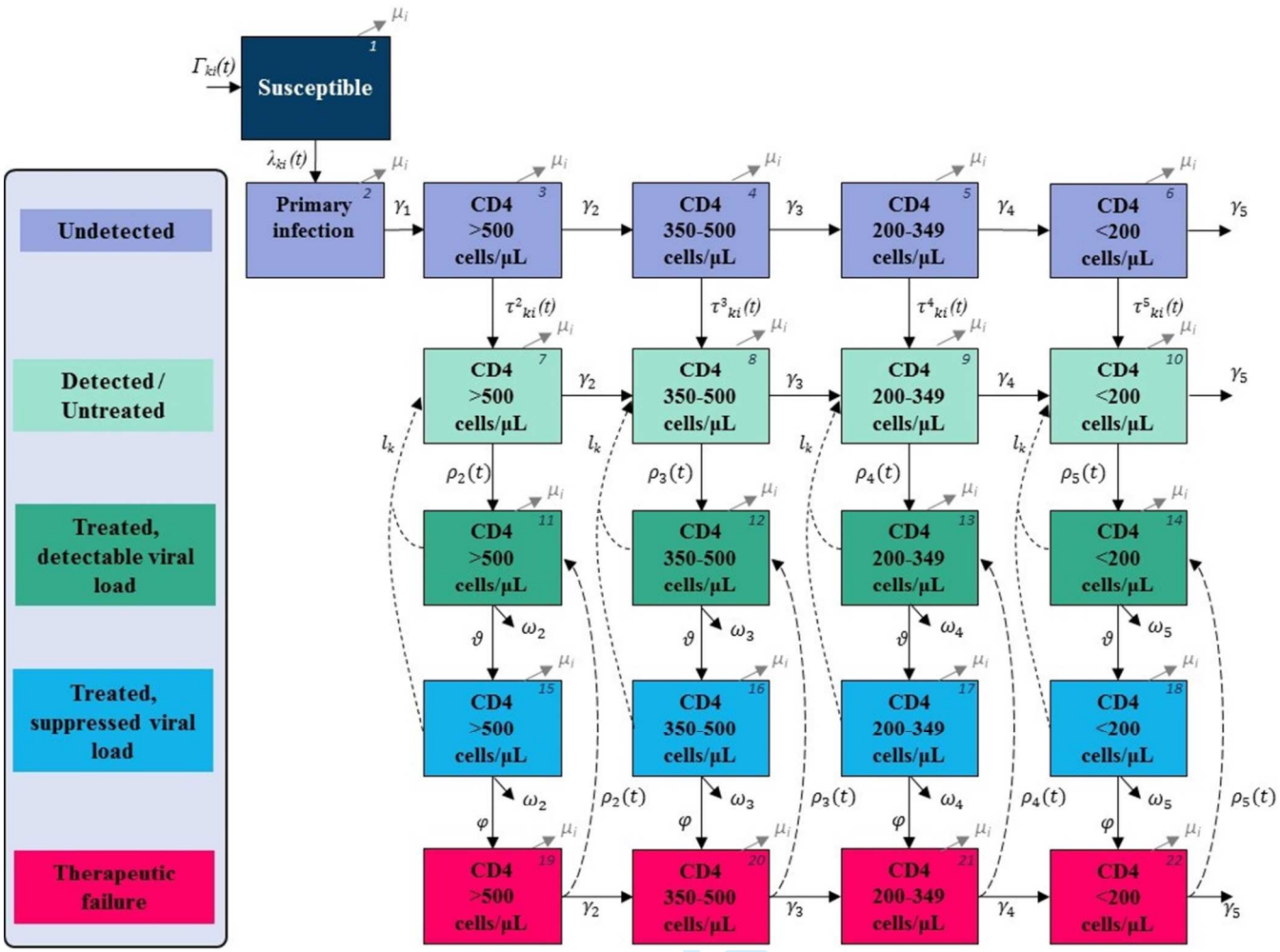


Figure S2. Model structure of HIV transmission, disease progression, and continuum of care. Where $\Gamma_{ki}(t)$ is the rate of entry in the sexually active population for members of risk group k and age class i (i.e., men start their sexually active life later than women and this proportion changes with time); μ_i is the HIV-unrelated background mortality rate for age class i; $\lambda_{ki}(t)$ is the force of infection at time t for individuals in risk group k and age class i; γ_s is the disease progression rate for the different stages of infections (defined by the CD4 levels and indexed by s); $\tau^s_{ki}(t)$ is the testing rate that varies by time, stage of infection, risk group, and age class; $\rho_s(t)$ is the antiretroviral (ART) recruitment rate which is a function of time and disease stage; ϑ is the rate at which individuals on ART become virally suppressed; l_k is the ART discontinuation rate; φ is the rate of therapeutic failures among virally suppressed individuals; and ω_s is the HIV-related mortality rate of individuals on ART that varies by disease stage.

In the remaining of this appendix, the different stages of infections are indexed by "*a*" and "*s*". The exponent "*a*" denotes the testing and ART status: *"0"* for undetected individuals, *"1"* for those tested but untreated, *"2"* for those treated with a detectable viral load, *"3"* for those virally suppressed, and *"4"* for those experiencing therapeutic failures. The second exponent "*s*" described the disease progression according to CD4 cell counts: *"1"* for acute infection, *"2"* for CD4>500 cells/μL, *"3"* for CD4 between 350 and 500 cells/μL, *"4"* for CD4 between 200 and 349 cells/μL, and *"5"* for CD4 <200 cells/μL.

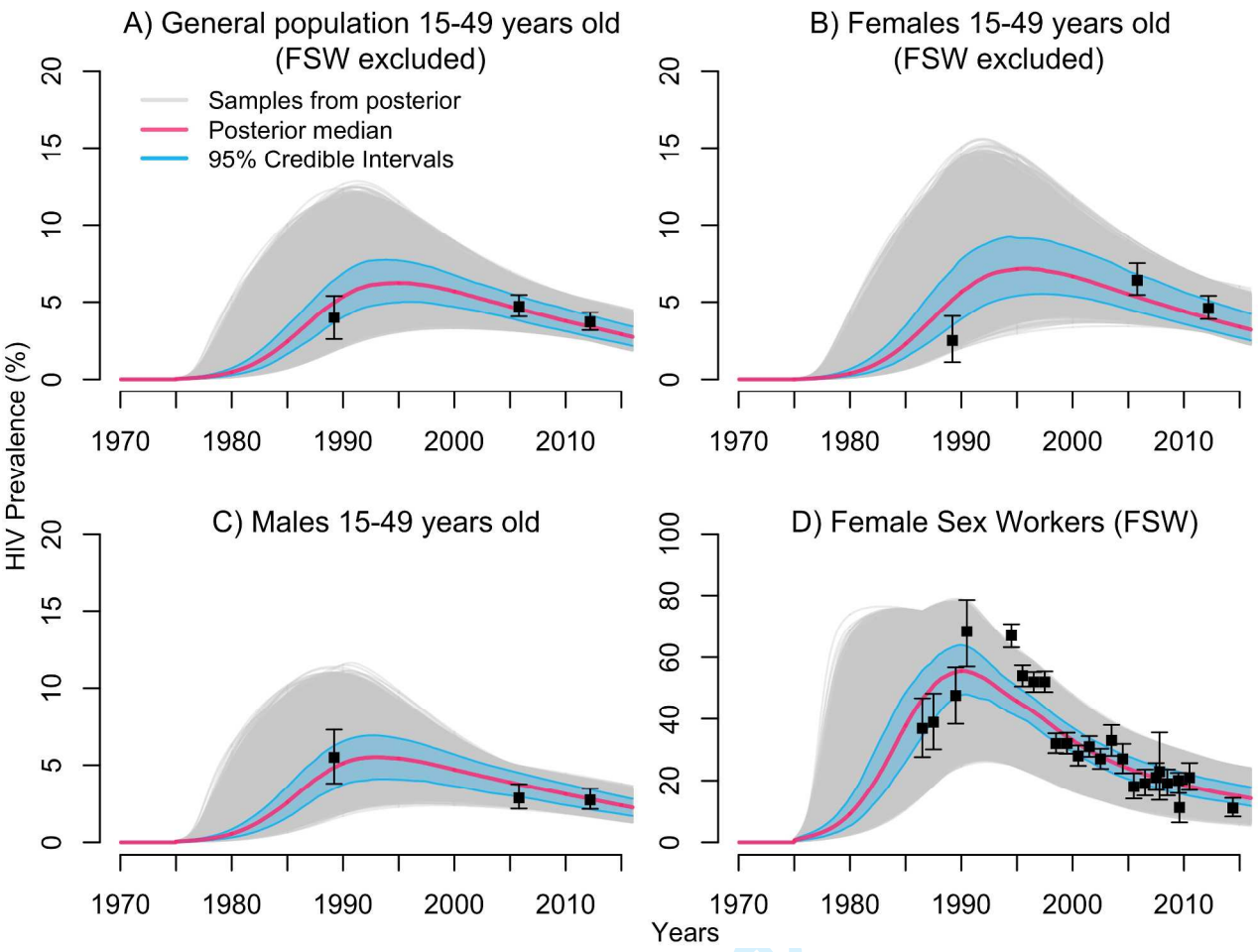


Figure S3: Observed prevalence, to which the model was calibrated to (mean with 95% confidence intervals), and predicted prevalence trends in A) the general population (15-49 years old) of Côte d'Ivoire, B) among females aged 15-49 years old, C) among males aged 15-49 years old, and D) among female sex workers (FSW). In A) and B) FSW are not assumed to be sampled in the household-based HIV prevalence surveys and were excluded in calculating model-based overall prevalence estimates. Incremental Mixture Importance Sampling (IMIS) resulted in 41,146 unique sets of parameters labelled samples from posterior (grey curves). One of these curves were resampled with probability proportional to their importance weights to derive the median (red) and 95% credible intervals (shaded blue area). The specific references for the data points plotted on the figures can be found in Table S8.

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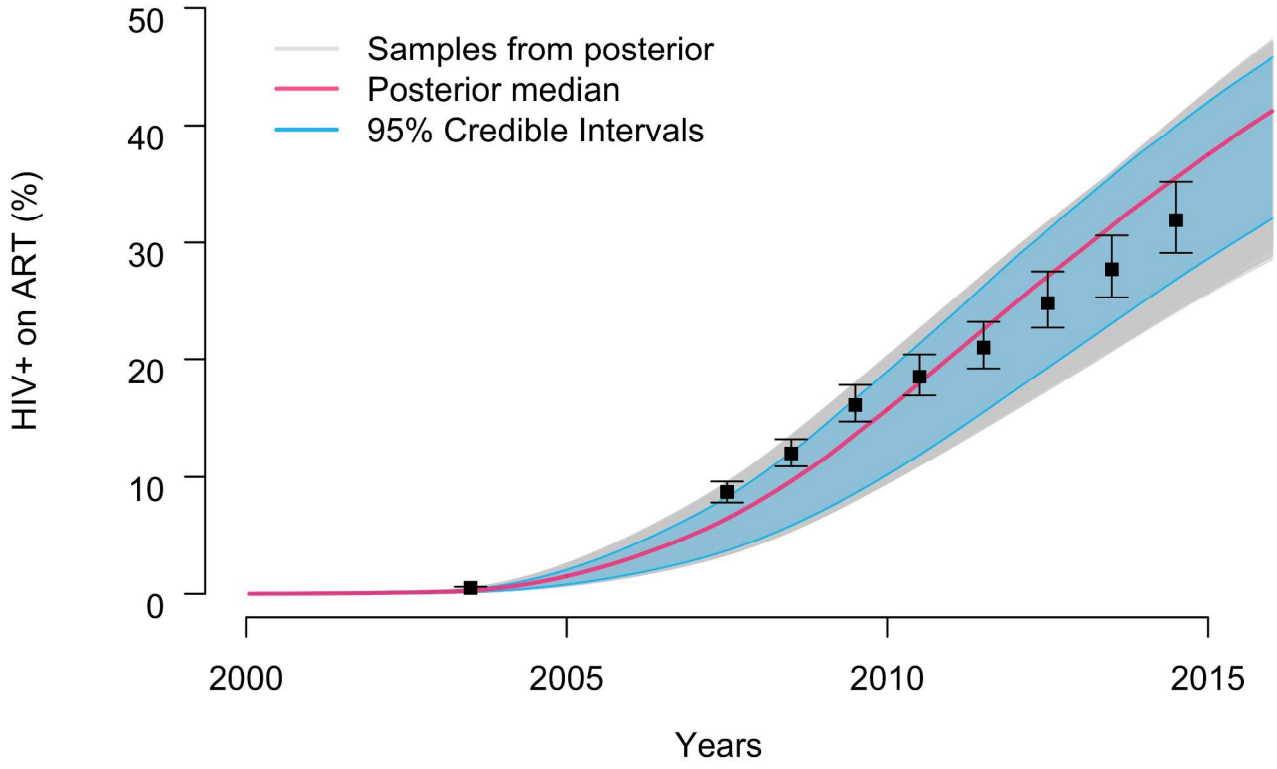


Figure S4: Model predicted ART coverage in Côte d'Ivoire with ART coverage data to which the model was calibrated to. The plotted points refer to UNAIDS estimates of ART coverage which are themselves based on data from the *Direction de l'information, de la planification et de l'évaluation* [1-7] (see Table S8).

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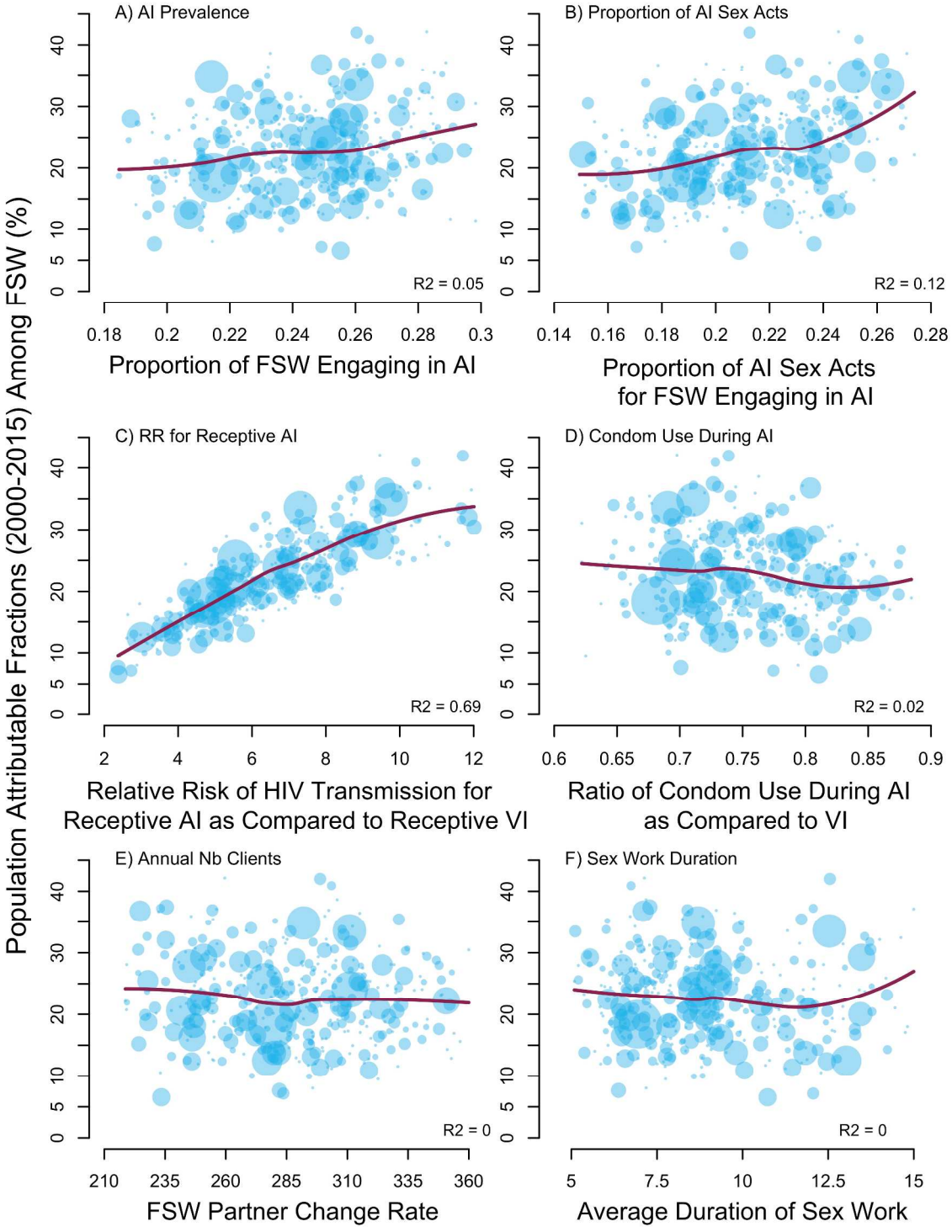


Figure S5: Sensitivity analysis of the impact of different model parameters the population attributable fraction (2000-2015) of anal intercourse (AI) among female sex workers (FSW). The following parameters are presented: A) the proportion of FSW engaging in AI and B) the proportion of sex acts that are AI among FSW engaging in this behavior and C) the relative risk (RR) of HIV transmission for receptive AI as compared to receptive vaginal intercourse (VI), D) the ratio of condom use during AI as compared to VI, E) the FSW partner change rage (per year), and F) the average duration of sex work. The four panels show the estimated population attributable fractions for FSW as a function of the parameters' posterior distribution. (Note: the size of the points is relative to their sampling importance weight.)

Table S1: Demographic parameters and the model's initial conditions.

Parameters	Symbol	Prior distributions	References
Initial conditions			
HIV prevalence in 1975 among FSW (%)	$Seed_{FSW}$	U(0.1%, 1%)	Assumption
HIV prevalence in 1975 among clients of FSW (%)	$Seed_{CFSW}$	U(0.1%, 0.5%)	Assumption
HIV prevalence in 1975 among MSM (%)	$Seed_{MSM}$	U(0.1%, 1%)	Assumption
Total population aged 15-59 years in 1970	N_0	2,711,050	[8]
Demography			
Population growth rate (year^{-1})	ε	0.032	[8]
Immigration rate of 25-49 years old (year^{-1})	χ	U(0.017, 0.029)	[8]
Mortality rate (1/life expectancy at 15, 25, and 50 years)			
15-24 years old (year^{-1})	$\mu_{1:2}$	U(0.020, 0.021)	[8]
25-49 years old (year^{-1})	μ_3	U(0.024, 0.025)	[8]
50-59 years old (year^{-1})	μ_4	U(0.044, 0.046)	[8]
Fertility rate of 15-24 years old (year^{-1})	$ASFR_{1:2}(t)$	Varies with time between 0.328 (1970) to 0.212 (2015)	[8]
Fertility rate of 25-49 years old (year^{-1})	$ASFR_3(t)$	Varies with time between 0.230 (1970) to 0.150 (2015)	[8]
Relative fertility reduction of HIV positive women	RR_{Fert}	T(0.76, 0.60, 0.89)	[9]
Size of sex, age, and risk groups			
Proportion of males in population		51.5%	[8]
Age class distributions			
15-19 years old (%)	PR_A_1	21.0%	[8]
20-24 years old (%)	PR_A_2	17.5%	[8]
25-49 years old (%)	PR_A_2	51.5%	[8]
50-59 years old (%)	PR_A_4	10.0%	[8]
Proportion of virgins females aged 15-19 years old (%) (k=1,2,3,4)	$Vir_k(t)$	1994 = 27.4% 1999 = 35.9% 2005 = 34.2% 2012 = 35.3%	[10] [11] [12] [13]
Proportion of virgins males aged 15-19 years old (%) (k=5,6,7,8,9)	$Vir_k(t)$	1999 = 44.3% 2005 = 48.9% 2012 = 57.3%	[11] [12] [13]
Proportion of high risk (>2 partners year^{-1}) heterosexual males (%)	PR_{HRM}	U(5%, 10%)	[11-13]
Proportion of high risk (>1 partner year^{-1}) heterosexual females (%)	PR_{HRF}	U(5%, 10%)	[11-13]
Proportion of MSM among males (%)	PR_{MSM}	U(0.8%, 1.6%)	[14-16]
Proportion of MSM who are bisexual (%)	PR_{Bi}	U(53.6%, 75.5%)	[17, 18]†
Ratio of FSW to MSM*	R_{FSW}	U(1, 1.7)	[11, 19, 20]
Proportion of FSW that engage in AI (%)	PR_{AI}	U(18.3%, 29.9%)	Based on [21]
Turnover rate from FSW to non-FSW females (year^{-1})	tur	U(1/15, 1/5)	Assumption

AI=anal intercourse; FSW=female sex worker; MSM=men who have sex with men; T(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); U(a,b)=Uniform distribution (a=minimum, b=maximum).
*The proportion of clients of FSW was indirectly estimated using the multiplier method, balancing the partner change rate reported by FSW and by clients of FSW. The proportion of clients of FSW was constrained to be smaller than 20%.
†Parameter informed by the analysis of primary data of respondent-driven sampling surveys conducted in 5 cities of Cote d'Ivoire.

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Table S2: Behavioral parameters.

Parameters	Symbols	Prior distributions or data	References
Partner change rate of sexually active			
Low risk females (year^{-1})	c_1	$U(0.8, 0.9)$	[11-13]
High risk females (year^{-1})	c_2	$U(2.4, 9.4)$	[11-13]
FSW (year^{-1})	$c_{3:4}$	$U(216, 360)$	[22-25]*
Low risk males (year^{-1})	c_5	$U(1.0, 1.2)$	[11-13]
High risk males (year^{-1})	c_6	$U(4.7, 6.8)$	[11-13]
Clients of FSW (with FSW) (year^{-1})	c_7	$U(23, 37)$	[26]
Clients of FSW (with women in the general population) (year^{-1})	c_{7b}	$U(1, 6.8)$	[11-13]
Bisexual MSM (year^{-1})	c_8	$U(1, 10)$	Assumption
Exclusive MSM (year^{-1})	c_9	$U(1, 10)$	[18]
Number of sex acts			
Low risk partners (partnership^{-1} year^{-1}) (k=1,5)	α_{kijl}	$U(40, 48)$	[13]
High risk partners (partnership^{-1} year^{-1}) (k=2,6)	α_{kijl}	$U(33, 66)$	[13]
MSM partners (partnership^{-1} year^{-1}) (k=8,9)	α_{kijl}	$U(33, 66)$	Assumption
Clients-FSW partners (partnership^{-1} year^{-1}) (k=3,4,7)	α_{kijl}	$U(1, 4)$	[13]
Sexual mixing parameters			
Sexual balance parameter as per Garnett et al. 1994 [27]†	η	$U(0, 1)$	Assumption
Fraction of partnerships that are with females for bisexual males (%)	Bi_{Pref}	$U(32\%, 44\%)$	Primary data‡
Tuning parameter between assortative and proportional mixing by age among MSM	MSM_{AgeMix}	$U(0, 1)$	Assumption
Other parameters			
Proportion of sex acts that are anal for FSW that engage in AI (%)	Pr_{ActsAI}	$U(14.8\%, 27.6\%)$	Based on [21, 23]

AI=anal intercourse; CFSW=clients of female sex workers; DHS=Demographic and Health Survey; FSW=female sex worker; MSM=men who have sex with men; U(a,b)=Uniform distribution (a=min, b=max).
*Based on the assumption that FSW engage in sex work 4 days per week, 50 weeks per year.
†CFSW were assumed to drive demand and FSW were de facto assumed to adjust their partner change rate in consequence. For MSM, we assumed that the balance parameter is equal to 0.5.
‡ Parameter informed by the analysis of primary data of respondent-driven sampling surveys conducted in 5 cities of Cote d'Ivoire.

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Table S3: Biological and treatment parameters.

Parameters	Symbols	Prior distributions or data	References
HIV transmission probability			
Female-to-male transmission probability (act^{-1})	β_{fm}	$U(0.00013, 0.00141)$	[28]
Male-to-female transmission probability (act^{-1})	β_{mf}	$U(0.00060, 0.00109)$	[28]
Changes in HIV transmission probability			
RR of HIV acquisition of receptive AI as compared to receptive VI (act^{-1})	RR_{RAI}	$T(10, 2, 20)$	[29]
RR of HIV acquisition of insertive AI as compared to insertive VI (act^{-1})	RR_{IAI}	2	[29]
RR of HIV acquisition for women 15-24 years old as compared to those aged ≥25 years (act^{-1})	$RR_{YoungFem}$	$U(1.25, 2.5)$	[30, 31]
RR of HIV transmission during acute infection (act^{-1})	RR_{Acute}	$T(9.17, 4.47, 18.81)$	[28]
RR of HIV transmission for individuals on ART (detectable viral load) (act^{-1})	RR_{VLD}	$T(0.5, 0.3, 0.8)$	Assumption
RR of HIV transmission for individuals on ART (virally suppressed; <50 copies/μL) (act^{-1})	RR_{ART}	$T(0.04, 0.01, 0.27)$	[32]
RR of HIV transmission when sex act is protected by a condom (act^{-1})	ς	$U(0.75, 0.942)$	[33]
Natural history progression			
Time duration of acute infection (years)	$1/\gamma_1$	$U(0.16, 0.50)$	[34]
Time duration from seroconversion to 350 CD4 cells/μL (years)	$1/\gamma_1+1/\gamma_2+1/\gamma_3$	$U(2.2, 4.6)$	[35]
Time duration from 350 CD4 cells/μL to 200 CD4 cells/μL (years)	$1/\gamma_4$	$U(3.9, 5.0)$	[35]
Time duration from 200 CD4 cells/μL to death (years)	$1/\gamma_5$	$U(1.9, 3.9)$	[35]
Time duration from unsuppressed to suppressed viral load (<50 copies/μL) (years) (probability converted to duration using $1/-ln(1-0.871)$)	ϑ	0.49	[36]
ART			
Survival extension cofactor for individuals on ART (RR)*	RR_{ω}	$U(2, 3)$	[37, 38]
Rate of therapeutic failures ($years^{-1}$)	φ	$U(0.049, 0.09)$	Based on [39, 40]
Rate of ART discontinuation ($years^{-1}$) (probability converted to rate using $-ln(1-P)/t$)	l	$U(0.15, 0.27)$	[2-7]
Relative risk of ART discontinuation for FSW	$RR_{LTFU\text{-}FSW}$	$U(1.25, 1.75)$	[41]
Relative risk of ART discontinuation for MSM	$RR_{LTFU\text{-}MSM}$	$U(1.25, 1.75)$	Assumed equal to that of FSW

AI=anal intercourse; ART=antiretroviral therapy; FSW=female sex worker; MSM=men who have sex with men; RR=relative risk; T(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); U(a,b)=Uniform distribution (a=minimum, b=maximum); VI=vaginal intercourse.

*HIV-related mortality (ω_s) for those on treatment is calculated as followed: $\omega_s=(\Sigma\gamma_s)/RR_{\omega}$.

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Table S4: Parameters used to estimate historical trends in the proportion of sex acts protected by a condom.

Parameters	Symbols	Prior distributions/ ranges or data	References
General population (excluding CFSW, FSW, MSM)			
Among 15-24 years old (%) (Proportion of protected sex acts)	$Condom_{1:2}(t)$	1981 = (0%, 5%)	[42, 43]
		1994 = (9.9%, 47.2%)	[10]*
		1999 = (11.5%, 55.7%)	[11]*
		2005 = (20.9%, 53.5%)	[12]*
		2012 = (20.7%, 59.5%)	[13]*
Among 25-49 years old (%)	$Condom_3(t)$	1981 = (0%, 2.5%)	[42, 43]
		1994 = (2.5%, 21.7%)	[10]*
		1999 = (3.1%, 21.8%)	[11]*
		2005 = (4.7%, 23.8%)	[12]*
		2012 = (7.3%, 24.2%)	[13]*
Among 50-59 years old (%)	$Condom_4(t)$	1981 = (0%, 2.0%)	[42, 43]
		1994 = (0.2%, 9.7%)	[10]*†
		1999 = (0.6%, 9.7%)	[11]*†
		2005 = (0.6%, 10.0%)	[12]*†
		2012 = (1.8%, 11.5%)	[13]*†
Female sex workers with their clients (VI)			
All age groups (%) (Proportion of protected sex acts)	*CondomSW(t)*	1981 = (0%, 5.0%)	Based on [42, 43]
		1991 = (57%, 68%)	[22]
		1993 = (74%, 81%)	[22]
		1995 = (73%, 88%)	[22]
		1997 = (88%, 93%)	[22]
		1998 = (88%, 98%)	[25]
		2002 = (91%, 99%)	[25]
		2007 = (90%, 99%)	[25]
		2011 = (90%, 95%)	[25]
		2014 = (85%, 93%)	[21, 23]
Relative reduction in condom use for FSW AI versus VI			
All age groups (RR)	RR_{CondAI}	T(0.75, 0.61, 0.92)	[21, 23]
Men who have sex with men			
All age groups (%) (Proportion of protected sex acts)	*CondomMSM(t)*	1981 = 0%	Assumption
		2004 = (35%, 50%)	Based on [44]
		2012 = (57%, 69%)	[17]
		2015 = (63%, 81%)	§
Year of condom increase in the 1980s			
General population (k=1,2,5,6)	$DateCond_k$	U(1981,1990)	Assumption
Sex work (k=3,4,7)	$DateCond_k$	U(1981,1990)	Assumption
MSM (k=8,9)	$DateCond_k$	U(1981,1990)	Assumption
Scaling factor for the proportion of sex acts protected by condoms‡			
15-24 years old (general population)	$CondPtl_{1:2}$	U(0, 1)	Assumption
25-49 years old (general population)	$CondPtl_3$	U(0, 1)	Assumption
50-59 years old (general population)	$CondPtl_4$	U(0, 1)	Assumption
FSW (all age groups)	*CondSWPtl*	U(0, 1)	Assumption
MSM (all age groups)	*CondMSMPtl*	U(0, 1)	Assumption

AI=anal intercourse; CFSW=client of female sex worker; FSW=female sex worker; MSM=men who have sex with men; RR=relative risk; T(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); U(a,b)=Uniform distribution (a=minimum, b=maximum); VI=vaginal intercourse.

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*The minimum of the range corresponds to the lower confidence bound of the estimate reported by females and the maximum to the upper confidence bound of the estimate reported by males.
†Only the 2005 AIDS Indicator Survey collected information on men aged 50-59 years old. When unavailable, estimates for this age class were approximated by extrapolating those of the 45-49 years old.
‡The estimates of the proportion of sex acts protected by a condom are sampled for each year using the same percentile of the distribution to longitudinally consistent estimates.
§Parameter informed by the analysis of primary data of respondent-driven sampling surveys conducted in 5 cities of Cote d'Ivoire.

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Table S5: Parameters used to estimate historical trends in HIV testing.

Parameters	Symbols	Prior distributions/ranges or data	References
HIV testing probability (last 12 months) for asymptomatic females (excluding those tested during ANC)*			
Among 15-24 years old (year^{-1})	$\tau_{k1:2}^{0}(t)$	2000 = 0	Based on [45]
(k=1,2)		2005 = (0.011, 0.024)	[12]
		2012 = (0.063, 0.086)	[13]
Among 25-49 years old (year^{-1})	$\tau_{k3}^{0}(t)$	2000 = 0	Based on [45]
(k=1,2)		2005 = (0.018, 0.045)	[12]
		2012 = (0.060, 0.080)	[13]
Among 50-59 years old (year^{-1})	$\tau_{k4}^{0}(t)$	2000 = 0	Assumption
(k=1,2)		2005 = (0.001, 0.027)	[12]†
		2012 = (0.041, 0.080)	[13]†
HIV testing probability (last 12 months) for asymptomatic males*			
Among 15-24 years old (year^{-1})	$\tau_{k1:2}^{0}(t)$	2000 = 0	Based on [45]
(k=5,6,7)		2005 = (0.013, 0.036)	[12]
		2012 = (0.058, 0.097)	[13]
Among 25-49 years old (year^{-1})	$\tau_{k3}^{0}(t)$	2000 = 0	Based on [45]
(k=5,6,7)		2005 = (0.029, 0.054)	[12]
		2012 = (0.089, 0.131)	[13]
Among 50-59 years old (year^{-1})	$\tau_{k4}^{0}(t)$	2000 = 0	Assumption
(k=5,6,7)		2005 = (0.008, 0.029)	[12]†
		2012 = (0.031, 0.081)	[13]†
Proportion of pregnant women accessing ANC and being tested for HIV‡			
Among 15-24 years old (year^{-1})	$ANC\tau_{1:2}(t)$	1999 = 0	Based on [45]
		2005 = (4.6%, 10.9%)	[12]
		2012 = (32.1%, 41.1%)	[13]
Among 25-49 years old (year^{-1})	$ANC\tau_{3}(t)$	1999 = 0	Based on [45]
		2005 = (10.9%, 18.9%)	[12]
		2012 = (36.6%, 44.9%)	[13]
Relative increase in testing rate for different groups			
Symptomatic stage (<200 CD4 cells/μL) (RR)	$Symp_RR_{Test}$	$U(2, 8)$	Assumption
Female sex worker (RR)	FSW_RR_{Test}	$U(1, 4)$	Based on [13, 25]
Men who have sex with men (RR)	MSM_RR_{Test}	$U(1, 4)$	Based on [13, 17]
Scaling factor for HIV testing§			
All age and risk groups (excluding ANC)	$TestPtl$	$U(0, 1)$	Assumption
Pregnant women tested during ANC	$ANCPtl$	$U(0, 1)$	Assumption

ANC=antenatal care; FSW=female sex worker; MSM=men who have sex with men; RR=relative risk; T(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); U(a,b)=Uniform distribution (a=minimum, b=maximum); VI=vaginal intercourse.

*Probabilities of being tested during last 12 months was converted to rate using Rate = -ln(1-Probability)

†Only the 2005 AIDS Indicator Survey collected information on men aged 50-59 years old. When unavailable, estimates for this age class were approximated by extrapolating those of the 45-49 years old.

‡Women aged 50-59 years old are assumed to have fertility rate of zero.

§The estimates for HIV testing rate and proportion of pregnant women tested as part of their ANC are sampled for each year using the same percentile of the distribution to obtain smoother estimates.

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Table S6: Parameters used to estimate historical trends in the availability of interventions for the prevention of mother-to-child transmission.

Parameters	Symbols	Prior distributions/ranges or data	References
Pregnant women tested positive for HIV during ANC receiving ART prophylaxis (%)*			
	$K(t)$	1999 = 0	Assumption
		2002 = (40.5%, 53.4%)	[46]
		2007 = (51.7%, 65.4%)	[7]
		2008 = (37.3%, 62.4%)	[7]
		2009 = (44.2%, 61.5%)	[6]
		2010 = (47.5%, 59.5%)	[5]
		2011 = (53.0%, 60.5%)	[4]
		2012 = (43.4%, 55.8%)	[3]
		2013 = (41.1%, 55.8%)	[2]
		2014 = (49.6%, 66.5%)	[1]
Pregnant women tested positive for HIV during ANC receiving ART treatment (%)†			
	$\Phi(t)$	1999 = 0	Assumption
		2008 = (9.6%, 11.9%)	[7]
		2009 = (10.4%, 10.7%)	[6]
		2010 = (10.7, 13.2%)	[5]
		2011 = (11.9, 14.7%)	[4]
		2012 = (11.9, 14.7%)	[3]
		2013 = (18.8%, 23.2%)	[2]
		2014 = (22.5%, 27.8%)	[1]
Scaling factor for PMTCT coverage‡			
ART prophylaxis	*ARTPxPtl*	$U(0, 1)$	Assumption
ART treatment	*ARTTxPtl*	$U(0, 1)$	Assumption

ANC=antenatal care; ART=antiretroviral therapy; PMTCT=prevention of mother-to-child transmission.
*The lower bound of the confidence interval corresponds to the proportion of infants receiving prophylaxis and the upper bound to the proportion of mothers receiving prophylaxis.
†The bound of the prior distribution were constructed by varying point estimates by ± 10%.
‡The estimates for proportion of pregnant women testing positive for HIV receiving prevention of mother-to-child transmission interventions are sampled for each year using the same percentile of the distribution to obtain smoother estimates.

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Table S7: Parameters used to estimate historical trends in antiretroviral therapy coverage.

Parameters	Symbols	Prior distributions	References
Recruitment rate into ART when symptomatic (<200 CD4 cells/μL) (years-1)	ρ_5	$U(0.5, 4)$	Assumption
Slope cofactor to define linear relation between CD4 stages and recruitment to ART	ι	$U(0, 1)$	Assumption

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Table S8: List of outcomes that the mathematical model was fitted to.

Outcomes	Year	Value	95% CI*	Prior Constraints		References
				Lower limit	Upper limit	
Outcomes included in the likelihood[£] (binomial likelihoods and pre-specified constraints)						
Female HIV prevalence						
15-24 years old	1989†	2.5%	(0.9%-4.4%)	0.0%	13.2%	[47]
	2005	2.4%	(1.6%-3.0%)	0.4%	5.3%	[12]
	2012	2.2%	(1.5%-3.0%)	0.4%	5.3%	[13]
25-49 years old	1989†‡	2.5%	(1.0%-4.3%)	0.0%	13.0%	[47]
	2005	9.9%	(8.4%-12.0%)	2.1%	21.0%	[12]
	2012	6.3%	(5.2%-8.0%)	1.3%	14.0%	[13]
50-59 years old	1989†‡	1.9%	(0.4%-4.4%)	0.0%	13.3%	[47]
	2005‡	10.2%	(6.2%-16.0%)	1.6%	28.0%	[12]
	2012‡	9.5%	(5.7%-15.0%)	1.4%	26.3%	[13]
Male HIV prevalence						
15-24 years old	1989†	2.4%	(0.8%-4.3%)	0.0%	13.0%	[47]
	2005	0.3%	(0.1%-1.0%)	0.0%	1.8%	[12]
	2012	0.3%	(0.1%-1.0%)	0.0%	1.8%	[13]
25-49 years old	1989†‡	7.7%	(5.5%-10.0%)	0.0%	30.1%	[47]
	2005	4.8%	(3.6%-6.0%)	0.9%	10.5%	[12]
	2012	4.3%	(3.3%-5.0%)	0.8%	8.8%	[13]
50-59 years old	1989†‡	1.7%	(0.4%-3.9%)	0.0%	11.7%	[47]
	2005‡	4.9%	(2.4%-10.0%)	0.6%	17.5%	[12]
	2012	8.7%	(5.4%-14.0%)	1.4%	24.5%	[13]
Female sex workers						
	1986†	36.9%	(27.6%-46.7%)	15.0%	75.0%	[48]
	1987†	38.9%	(30.1%-48.2%)	15.0%	85.0%	[48]
	1989†	47.6%	(38.4%-56.7%)	20.0%	90.0%	[48]
	1990†	68.4%	(57.0%-78.6%)	25.0%	95.0%	[48]
	1994	67.0%	(63.2%-70.8%)	25.0%	85.0%	[22]††
	1995	54.0%	(50.5%-57.4%)	20.0%	80.0%	[22]††
	1996	52.0%	(48.7%-55.2%)	20.0%	75.0%	[22] ††
	1997	52.0%	(48.7%-55.4%)	20.0%	70.0%	[22] ††
	1998	32.0%	(28.9%-35.3%)	15.0%	65.0%	[49] ††
	1999	32.0%	(28.7%-35.5%)	15.0%	65.0%	[49] ††
	2000	28.0%	(24.8%-31.4%)	12.5%	55.0%	[49] ††
	2001	31.0%	(27.7%-34.4%)	12.5%	55.0%	[49] ††
	2002	27.0%	(23.8%-30.3%)	12.5%	55.0%	[49] ††
	2003	33.0%	(28.0%-38.0%)	12.5%	55.0%	[50] ††
	2004	27.0%	(22.4%-31.9%)	10.0%	55.0%	[50] ††
	2005	18.0%	(14.1%-22.4%)	7.5%	50.0%	[50] ††
	2006	19.0%	(15.1%-23.6%)	7.5%	50.0%	[50] ††
	2007	21.0%	(16.9%-25.7%)	7.5%	45.0%	[50] ††
	2007	22.9%	(13.7%-35.6%)	7.5%	45.0%	[51]
	2008	19.0%	(15.1%-23.6%)	5.0%	40.0%	[50] ††
	2009	20.0%	(15.9%-22.5%)	5.0%	35.0%	[50] ††
	2009	11.2%	(6.4%-18.9%)	5.0%	35.0%	[51]
	2010	21.0%	(16.9%-25.7%)	5.0%	35.0%	[50] ††
	2014	11.0%	(8.3%-14.3%)	5.0%	25.0%	[21]

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Men who have sex with men						
15-24 years	2012	12.5%	(6.8%-18.2%)	5.0%	25.0%	[17]
	2015	11.4%	(6.6%-19.0%)	5.0%	25.0%	¶
25-49 years	2012	25.8%	(16.7%-34.9%)	15.0%	40.0%	[17]
	2015	16.3%	(7.5%-32.0%)	5.0%	35.0%	¶
Clients of female sex workers						
	1999	13.4%	(6.7%-22.2%)	2.6%	29.9%	[26]‡‡
Outcomes included in the likelihood using pre-specified constraints§						
ART coverage						
Adults (15+)	2003	0.5%	(0.5-0.6%)	0%	6%	[52]
	2007	8.7%	(8-10%)	2%	15%	[7]
	2008	12%	(11-13%)	5%	19%	[7]
	2009	16%	(15-18%)	8%	23%	[6]
	2010	19%	(17-20%)	11%	26%	[5]
	2011	21%	(19-23%)	14%	29%	[4]
	2012	25%	(23-28%)	17%	33%	[3]
	2013	28%	(25-31%)	20%	36%	[2]
	2014	32%	(29-35%)	24%	41%	[1]

*95% CI: 95% confidence intervals.
£The overall likelihood of the model is calculated by summing the binomial log-likelihoods of the relevant model's outcomes and assigning a likelihood of zero if any of the outcomes fall outside any of the pre-specified constraints.
†Surveys were adjusted for imperfect sensitivity and specificity of the diagnostic assays (see[53, 54]).
‡Age categories in the surveys do not exactly match. For the 1989 survey the 25-49 age category corresponds to prevalence of the 25-54 years old and the 50-59 age category correspond to prevalence in the 55-64 years old. For the 2005 AIDS Indicator Survey, the 50-59 age category corresponds to prevalence from the 45-49 years old. For the 2011-12 Demographic and Health Survey, the 50-59 age category for females corresponds to prevalence in females aged 45-49 years old.
¶ Parameter informed by the analysis of primary data of respondent-driven sampling surveys conducted in 5 cities of Cote d'Ivoire. The city-specific prevalence estimates were pooled by weighting each city by its total population.
††These prevalence estimates are from first time attendees of the Clinique de Confiance in Abidjan. A design effect of 5 was applied to obtain an effective sample size in the likelihood calculations to take into account the potentially non-representativeness of these data points.
‡‡Confidence intervals were adjusted for the clustered design of the survey by using the number of cluster (n=84) as the effective sample size.
§ART coverage was not included in the binomial likelihood because this was derived from programmatic data on the number of individuals on ART (numerator) and the number of HIV positive individuals in Côte d'Ivoire estimated by UNAIDS. As such, there was no sample size to use in the binomial likelihood.

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Text S1: Details on sexual mixing patterns

Sexual mixing

Sexual mixing is a function of age, sex, and the risk category of individuals. The probability p_{kijl} of a sexual contact between someone of risk category k and age i with an individual of risk category j and age l is estimated using the following equation:

$$p_{kijl} = WMW_{kj}(M_{kj})\Lambda_{kil}$$

$$WMW_{kj} = \begin{pmatrix} & F_{LR} & F_{HR} & F_{FSW} & F_{FSW_{AI}} & M_{LR} & M_{HR} & M_{CFSW} & M_{BI} & M_{MSM} \\ F_{LR} & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\ F_{HR} & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\ F_{FSW} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ F_{FSW_{AI}} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ M_{LR} & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ M_{HR} & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ M_{CFSW} & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ M_{BI} & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ M_{MSM} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{pmatrix}$$

$$M_{kj} = \begin{pmatrix} & F_{LR} & F_{HR} & F_{FSW} & F_{FSW_{AI}} & M_{LR} & M_{HR} & M_{CFSW} & M_{BI} & M_{MSM} \\ F_{LR} & 0 & 0 & 0 & 0 & 0.91 & \frac{0.09*M_{HR}}{M_{HR+CFSW+Bi}} & \frac{0.09*M_{CFSW}}{M_{HR+CFSW+Bi}} & \frac{0.09*M_{Bi}}{M_{HR+CFSW+Bi}} & 0 \\ F_{HR} & 0 & 0 & 0 & 0 & 0.88 & \frac{0.12*M_{HR}}{M_{HR+CFSW+Bi}} & \frac{0.12*M_{CFSW}}{M_{HR+CFSW+Bi}} & \frac{0.12*M_{Bi}}{M_{HR+CFSW+Bi}} & 0 \\ F_{FSW} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ F_{FSW_{AI}} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ M_{LR} & 0.91 & 0.09 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ M_{HR} & 0.88 & 0.12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ M_{CFSW} & 0.88(1-CFSW_{Mix}) & 0.12(1-CFSW_{Mix}) & CFSW_{Mix}(1-\Pr_{AI}) & CFSW_{Mix}\Pr_{AI} & 0 & 0 & 0 & 0 & 0 \\ M_{BI} & 0.88(Bi_{Pref}) & 0.12(Bi_{Pref}) & 0 & 0 & 0 & 0 & 0 & \Pr_{Bi}(1-Bi_{Pref}) & (1-\Pr_{Bi})(1-Bi_{Pref}) \\ M_{MSM} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Pr_{Bi} & 1-\Pr_{Bi} \end{pmatrix}$$

The binary *WMW* matrix described the types of contacts allowed in the model for the following risk groups: low risk female (F_{LR}), high risk female (F_{HR}), female sex worker (F_{FSW}), female sex worker that practice anal intercourse (F_{FSWAI}), low risk males (M_{LR}), high risk males (M_{HR}), clients of female sex workers (M_{CFSW}), bisexual men who have sex with men (M_{BI}), and exclusive men who have sex with men (M_{MSM}).

The size of the low and high risk groups were defined using data from the 2011-12 Demographic and Health Survey (DHS) based on the number of sexual partners during the last 12 months (F_{HR} defined as >1 partner year^{-1}; M_{HR} defined as >2 partners year^{-1}) [13]. Mixing by risk groups was calculated using these individual-level records for low and high risk males and females. Due to data limitation, mixing by risk groups was only available for couples living in the same household who both agreed to be interviewed and reported complete data on their sexual partners. Because some unions in Côte d'Ivoire are polygamous, mixing by risk group was analyzed from the female perspective. This DHS-reported matrix *M* was expanded to include the other risk groups and their associated parameters: Bi_{Pref} being the fraction of partnerships that are with females for

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bisexual males, Pr_{Bi} the fraction of MSM who are bisexual (implicitly assuming proportional mixing between bisexual and exclusive MSM),, and $CFSW_{Mix}$ the fraction of partnerships that are with FSW for CFSW ($CFSW_{Mix}=c_7/(c_7+c_{7b})$).

Mixing patterns by age (Λ) were informed using data from the 2011-12 DHS [13] for the general population. The data refers to the reported age of the most recent sexual partner among the population that was sexually active in the 12 months preceding the interview. The age mixing matrices differs for males and females. For sex workers and clients, it was assumed that age mixing would correspond to that reported by males in the general population. For MSM, it was assumed that age mixing would be somewhere between completely assortative and proportional mixing using the parameter MSM_{AgeMix}, which was given a non-informative distribution.

$$\Lambda_{kil}=\begin{cases}\begin{pmatrix}0.130 & 0.130 & 0.719 & 0.021\\ 0.130 & 0.130 & 0.719 & 0.021\\ 0.003 & 0.003 & 0.753 & 0.241\\ 0 & 0 & 0.187 & 0.813\end{pmatrix}; & \text{for } k=1,2 \ \ (i \text{ indexes row and } l \text{ columns})\\ \begin{pmatrix}0.483 & 0.483 & 0.035 & 0\\ 0.483 & 0.483 & 0.035 & 0\\ 0.194 & 0.194 & 0.609 & 0.004\\ 0.125 & 0.125 & 0.808 & 0.167\end{pmatrix}; & \text{for } k=3,4,5,6,7\\ (1-MSM_{AgeMix})\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}+MSM_{AgeMix}\begin{pmatrix}0.152 & 0.188 & 0.553 & 0.107\\ 0.152 & 0.188 & 0.553 & 0.107\\ 0.152 & 0.188 & 0.553 & 0.107\\ 0.152 & 0.188 & 0.553 & 0.107\end{pmatrix}; & \text{for } k=8,9\end{cases}$$

The probability of sexual contact is calculated separately for each type of partnership (*kijl)*. Imbalances between demand of sexual partnerships by one group and offer by another group are thus possible. Balance between supply and demand of sexual partnership was achieved by altering the partner change rate (c_{kijl}^{*}) using the methods described by Garnett and Anderson [27] and is described below.

$$\Delta_{kijl}=\frac{c_{jl}p_{jlki}N_{jl}}{c_{ki}p_{kijl}N_{ki}}$$

$$c_{kijl}^{*}=c_{ki}\Delta_{kijl}^{\ \eta_k}$$

$$c_{jlki}^{*}=c_{jl}\Delta_{kijl}^{\ -(1-\eta_k)}$$

where Δ_{kijl} measure the degree of initial imbalance in supply and demand for sexual partnerships of type *kijl* and η_k is the balance parameter that determines the degree to which partners are submissive (i.e., the degree to which they alter their demand/offer of sexual partnership). For clients and FSW, we assumed that clients would drive demand. For MSM, the balance parameter was assumed to be equal to 0.5.

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Text S2: HIV transmission model's ordinary differential equations

The dynamic system formed by the different model's compartments can be represented through 22 differential equations. All susceptible individuals at time t in risk category k and age i are represented by $S_{ki}(t)$. The different stages of infections are indexed by I_{ki}^{as}. The superscript "a" denotes the testing and antiretroviral therapy (ART) status: *"0"* for undetected individuals, *"1"* for those tested but untreated, *"2"* for those treated with a detectable viral load, *"3"* for those virally suppressed, and *"4"* for those experiencing therapeutic failures. The second superscript "s" described the disease progression according to CD4 cell counts: *"1"* for acute infection, *"2"* for CD4>500 cells/µL, *"3"* for CD4 between 350 and 500 cells/µL, *"4"* for CD4 between 200 and 349 cells/µL, and *"5"* for CD4 <200 cells/µL.

1. Susceptible

$$\frac{dS_{ki}(t)}{dt} = E_{ki}(t) + W_i^1 - S_{ki}(t)\sum\nolimits_{jl}\left(\lambda_{kijl}(t)\right) - S_{ki}(t)(\mu_i + Aging_i)$$

$$\frac{dE_{ki}(t)}{dt} = \begin{cases} \left(\begin{array}{l} \sum \mu_1 V_k(t) + \sum\left(\mu_i\left(I_{ki}^{as}(t) + S_{ki}(t)\right)\right) + \gamma_5\left(I_{ki}^{0,5}(t) + I_{ki}^{1,5}(t) + I_{ki}^{4,5}(t)\right) + \\ \sum_{s=2}^{5} I_{ki}^{2,s}(t)\omega_{s-1} + \sum_{s=2}^{5} I_{ki}^{3,s}(t)\omega_{s-1} + \varepsilon\sum\left(I_{ki}^{as}(t) + S_{ki}(t) + V_k(t)\right) + \\ \sum\left(Aging_4\left(I_{k,4}^{as}(t) + S_{k,4}(t)\right)\right) \end{array}\right)(1 - Vir_k(t)); \text{ if } i = 15-19 \text{ years old} \\ V_k(t)Aging_2; \text{ if } i = 20\text{-}24 \text{ years old} \\ \chi\sum\left(I_{ki}^{as}(t)\right); \text{ if } i = 25\text{-}49 \text{ years old} \\ 0; \text{ if } i = 50\text{-}59 \text{ years old} \end{cases}$$

$$\frac{dV_k(t)}{dt} = \left(\begin{array}{l} \sum \mu_1 V_k(t) + \sum\left(\mu_i\left(I_{ki}^{as}(t) + S_{ki}(t)\right)\right) + \gamma_5\left(I_{ki}^{0,5}(t) + I_{ki}^{1,5}(t) + I_{ki}^{4,5}(t)\right) + \\ \sum_{s=2}^{5} I_{ki}^{2,s}(t)\omega_{s-1} + \sum_{s=2}^{5} I_{ki}^{3,s}(t)\omega_{s-1} + \varepsilon\sum\left(I_{ki}^{as}(t) + S_{ki}(t) + V_k(t)\right) + \\ \sum\left(Aging_4\left(I_{k,4}^{as}(t) + S_{k,4}(t)\right)\right) \end{array}\right) Vir_k(t) - V_k(t)(\mu_1 + Aging_1)$$

$E_k(t)$ represents individuals of category k and age class i entering the susceptible compartment at time t. These individuals are those lost by the system at time t_{-1} as a result of background mortality, HIV-related mortality, and exit of sexually active life. Immigration occurs at a rate χ and immigrants are assumed to be aged between 25 and 49 years old. The Côte d'Ivoire population grows at a rate ε. It should be noted that individuals entire the sexual active life either at 15 or 20 years old, according to the proportion $Vir_k(t)$ and $V_k(t)$ are the individuals 15-19 years of age who are not yet sexually active. They do not get infected and cannot die of AIDS but are subjected to the same background mortality rate. Aging rates are stored in the homonymous vector and the aging process is defined the following way.

$$\frac{dAged_{ki}^{a,s}(t)}{dt} = \begin{cases} 0; & \text{if } i\text{=15-19 years old} \\ I_{k(i-1)}^{as}(t)Aging_{(i-1)}; & \text{if } i \neq \text{15-49 years old} \end{cases}$$

$$\text{where } Aging = \left\{\frac{1}{5}, \frac{1}{5}, \frac{1}{25}, \frac{1}{10}\right\}$$

Female sex workers (FSW) will be involved in sex work for a certain period of time before exiting this practice and returning to the group composed of high risk females. This turnover (symbol in tables: *tur*) is denoted by the symbol W_{ki}^c (where c indexes the compartment's number that varies from 1 to 22). It occurs independently of HIV status and disease progression. An equal number of high

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risk females will then enter the FSW risk group to maintain stable the size of the FSW population. The decision tree used to model mother-to-child transmission (described elsewhere [53, 54]) also calculates the number of HIV positive pregnant women that will be tested at time *t* or be given antiretroviral treatment. These women are then attributed to the relevant compartment using the symbol $P_{ki}^{c}(t)$. Finally, immigration into the 25-49 years old age group of infected individuals (assumed undetected and untreated) is denoted by U_{ki}^{as}. These immigrants are assumed to have the same HIV prevalence as observed in Côte d'Ivoire at time *t*.

2. Primary Infection

$$\frac{dI_{ki}^{0,1}(t)}{dt} = Aged_{ki}^{0,1}(t) + S_{ki}(t)\sum_{jl}\left(\lambda_{kijl}(t)\right) + W_{ki}^{2}(t) + U_{ki}^{0,1}(t) - I_{ki}^{0,1}(t)(\gamma_1 + \mu_i + Aging_i)$$

$$U_{ki}^{0,1}(t) = \begin{cases} \chi(\sum_a I_{ki}^{a,1}(t)); & \text{if } i\text{=25-49 years old} \\ 0; & \text{if } i \neq \text{25-49 years old} \end{cases}$$

3. Undetected HIV positive with CD4>500 cell/μL

$$\frac{dI_{ki}^{0,2}(t)}{dt} = Aged_{ki}^{0,2}(t) + I_{ki}^{0,1}(t)\gamma_1 + W_{ki}^{3}(t) + U_{ki}^{0,2}(t) - I_{ki}^{0,2}(t)\left(\tau_{ki}^{1}(t) + \gamma_2 + \mu_i + Aging_i\right) - P_{ki}^{3}(t)$$

$$U_{ki}^{0,2}(t) = \begin{cases} \chi(\sum_a I_{ki}^{a,2}(t)); & \text{if } i\text{=25-49 years old} \\ 0; & \text{if } i \neq \text{25-49 years old} \end{cases}$$

4. Undetected HIV positive with CD4 between 350 and 500 cells/μL

$$\frac{dI_{ki}^{0,3}(t)}{dt} = Aged_{ki}^{0,3}(t) + I_{ki}^{0,2}(t)\gamma_2 + W_{ki}^{4}(t) + U_{ki}^{0,3}(t) - I_{ki}^{0,3}(t)\left(\tau_{ki}^{1}(t) + \gamma_3 + \mu_i + Aging_i\right) - P_{ki}^{4}(t)$$

$$U_{ki}^{0,3}(t) = \begin{cases} \chi(\sum_a I_{ki}^{a,3}(t)); & \text{if } i\text{=25-49 years old} \\ 0; & \text{if } i \neq \text{25-49 years old} \end{cases}$$

5. Undetected HIV positive with CD4 between 200 and 349 cells/μL

$$\frac{dI_{ki}^{0,4}(t)}{dt} = Aged_{ki}^{0,4}(t) + I_{ki}^{0,3}(t)\gamma_3 + W_{ki}^{5}(t) + U_{ki}^{0,4}(t) - I_{ki}^{0,4}(t)\left(\tau_{ki}^{1}(t) + \gamma_4 + \mu_i + Aging_i\right) - P_{ki}^{5}(t)$$

$$U_{ki}^{0,4}(t) = \begin{cases} \chi(\sum_a I_{ki}^{a,4}(t)); & \text{if } i\text{=25-49 years old} \\ 0; & \text{if } i \neq \text{25-49 years old} \end{cases}$$

6. Undetected HIV positive with CD4<200 cells/μL

$$\frac{dI_{ki}^{0,5}(t)}{dt} = Aged_{ki}^{0,5}(t) + I_{ki}^{0,4}(t)\gamma_4 + W_{ki}^{6}(t) + U_{ki}^{0,5}(t) - I_{ki}^{0,5}(t)\left(\tau_{ki}^{2}(t) + \gamma_5 + \mu_i + Aging_i\right) - P_{ki}^{6}(t)$$

$$U_{ki}^{0,5}(t) = \begin{cases} \chi(\sum_a I_{ki}^{a,5}(t)); & \text{if } i\text{=25-49 years old} \\ 0; & \text{if } i \neq \text{25-49 years old} \end{cases}$$

7. Detected/untreated HIV positive with CD4>500 cells/μL

$$\frac{dI_{ki}^{1,2}(t)}{dt} = Aged_{ki}^{1,2}(t) + I_{ki}^{0,2}(t)\tau_{ki}^{1}(t) + l_k(I_{ki}^{2,2}(t) + I_{ki}^{3,2}(t)) + W_{ki}^{7}(t) + P_{ki}^{7}(t) - I_{ki}^{1,2}(t)\left(\rho_2(t) + \gamma_2 + \mu_i + Aging_i\right)$$

8. Detected/untreated HIV positive with CD4 between 350 and 500 cells/μL

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$$\frac{dI_{ki}^{1,3}(t)}{dt} = Aged_{ki}^{1,3}(t) + I_{ki}^{1,2}(t)\gamma_2 + I_{ki}^{0,3}(t)\tau_{ki}^{1}(t) + l_k(I_{ki}^{2,3}(t) + I_{ki}^{3,3}(t)) + W_{ki}^{8}(t) + P_{ki}^{8}(t) - I_{ki}^{1,3}(t)\left(\rho_3(t) + \gamma_3 + \mu_i + Aging_i\right)$$

9. Detected/untreated HIV positive with CD4 between 200 and 349 cells/μL

$$\frac{dI_{ki}^{1,4}(t)}{dt} = Aged_{ki}^{1,4}(t) + I_{ki}^{1,3}(t)\gamma_3 + I_{ki}^{0,4}(t)\tau_{ki}^{1}(t) + l_k(I_{ki}^{2,4}(t) + I_{ki}^{3,4}(t)) + W_{ki}^{9}(t) + P_{ki}^{9}(t) - I_{ki}^{1,4}(t)\left(\rho_4(t) + \gamma_4 + \mu_i + Aging_i\right)$$

10. Detected/untreated HIV positive with CD4 <200 cells/μL

$$\frac{dI_{ki}^{1,5}(t)}{dt} = Aged_{ki}^{1,5}(t) + I_{ki}^{1,4}(t)\gamma_4 + I_{ki}^{0,5}(t)\tau_{ki}^{2}(t) + l_k(I_{ki}^{2,5}(t) + I_{ki}^{3,5}(t)) + W_{ki}^{10}(t) + P_{ki}^{10}(t) - I_{ki}^{1,5}(t)\left(\rho_4(t) + \gamma_5 + \mu_i + Aging_i\right)$$

11. Treated HIV positive, with detectable viral load and CD4>500 cells/μL

$$\frac{dI_{ki}^{2,2}(t)}{dt} = Aged_{ki}^{2,2}(t) + \rho_2(t)(I_{ki}^{1,2}(t) + I_{ki}^{4,2}(t)) + W_{ki}^{11} + P_{ki}^{11}(t) - I_{ki}^{2,2}(t)\left(l_k + \vartheta + \omega_1 + \mu_i + Aging_i\right)$$

12. Treated HIV positive, with detectable viral load and CD4 between 350 and 500 cells/μL

$$\frac{dI_{ki}^{2,3}(t)}{dt} = Aged_{ki}^{2,3}(t) + \rho_3(t)(I_{ki}^{1,3}(t) + I_{ki}^{4,3}(t)) + W_{ki}^{12}(t) + P_{ki}^{12}(t) - I_{ki}^{2,3}(t)\left(l_k + \vartheta + \omega_2 + \mu_i + Aging_i\right)$$

13. Treated HIV positive, with detectable viral load and CD4 between 200 and 349 cells/μL

$$\frac{dI_{ki}^{2,4}(t)}{dt} = Aged_{ki}^{2,4}(t) + \rho_4(t)(I_{ki}^{1,4}(t) + I_{ki}^{4,4}(t)) + W_{ki}^{13}(t) + P_{ki}^{13}(t) - I_{ki}^{2,4}(t)\left(l_k + \vartheta + \omega_3 + \mu_i + Aging_i\right)$$

14. Treated HIV positive, with detectable viral load and CD4<200 cells/μL

$$\frac{dI_{ki}^{2,5}(t)}{dt} = Aged_{ki}^{2,5}(t) + \rho_5(t)(I_{ki}^{1,5}(t) + I_{ki}^{4,5}(t)) + W_{ki}^{14}(t) + P_{ki}^{14}(t) - I_{ki}^{2,5}(t)\left(l_k + \vartheta + \omega_4 + \mu_i + Aging_i\right)$$

15. Treated HIV positive, with undetectable viral load and CD4>500 cells/μL

$$\frac{dI_{ki}^{3,2}(t)}{dt} = Aged_{ki}^{3,2s}(t) + I_{ki}^{2,2}(t)\vartheta + W_{ki}^{15} - I_{ki}^{3,2}(t)\left(l_k + \varphi + \omega_1 + \mu_i + Aging_i\right)$$

16. Treated HIV positive, with undetectable viral load and CD4 between 350 and 500 cells/μL

$$\frac{dI_{ki}^{3,3}(t)}{dt} = Aged_{ki}^{3,3}(t) + I_{ki}^{2,3}(t)\vartheta + W_{ki}^{16}(t) - I_{ki}^{3,3}(t)\left(l_k + \varphi + \omega_2 + \mu_i + Aging_i\right)$$

17. Treated HIV positive, with undetectable viral load and CD4 between 200 and 349 cells/μL

$$\frac{dI_{ki}^{3,4}(t)}{dt} = Aged_{ki}^{3,4}(t) + I_{ki}^{2,4}(t)\vartheta + W_{ki}^{17}(t) - I_{ki}^{3,4}(t)\left(l_k + \varphi + \omega_3 + \mu_i + Aging_i\right)$$

18. Treated HIV positive, with undetectable viral load and CD4<200 cells/μL

$$\frac{dI_{ki}^{3,5}(t)}{dt} = Aged_{ki}^{3,5}(t) + I_{ki}^{2,5}(t)\vartheta + W_{ki}^{18}(t) - I_{ki}^{3,5}(t)\left(l_k + \varphi + \omega_4 + \mu_i + Aging_i\right)$$

19. HIV positive experiencing treatment failure and with CD4>500 cells/μL

$$\frac{dI_{ki}^{4,2}(t)}{dt} = Aged_{ki}^{4,2}(t) + I_{ki}^{3,2}(t)\varphi + W_{ki}^{19}(t) - I_{ki}^{4,2}(t)\left(\gamma_2 + \rho_2(t) + \mu_i + Aging_i\right)$$

20. HIV positive experiencing treatment failure and with CD4 between 350 and 500 cells/μL

$$\frac{dI_{ki}^{4,3}(t)}{dt} = Aged_{ki}^{4,3}(t) + I_{ki}^{3,3}(t)\varphi + I_{ki}^{4,2}(t)\gamma_2 + W_{ki}^{20}(t) - I_{ki}^{4,3}(t)\left(\gamma_3 + \rho_3(t) + \mu_i + Aging_i\right)$$

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21. HIV positive experiencing treatment failure and with CD4 between 200 and 349 cells/μL

$$\frac{dI_{ki}^{4,4}(t)}{dt} = Aged_{ki}^{4,4}(t) + I_{ki}^{3,4}(t)\varphi + I_{ki}^{4,3}(t)\gamma_3 + W_{ki}^{21}(t) - I_{ki}^{4,4}(t)\left(\gamma_4 + \rho_4(t) + \mu_i + Aging_i\right)$$

22. HIV positive experiencing treatment failure and with CD4<200 cells/μL

$$\frac{dI_{ki}^{4,5}(t)}{dt} = Aged_{ki}^{4,5}(t) + I_{ki}^{3,5}(t)\varphi + I_{ki}^{4,4}(t)\gamma_4 + W_{ki}^{22}(t) - I_{ki}^{4,5}(t)\left(\gamma_5 + \rho_5(t) + \mu_i + Aging_i\right)$$

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Text S3: Equations for the force of infection

The force of infection (FOI) is defined as the annual probability of HIV transmission from an individual of risk group *j* and age class *l* to an individual of risk group *k* and age class *i* [55]. Five equations are used to describe the force of infection, depending on partnership and type of sexual contact in the partnership: 1) vaginal female-to-male or 2) vaginal male-to-female, 3) receptive and insertive anal male-to-male, 4) vaginal and anal female-to-male, 4) vaginal and anal male-to-female. The $\lambda_{kijl}(t)$ matrix contains the forces of infection for each partnership combination of category *k/j* and age *i/l*, where the susceptible partner is the one indexed by *ki*.

1) Force of infection for HIV transmission between a female (j) and a male (k).

$$\lambda_{kijl}(t) = c^*_{kijl} p_{kijl} \left[\sum_a^s \left(\left(\frac{I^{as}_{jl}(t)}{\sum_a^s I^{as}_{jl}(t) + S_{jl}(t)} \right) \left(1 - \left(\left(1 - \beta_{fm} R^{as}_{ji} \right)^{\alpha_{kijl}(1-v_{ki}(t))} \left(1 - \beta_{fm} R^{as}_{ji} (1-\varsigma) \right)^{\alpha_{kijl}(v_{ki}(t))} \right) \right) \right) \right]$$

(2) Force of infection for HIV transmission between a male (j) and a female (k).

$$\lambda_{kijl}(t) = c^*_{kijl} p_{kijl} \left[\sum_a^s \left(\left(\frac{I^{as}_{jl}(t)}{\sum_a^s I^{as}_{jl}(t) + S_{jl}(t)} \right) \left(1 - \left(\left(1 - \beta_{mf} R^{as}_{ji} \right)^{\alpha_{kijl}(1-v_{ki}(t))} \left(1 - \beta_{mf} R^{as}_{ji} (1-\varsigma) \right)^{\alpha_{kijl}(v_{ki}(t))} \right) \right) \right) \right]$$

(3) Force of infection for HIV transmission between a male (j) and a male (k).

$$\lambda_{kijl}(t) = c^*_{kijl} p_{kijl} \left[\sum_a^s \left(\left(\frac{I^{as}_{jl}(t)}{\sum_a^s I^{as}_{jl}(t) + S_{jl}(t)} \right) \left(1 - \left(\begin{array}{l} \left(1 - \beta_{fm} Z^{as}_{ji} \right)^{\alpha_{kijl}(1-v_{ki}(t))*0.5} \left(1 - \beta_{fm} Z^{as}_{ji} (1-\varsigma) \right)^{\alpha_{kijl}(v_{ki}(t))*0.5} \\ \left(1 - \beta_{mf} L^{as}_{ji} \right)^{\alpha_{kijl}(1-v_{ki}(t))*0.5} \left(1 - \beta_{mf} L^{as}_{ji} (1-\varsigma) \right)^{\alpha_{kijl}(v_{ki}(t))*0.5} \end{array} \right) \right) \right) \right]$$

(4) Force of infection for HIV transmission between a female (j) and a male (k) who engage in both anal and vaginal intercourse.

$$\lambda_{kijl}(t) = c^*_{kijl} p_{kijl} \left[\sum_a^s \left(\left(\frac{I^{as}_{jl}(t)}{\sum_a^s I^{as}_{jl}(t) + S_{jl}(t)} \right) \left(1 - \left(\begin{array}{l} \left(1 - \beta_{mf} R^{as}_{ji} \right)^{VI_{kijl}(1-v_{ki}(t))} \left(1 - \beta_{mf} R^{as}_{ji} (1-\varsigma) \right)^{VI_{kijl}(v_{ki}(t))} \\ \left(1 - \beta_{fm} L^{as}_{ji} \right)^{AI_{kijl}(1-CondAI(t))} \left(1 - \beta_{fm} L^{as}_{ji} (1-\varsigma) \right)^{AI_{kijl}(CondAI(t))} \end{array} \right) \right) \right) \right]$$

(5) Force of infection for HIV transmission between a male (j) and a female (k) who engage in both anal and vaginal intercourse.

$$\lambda_{kijl}(t) = c^*_{kijl} p_{kijl} \left[\sum_a^s \left(\left(\frac{I^{as}_{jl}(t)}{\sum_a^s I^{as}_{jl}(t) + S_{jl}(t)} \right) \left(1 - \left(\begin{array}{l} \left(1 - \beta_{mf} R^{as}_{ji} \right)^{VI_{kijl}(1-v_{ki}(t))} \left(1 - \beta_{mf} R^{as}_{ji} (1-\varsigma) \right)^{VI_{kijl}(v_{ki}(t))} \\ \left(1 - \beta_{mf} Z^{as}_{ji} \right)^{AI_{kijl}(1-CondAI(t))} \left(1 - \beta_{mf} Z^{as}_{ji} (1-\varsigma) \right)^{AI_{kijl}(CondAI(t))} \end{array} \right) \right) \right) \right]$$

Where c^*_{kijl} is the balanced partner change rate and p_{kijl} is the probability of a sexual contact between an individual of risk category *k* and age class *i* with an individual of risk category *j* and age class *l*. The terms β_{mf} and β_{fm} represent the per act probability of HIV transmission from an infected partner with whom receptive vaginal intercourse (β_{mf}) and insertive vaginal intercourse (β_{fm}) is performed, respectively. The matrix R^{as}_{ji} contains the coefficients for the relative risk of associated

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with different stage of infection (indexed by exponent *a*), treatment (indexed by exponent *s*), or susceptibility of young women (*i*).

For the FOI between two males (Equation 3), two matrices of coefficients are introduced and contains the adjusted relative risk estimates specific to anal intercourse. Z_{ji}^{as} is similar to R_{ji}^{as}, except that it includes coefficient for relative risk that takes into account the increase probability of HIV transmission for receptive anal intercourse. Similarly, the matrix L_{ji}^{as} contains the coefficients for increased relative risk of HIV transmission due to insertive anal intercourse. It was assumed that, within each MSM partnership, half of sex acts would be performed as the receptive partner and the other half as the insertive partner. When both anal and vaginal intercourse are involved in a partnership (Equations 4 and 5), it was assumed that each sexual contact would either involve anal intercourse or vaginal intercourse - but not both.

Condom efficacy was modeled using the term ς, which reduces probability of HIV transmission. The proportion of sex acts protected by a condom is equal to $v_{ki}(t)$ and the number of sex acts between individuals *ki* and *jl* is α_{kijl}. When both vaginal and anal sex acts are involved in a partnership, we divided these sex acts between those that are vaginal ($VI_{kijl}= \alpha_{kijl}*(1-Pr_{ActsAI})$) and anal ($AI_{kijl}= \alpha_{kijl}*Pr_{ActsAI}$). It should be noted that the additive scale was used to calculate the effect of multiple risk factors in matrices R_{ji}^{as}, L^{as}, and Z_{ji}^{as}. This was necessary because the multiplicative risk scale resulted, for some combination of parameters, in per act transmission probability greater than one. This suggested interaction of some risk factors on the multiplicative scale and provided evidence that the additive scale was more appropriate. When the effect was protective (reducing transmission), however, we used the multiplicative scale has not to underestimate the impact of potential intervention. This matrix was calculated as follows:

$$R_{ji}^{as}=\begin{cases} RR_{Acute}; & \text{for } j=(1{:}9);\ i=(1{:}4);\ a=0;\ \text{and } s=1 \\ 1+(RR_{Acute}-1)+(RR_{YoungFem}-1); & \text{for } j=(5{:}8);\ i=(1,2);\ a=0;\ \text{and } s=1 \\ 1; & \text{for } j=(1{:}9);\ i=(1{:}4);\ a=(0,1,4);\ \text{and } s=(2{:}5) \\ RR_{YoungFem}; & \text{for } j=(5{:}8);\ i=(1,2);\ a=(0,1,4);\ \text{and } s=(2{:}5) \\ RR_{VLD}; & \text{for } j=(1{:}9);\ i=(1{:}4);\ a=2;\ \text{and } s=(2{:}5) \\ RR_{VLD}RR_{YoungFem}; & \text{for } j=(5{:}8);\ i=(1,2);\ a=2;\ \text{and } s=(2{:}5) \\ RR_{ART}; & \text{for } j=(1{:}9);\ i=(1{:}4);\ a=3;\ \text{and } s=(2{:}5) \\ RR_{ART}RR_{YoungFem}; & \text{for } j=(5{:}8);\ i=(1,2);\ a=3;\ \text{and } s=(2{:}5) \end{cases}$$

$$Z_{ji}^{as}=\begin{cases} 1+(RR_{Acute}-1)+(RR_{RAI}-1); & \text{for } j=(7{:}9);\ i=(1{:}4);\ a=0;\ \text{and } s=1 \\ 1+(RR_{Acute}-1)+(RR_{YoungFem}-1)+(RR_{RAI}-1); & \text{for } j=7;\ i=(1,2);\ a=0;\ \text{and } s=1 \\ RR_{RAI}; & \text{for } j=(7{:}9);\ i=(1{:}4);\ a=(0,1,4);\ \text{and } s=(2{:}5) \\ 1+(RR_{YoungFem}-1)+(RR_{RAI}-1); & \text{for } j=7;\ i=(1,2);\ a=(0,1,4);\ \text{and } s=(2{:}5) \\ RR_{VLD}RR_{RAI}; & \text{for } j=(7{:}9);\ i=(1{:}4);\ a=2;\ \text{and } s=(2{:}5) \\ RR_{VLD}(1+(RR_{AI}-1)+(RR_{YoungFem}-1)); & \text{for } j=7;\ i=(1,2);\ a=2;\ \text{and } s=(2{:}5) \\ RR_{ART}RR_{RAI}; & \text{for } j=(7{:}9);\ i=(1{:}4);\ a=3;\ \text{and } s=(2{:}5) \\ RR_{ART}(1+(RR_{AI}-1)+(RR_{YoungFem}-1)); & \text{for } j=7;\ i=(1,2);\ a=3;\ \text{and } s=(2{:}5) \end{cases}$$

$$L_{ji}^{as}=\begin{cases} 1+(RR_{Acute}-1)+(RR_{IAI}-1); & \text{for } j=(4,8,9);\ i=(1{:}4);\ a=0;\ \text{and } s=1 \\ RR_{IAI}; & \text{for } j=(4,8,9);\ i=(1{:}4);\ a=(0,1,4);\ \text{and } s=2{:}5 \\ RR_{VLD}RR_{IAI}; & \text{for } j=(4,8,9);\ i=(1{:}4);\ a=2;\ \text{and } s=2{:}5 \\ RR_{ART}RR_{IAI}; & \text{for } j=(4,8,9);\ i=(1{:}4);\ a=3;\ \text{and } s=2{:}5 \end{cases}$$

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Text S4: Details on the estimation of historical trends in the proportion of sex acts protected by a condom, HIV testing, and antiretroviral therapy coverage.

Proportion of sex acts protected by a condom

Few estimates on the proportion of sex acts protected by condom ($v_{ki}(t)$)were available during the 1980s. We used data from the 1980-81 World Fertility Survey (WFS) as an approximation of the baseline proportion of condom-protected sex acts [42, 43]. The next estimates available are from the early-to-mid 1990s, depending on the risk groups. The latter being considerably higher than reports found in the 1980-81 WFS. Because of the uncertainties associated with the timing of increases in condom use, the model was parameterized using a uniform prior distribution for the date of condom use increase between 1981 and 1990 ($DateCond_k$). Independent distributions were used for the following groups: general population, FSW, and MSM. Because each estimate of condom use had it associated uncertainty and to maintain temporal consistency, the following quantities were computed for each date were data was available, the following quantities were computed by uniformly sampling a percentile of the uniform distribution for all time points (Figure A).

$$v_{ki}(t) = \begin{cases} Condom_i(t) * CondPtl; & \text{for } k=(1,2,5,6,7) \\ CondomSW(t) * CondSWPtl; & \text{for } k=(3,4) \\ CondomMSM(t) * CondMSMPtl; & \text{for } k=(8,9) \end{cases}$$

Date of condom increase during the 1980s

$$v_{ki}(DateCond_k) = v_{ki}(1981)$$

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$$CondAI(t) = v_4(t) * RR_{CondAI}$$

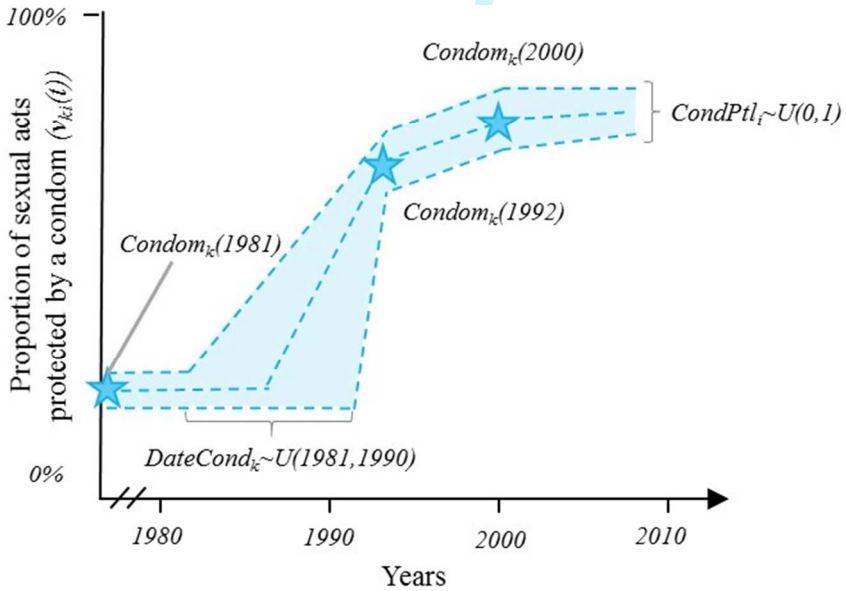


Figure A: Schematic representation of historical trends estimation of the proportion of sex acts protected by a condom. The stars represent data points from which survey estimates are available. These are sampled by using the same percentile ($CondPtl_i$) of their uniform distributions. No data points are available from 1981 to 1990s and condom use during that period rose rapidly. The specific date of increase remains unknown,

however. This uncertainty was taken into account by maintaining fixed the proportion of sex acts protected by a condom until a specific date has been reached ($DateCond_k$), date after which condom use increases.

Finally, a shape-preserving cubic piecewise interpolation was used to estimate the proportion of sex acts protected by a condom for the years were this information was not available. Extrapolation beyond the last available estimate (i.e., the 2011-12 Demographic and Health Survey) was achieved by assuming that this estimate would remain constant.

HIV testing

The first population-based survey that collected information on HIV testing was conducted in 2000 [45]. It only recorded if women reported having ever been tested for HIV and it was not possible to know if it was as part of antenatal care visits (ANC). The survey's results show that 3.9% and 6.0% of women had ever been tested for HIV among the 15-24 and 25-49 years old, respectively. We therefore conservatively assumed testing rates of zero for men and women before 1996. The 2005 AIDS Indicator Survey and 2011-12 Demographic and Health Survey were used to inform testing rate and proportion of pregnant women accessing ANC and being tested [12, 13]. Probability of being tested for HIV during last year were converted to rate using the following formula: *Rate = -ln(1-Prob)*. Testing for each risk and age categories were computed as followed for each date were data was available:

$$\tau_{ki}^{s}(t) = \begin{cases} \tau_{ki}^{0}(TestPtl); & \text{for } k=(1,2,5,6,7) \text{ and } s=(2,3,4) \\ \tau_{ki}^{0}(Symp_RR_{Test})Test; & \text{for } k=(1,2,5,6,7) \text{ and } s=5 \\ \tau_{ki}^{0}(FSW_RR_{Test})TestPtl; & \text{for } k=(3,4) \text{ and } s=(2,3,4) \\ \tau_{ki}^{0}(1+(FSW_RR_{Test}-1)+(Symp_RR_{Test}-1))TestPtl; & \text{for } k=(3,4) \text{ and } s=5 \\ \tau_{ki}^{0}(MSM_RR_{Test})TestPtl; & \text{for } k=(8,9) \text{ and } s=(2,3,4) \\ \tau_{ki}^{0}((1+(MSM_RR_{Test}-1)+(Symp_RR_{Test}-1))TestPtl; & \text{for } k=(8,9) \text{ and } s=5 \end{cases}$$

HIV testing for pregnant women as part of ANC visits were calculated as follow (this is the marginal probability of ANC attendance and of being tested for HIV):

$$\delta_i(t) = ANC\tau_i * ANCPtl$$

HIV testing rates and probability of being tested for pregnant women were both interpolated using a shape-preserving cubic piecewise algorithm. Because programmatic data [1-7] suggested a sustained increased in HIV testing rates beyond 2012, we extrapolated the trends observed during the 2005-2012 period.

Antiretroviral therapy

The UNAIDS initiative's pilot phase for treatment access was officially launched in Côte d'Ivoire in November of 1997 and was supposed to provide ART to 4000 individuals [56]. In August of 1998, the Minister of Health announced at a press conference that ART would become effectively accessible at the end of that month. At that time, the only individuals benefiting from free/subsidized ART in Côte d'Ivoire were those enrolled in clinical trials. From August 1998 to March 2000, 422 patients enrolled in the Retro-CI project were able to access ART [56]. In May of 2002, it is reported that 703 patients had obtained ART in Côte d'Ivoire [56]. Ministry of Health data indicated that a total of 3,190 individuals received ART from 1998 to 2002 [57]. For the purpose of the modeling exercise, it was assumed in the model that individuals could receive ART after 2000. Comprehensive data on the number of people receiving ART was abstracted from government reports for the years 2002 and from 2007 to 2014 [1-7].

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Precise quantification of ART coverage scale-up and differential recruitment into ART according to CD4 cell counts is difficult. ART eligibility criteria were expanded in 2012 to include all patients with a CD4≤350 cells/µL or with WHO stage 4 clinical disease [58] but the country has yet to adopt the new WHO guidelines [59]. Further, CD4 cells counts are not believed to have been widely available in Côte d'Ivoire [2]. A flexible approach was therefore adopted. Specifically, we assumed that ART coverage would increase at a rate corresponding to the ratio of number of individuals on ART at time *t* to the number of individuals on ART in 2014. The parameter *σ(t)* is used to identify availability of ART at time *t* and linearly varied (as suggested by data on ART coverage) from 0 in 2000, to 0.018 in 2003 (2399/133143), to 1 in 2015. Individuals with low CD4 cell counts (i.e., <200 CD4 cells/µL) could be more likely to exhibit clinical symptoms and, thereby, to be recruited on ART. A linear relation was thus assumed between CD4 count stage and recruitment rate using parameter ι. This parameter was given a non-informative prior, uniformly distributed between 0 and 1 so that lower CD4 cell counts had higher recruitment rate. The model was calibrated using the <200 CD4 cells/µL stage as the referent category. For this stage, it was assumed that the recruitment rate into ART (in 2014) would be between 0.5 and 4 years (ρ_5). Recruitment rate was hence modeled using the following equation:

$$\rho_s(t) = \rho_s \sigma(t)$$

$$where$$

$$m = \left((0 - \rho_5)/9.25\right)\iota$$

$$\rho_4 = 3m + \rho_5$$

$$\rho_3 = 6m + \rho_5$$

$$\rho_2 = 9m + \rho_5$$

$$\iota \sim U(0,1)$$

$$\rho_5 \sim U(0.5,4)$$

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Anal intercourse among female sex workers in Côte d'Ivoire: prevalence, determinants, and model-based estimates of the population-level impact on HIV transmission

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ABSTRACT

Current evidence suggests that anal intercourse (AI) during sex work is common in sub-Saharan Africa, but few studies investigated the contribution of heterosexual AI to HIV epidemics. Using a respondent-driven sampling survey of female sex workers (FSW) in Abidjan (2014), we estimated AI prevalence and frequency. Poisson regressions were used to identify AI determinants. About 20% of FSW (N=466) engaged in AI during a normal week (95% confidence intervals: 15-26%). Women who performed AI were generally younger, had been selling sex for longer, were born in Côte d'Ivoire, reported higher sex-work income, more frequent sex in public places, and violence from clients than women not reporting AI. Condom use was lower, condom breakage/slippage more frequent, and use of water-based lubricants was less frequently reported for AI than for vaginal intercourse (VI). Using a dynamic transmission model, we estimated that 22% (95% credible intervals: 11-37%) of new HIV infections could have been averted among FSW during 2000-2015 if AI had been substituted for VI acts. Despite representing a small fraction of all sex acts, AI is an underestimated source of HIV transmission. Increasing availability/uptake of condoms, lubricants, and pre-exposure prophylaxis for women engaging in AI could help mitigate HIV risk.

Keywords: Anal sex; Ivory Coast, Female sex worker; HIV/AIDS; Mathematical model; Respondent-driven sampling; West Africa

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Female sex workers (FSW) share a disproportionately high burden of HIV worldwide (1). This results from an intertwined sets of behavioral, biological, and socio-structural factors that enhance their vulnerability to HIV acquisition (2). Although sex work intersects with injecting drug use in some settings, the primary mode of HIV acquisition and transmission for FSW is thought to be vaginal intercourse (VI). Insertive, and receptive anal intercourse (AI) in particular, carry a well-recognized heightened risk of HIV transmission as compared to VI (3, 4), which does not substantially differ between male-female and male-male contacts (5, 6). Paradoxically, the role of heterosexual AI in HIV epidemics seems to have been minimized in prevention, assuming that AI contributes little to HIV transmission despite growing evidence that this behavior is quite common among heterosexual men and women of all ages (7-9). An emerging body of work also suggests that AI during sex work is ubiquitous and reported by FSW across sub-Saharan Africa, with lifetime prevalence estimates of AI ranging from 6-41% (10).

Collecting reliable information on AI prevalence, its frequency, and its determinants are key to design more effective HIV prevention efforts. Targeted interventions among high-risk populations, such as FSW performing receptive AI, could be an effective way to further curb HIV transmission (11). Specifically, evidence suggests that condom use during AI is lower and breakage more frequent than during VI (3, 12-14). Studies have also associated substance abuse, sexual violence, and coercion to AI practices (10, 15-17). These factors could further enhance HIV transmission during AI and understanding these vulnerability patterns remains important to prevention efforts.

Even though sex work is a recognized risk factor for HIV, the specific population-level impact of heterosexual AI on HIV transmission, and particularly during sex work, has rarely been studied. Recent studies show that that the contribution of sex work to overall HIV transmission in

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Côte d'Ivoire is important (18, 19). Yet, the specific impact of receptive and insertive AI performed by FSW and clients, respectively, on population-level HIV transmission remains unknown. Even if only a small proportion of individuals practice AI during commercial sex, this impact could also extend beyond FSW-clients partnerships through further sexual mixing of clients with women not engaging in sex work.

With the ultimate goal of improving prevention strategies towards FSW, this paper addresses two separate objectives. First, a respondent-driven sampling (RDS) survey conducted among FSW in Côte d'Ivoire was analyzed to estimate AI prevalence, its frequency, and to identify the determinants of this practice. Second, the population-level impact of AI during sex work on HIV transmission was estimated for Côte d'Ivoire using a dynamic transmission model. This will enable us to assess the contribution of AI to the HIV epidemic and help inform prevention activities.

METHODS

Study design and population

A cross-sectional RDS survey was conducted among FSW in Abidjan (Côte d'Ivoire) during March-July 2014. The survey collected information on HIV prevalence, sexual behaviors, reproductive health, and engagement in HIV prevention and treatment services. The study design and recruitment procedure have been described elsewhere (20, 21). Briefly, RDS is a network-based technique used to sample hard-to-reach populations (22). The technique starts with a convenience sample of 'seeds' who then further recruit members of this population using a chain-referral procedure (23). Five seeds were selected in Abidjan and each participant could recruit a maximum of three FSW until the target sample size, based on convergence of HIV prevalence, was met (N=466). Eligibility criteria for participation were being assigned female at birth, being

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over 18 years of age, reporting more than half of income from sex work, and having resided in Abidjan for the past three months.

Structured questionnaires were administered face-to-face by trained interviewers in French or English. With respect to sexual behaviors, participants were asked during a "normal week" how many sexual partners they usually have (including clients and non-paying partners), the number of VI and AI acts performed, and frequency of condom use in the last year for VI and AI. Women were then asked the number of new clients, regular clients, and non-paying partners with whom they had VI and AI during the last month. From this set of questions, we estimated AI prevalence and frequency during a "normal week", and AI prevalence during last month. AI prevalence during last year was indirectly derived from the question about condom use during AI over the last 12 months. If women had not practiced AI during the last year, this was recorded in the questionnaire using the 'not applicable' response option. Self-reports of clinical sexually transmitted infection (STI) diagnosis in the last 12 months were also collected.

Upon completion of the questionnaire, a trained nurse provided HIV counselling and testing. HIV status was determined using a testing algorithm composed of three rapid tests (Determine, HIV 1/2 STAT-PAK®, and Genie® III) (20).

Statistical analyses

Descriptive statistics are presented both as crude and adjusted estimates based on RDS sampling weights (i.e., RDS-II) (24). Confidence intervals were calculated for crude and adjusted estimates by clustering the standard errors at the recruiter level.

To examine determinants of AI, univariate and multivariable Poisson regression models were used to estimate prevalence ratios. Weekly prevalence of AI was chosen as the outcome because it had no missing value and was directly measured in the questionnaire (AI during last

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year was indirectly ascertained). Potential determinants of AI that had few missing values and were accurately measured, and for which an association with AI was previously reported or was deemed plausible were considered. These include: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, education level, country of birth, marital status, religion, having sex with clients in public places, sharing of earnings with someone providing a service for sex work, drug consumption in last year, excessive alcohol drinking, clients using violence/force in last year to have certain types of sexual intercourse, knowledge that AI carries the highest HIV risk, and consistent condom use for VI during last year. Clustering of participants by recruiter was taken into account using Generalized Estimating Equations and an exchangeable correlation structure (25). Continuous independent variables were entered in the model using natural cubic splines with two degrees of freedom (26). Observations with missing values for the covariates were removed from the analyses (n=5).

The association between AI exposure and HIV prevalence or STI was also examined for different exposure definitions. Given the lack of balance between covariates between those reporting and not reporting AI, nearest neighbor matching on the Mahalanobis distance was applied (27). We matched on covariates based on our a priori knowledge of potential confounders. These include: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, consistent condom use during the last year for VI, country of birth, marital status, performing sex work in public places, and excessive alcohol consumption. Results from both un-matched and matched Poisson regressions are presented. All statistical analyses were performed using the R statistical software (28) and relevant analytic packages (29-32).

Modeling population-level impact of anal intercourse on HIV transmission

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An age-stratified dynamic model of HIV transmission was developed for Côte d'Ivoire and calibrated to local epidemiological and programmatic data (33, 34). The model represents an open population of sexually active individuals stratified by age (15-19, 20-24, 25-49, and 50-59 years). Behavioral heterogeneity is incorporated in the model through the following mutually-exclusive groups: low-risk females, high-risk females (>1 partner year^{-1}), FSW not practicing AI, FSW practicing AI, low-risk males, high-risk males (>2 partners year^{-1}), clients of FSW, bisexual men who have sex with men (MSM), and exclusive MSM.

In this model, the force of HIV infection depends on: number and type of sexual partners and associated HIV prevalence, infectiousness (which varies by disease stage, ART treatment status, and viral suppression), sexual mixing between age and risk groups, the fraction of condom-protected sexual acts, and the uninfected partner's susceptibility. For the latter, we assumed that young women have higher risk of HIV acquisition (35, 36) and that insertive/receptive AI also increases susceptibility. Specifically, receptive AI increased risk of HIV transmission by a factor varying between 2 and 20 as compared to receptive VI, and insertive AI by a factor of 2 as compared to insertive VI (4). Based on the proportion of FSW reporting AI during the last year in the RDS survey, women entering the sex trade are assumed to either engage in AI at a certain frequency or not until they retire from sex work (recruitment in/out of sex work is independent of age).

The model was parameterized following a comprehensive review of the scientific and grey literature. Because we modeled HIV transmission in Côte d'Ivoire from the 1970s onwards, other FSW surveys were also used to parametrize and calibrate the model. The full list of model parameters can be found in appendix (Tables S1-S7). Uncertainty associated with the model's parameters was captured through the elicitation of prior distributions. The model was then

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calibrated to HIV prevalence and coverage of antiretroviral therapy (Table S8) using a Bayesian framework with Incremental Mixture Importance Sampling (37). Further information on sexual mixing patterns (Text S1), the model's equations (Texts S2-S3), the estimation of historical trends in condom use, HIV testing, and ART coverage (Text S4), and selected model fits are presented as supplementary material (Figures S3-S4).

The contribution of AI performed by FSW with their partners on HIV transmission was estimated using the Population Attributable Fraction (PAF) calculated over the 2000-2015 period. The PAF is the proportion of cumulative number of new HIV infections occurring over a certain time period that would not have been acquired had the risk factor (i.e., the excess risk of AI versus VI) been removed. This was achieved by setting the relative risk of insertive/receptive AI versus VI to one. In other words, we assumed that AI acts were substituted with VI acts. Two scenarios were investigated: first the impact of AI alone was considered; second, the PAF also took into account the lower condom use during AI by increasing condom use to the same fraction as for VI.

Ethics

All women were informed about the study procedures and provided written informed consent before the interview. The study was approved following ethical review by the *Comité national d'éthique et de la recherche* in Côte d'Ivoire, the *Johns Hopkins School of Public Health Institutional Review Board* in the United States of America, and the *Imperial College Research Ethics Committee* in the United Kingdom.

RESULTS

The five seeds recruited 593 women of which 466 met the eligibility criteria and consented participation. The average age of participants was 27 years old (ranging between 18

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and 57 years old). The majority of FSW were born in Côte d'Ivoire, had some secondary education, and had been selling sex for an average of 6 years (Table 1).

RDS-adjusted estimates of prevalence and frequency of anal intercourse

About 20% of FSW reported performing AI during a normal week (95% confidence intervals [CI]: 15-26%; Table 1). This increased slightly to 24% (95%CI: 18-30%) if the recall period extends to the last month and 24% (95%CI 18-30%) over the last 12 months, suggesting relative consistency of AI practice over the course of a year. Among all FSW, the average frequency of AI was 1.9 (95%CI: 0.8-2.9) acts per week compared to 32 (95%CI: 28-37) VI acts per week, resulting in 4% (95%CI: 2-6%) of all sex acts being AI. If restricted to FSW reporting AI on a weekly basis, the fraction of all sex acts that are AI reaches 21% (95%CI: 15-28%). Knowledge that AI carries the highest sexual HIV risk was only 6% (95%CI: 4-9%).

Among FSW who engaged in AI during last year, 82% (95%CI: 70-90%) reported often or always using a condom during VI, compared to 59% (95%CI: 46-71%) during AI (28% never used a condom during AI; 95%CI: 18-41%). Condom breakage/slippage during the last month was more frequently reported by women having engaged in AI in the last month: 38% (95%CI: 25-53%) for those reporting AI compared to 21% (95%CI: 15-29%) for those not reporting it. This could be due to the fact that use of appropriate water-based lubricants are less frequently reported for AI (9%; 95%CI: 5-17%) than for VI (27%; 95%CI: 21-33%). In Abidjan, the average price for VI protected by a condom was $8 USD (95%CI: $7-10) compared to an average price almost three times higher without condom ($25; 95%CI: $19-30). Condom-protected AI was about twice as expensive as condom-protected VI ($20 USD; 95%CI: $14-26). Condomless AI was the priciest ($27; 95%CI: $19-36).

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AI was commonly and similarly reported with all partner types: AI prevalence during last month was 13% (95%CI: 9-18%) with new clients, 13% (95%CI: 10-18%) with regular clients, and 14% (95%CI: 10-19%) with non-paying partners (Table 2). Consistent condom use for VI, however, varied markedly by partner type and was much lower during AI for both new and regular clients, and similarly low with non-paying partners (Table 2).

Determinants of anal intercourse during normal week

In univariate analyses, most variables were associated with weekly AI prevalence (Table 3). After adjustment for potential confounders, results from the multivariable regression show that AI declines with age but increases with time since first paid sex. There was also a positive association between reports of weekly AI and income from sex work. Women born outside of Côte d'Ivoire were 80% less likely to report AI than those born in the country (Prevalence Ratio [PR]=0.20; 95%CI: 0.05-0.86). Women who have sex with clients in public spaces (PR=2.20; 95%CI: 1.50-3.24) and women reporting sexual violence from clients (PR=1.75; 95%CI: 1.20-2.56) were more likely to report AI than those who did not report such experiences.

Association between anal intercourse, HIV, and STI

Women who reported performing AI during a normal week were less likely to test positive for HIV (5.7% HIV positive; 95%CI: 1.9-16.0%) than those that do not perform AI (12.6% HIV positive; 95%CI: 8.4-18.0%). However, when using exposure to AI over longer recall periods, the estimates became closer to the null value (Table 4). After matching on potential confounders to minimize imbalances, exposure to AI reported over the past month or last year was positively associated, albeit not significantly, with testing HIV positive. AI was not associated with reports of having been diagnosed with an STI but all the effect size measures had large confidence intervals.

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Population-level impact of AI performed by female sex worker on HIV transmission

Selected model parameters, their prior distribution, and the posterior distributions are summarized in Table 5. The posterior median size of the FSW population was 1.6% (Credible Interval [CrI]: 1.1-2.2%) of the female population aged 15-59 years old. The posterior fraction of FSW engaging in AI and the proportion of AI sex acts for this group had medians of 25% (95%CrI: 20-29%) and 21% (95%CrI: 15-26%), respectively. Finally, the posterior median of the relative risk of receptive AI, versus receptive VI, was 6.3 (95%CrI: 3.0-11.1) (it was fixed at 2 for insertive AI).

The fraction of new HIV infections due to AI among FSW over 2000-2015 was estimated at 22% (95%CrI: 11-37%) if we assumed that condom use remains unchanged for these AI acts (Figure 1). Among clients, this PAF was estimated at 9% (95%CrI: 4-16%) for the same period. Overall, if all AI acts performed by FSW were replaced by VI acts, a total of 4% (95%CrI: 2-9%) of new HIV infections would have been averted at the population level over the 2000-2015 period (Figure 1). Because condom use is lower for AI than for VI, PAF can also be computed by replacing all AI acts with VI acts and protecting them with condom at the same rate as for VI acts. Doing so, the PAF estimates are slightly higher with 26% (95%CrI: 13-41%) of new HIV infections averted among FSW, 11% (95%CrI: 6-20%) among CFSW, and 6% (95%CrI: 3-11%) in the whole population.

DISCUSSION

As many as a fifth of FSW in Abidjan reported practicing AI on a weekly basis and about a fourth did so during the last year. FSW reported practicing AI with all partner types in relatively equal proportions. Among those practicing AI, anal sex accounted for about 21% of their weekly sex acts. This meant that about 22% of new HIV infections in FSW may be due to

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AI and could have been averted if VI had been practiced instead. At the population-level, even if FSW constitute 1.6% (95%CrI: 1.1-2.2%) of the female population and only 3-7% of all sex acts performed by FSW are AI, we estimated that AI practiced during sex work could account for 4% (95%CrI: 2-9%) of all new HIV infections during 2000-2015. This estimate does not consider women not engaging in sex work that do engage in AI and should be considered conservative.

The prevalence of AI observed here are consistent with those from other studies of FSW in sub-Saharan Africa (10). We found that women born outside of Côte d'Ivoire were less likely to report AI than those born in the country but religion was not associated. Our results also suggest that young women, those having sex in public spaces, and those who have been selling sex for longer were the most likely to practice AI - highlighting a heightened pattern of vulnerability. Sexual violence and coercion have often been associated with AI (10, 15, 17, 38) and FSW reporting sexual violence by clients in Abidjan were 75% more likely to have engaged in AI. If AI is performed in a context of sexual violence, the HIV risk posed by this practice could be higher since traumatic abrasions of the rectal mucosa can facilitate transmission (10, 39). On the other hand, AI was also reported by women who had higher weekly income and the price charged for AI was more than twice that of VI. Given such financial incentives, AI may not always be performed in a coercive context. Reflecting low awareness of HIV risk associated with AI, condom use was low with 28% of women never using condom during AI.

In this cross-sectional sample of FSW, we did not find any consistent associations between AI reports and HIV prevalence. First, AI practice was measured over short time-periods and our exposure measurements may not reflect this behavior at the time of HIV infection. Second, the lack of association could be due to unmeasured confounders. Third, there were strong covariate imbalances between women engaging in AI and those who did not. Matching was used

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to alleviate this issue but the resulting matched sample sizes for these analyses were small, leading to wide confidence intervals. Findings from cross-sectional studies on the association between AI and HIV prevalence were also found to be inconsistent in a recent review (10). Prospective studies of the effect of sexual risk behaviors on HIV incidence are more appropriate to determine causality and there is indeed strong empirical evidence that AI enhances HIV risk (6). A recent meta-analysis of per-act probabilities of HIV transmission for unprotected receptive AI found them to be substantially higher than those of male-to-female VI (6).

Our results need to be interpreted in light of a number of limitations. First, estimating AI prevalence among FSW is challenging for several reasons: the practice can be stigmatized, is often taboo, and the AI questions can be misunderstood. This can affect the accuracy of self-reports and AI can potentially be underestimated due to social desirability bias (6). Further, AI could be underreported in face-to-face interviews such as the one conducted in this study (10). Second, these challenges are further compounded by difficulties related to selecting representative samples of FSW, which are hard-to-reach and marginalized populations. This, along with the characteristics of the different survey instruments, could explain why FSW in our sample generally report higher number of sexual acts than previous studies in Côte d'Ivoire (40-42). ~~Further, AI could be underreported in face-to-face interviews such as the one conducted in this study (10).~~ Third, the dynamic model used to assess the population-level impact of AI on HIV transmission assumed that AI behaviors are constant over time and do not change as long as the women are~~is~~ involved in sex work. Given the cross-sectional nature of this survey, disentangling cohort and period effects on AI prevalence would have been challenging, however. A sensitivity analysis, examining the influence of different parameters on the PAF estimates nevertheless showed that the most important source of parameter uncertainty was not AI

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prevalence, frequency, or condom use during AI but the relative risk of receptive AI versus receptive VI (Figure S5). Finally, our results do not account for other modes of HIV transmission such as through ~~parenteral~~ blood exposures. This is unlikely to affect our PAF estimates, however, since injecting drug use is uncommon in Abidjan (43) and unsafe medical injections are~~is~~ nowadays believed to account for a small proportion of incident HIV infections in sub-Saharan Africa (44-47). However, this assumption has been challenged in the past (48-50) and necessitates ongoing surveillance to assess prevalence of unsafe injections and ultimate parenteral HIV acquisition risk in Côte d'Ivoire.

The study's strengths include the detailed characterization of AI practice and quantification of the population-level of AI during sex work on HIV transmission. The high PAF observed for AI among FSW suggest potential opportunities for further targeted interventions. Specifically, this study highlighted that both condom use during AI and knowledge of HIV risk associated with AI among FSW in Côte d'Ivoire are low.

In conclusion, AI is commonly practiced among FSW and their partners in Côte d'Ivoire. Despite consisting of only a small fraction of total sex acts performed by FSW, AI is an important and underappreciated factor for HIV acquisition and transmission in this group. More attention should be paid to this risk factor in product development and prevention. Transmission risk associated with AI could be mitigated through increased condom use and promotion of appropriate water-based lubricants to reduce condom breakage during AI. Given both the important financial incentives associated with condomless AI and the context of violence/coercion associated with this practice, this could prove challenging, however. In such instances, the use of pre-exposure prophylaxis for women engaging in AI could be considered.

AUTHOR CONTRIBUTION

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DD, KA, SB developed the questionnaire and oversaw data collection. MCB and MMG formulated the research questions and designed the study. JFV, MCB, and MMG developed the mathematical model. JFV and MMG implemented the coding. MA, MMG and SD gathered programmatic and epidemiological data to inform model parameters. MMG fitted the model, performed the statistical analyses, and interpreted the results. MMG wrote the paper while DD, KA, JFV, MA, MCB, SB, and SD critically reviewed it. All authors have read and approved the final version of the paper.

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Table 1: Characteristics of surveyed female sex workers in Abidjan, Côte d'Ivoire in 2014 (n=466, unless stated otherwise).

Characteristics	Crude Estimates (95%CI)	RDS-Adjusted Estimates (95%CI)
Socio-demographic characteristics		
Age (years)	28 (27-28)	27 (26-28)
Country of birth		
Côte d'Ivoire	76% (70-81%)	80% (74-86%)
Nigeria	23% (18-29%)	18% (13-25%)
Other	2% (1-3%)	1% (1-3%)
Education		
No school / Outside System / Other	18% (15-22%)	20% (15-27%)
Some or completed primary	33% (29-38%)	39% (32-45%)
Incomplete secondary	43% (38-48%)	37% (30-43%)
Completed secondary or higher	6% (5-9%)	5% (3-8%)
Currently married	7% (4-10%)	7% (4-12%)
Religion (1 missing value)		
Muslim	13% (10-17%)	13% (8-19%)
Christian	77% (72-81%)	78% (70-83%)
Other	10% (8-14%)	10% (7-14%)
Sex work characteristics		
Age at first paid sex (years)	22 (21-22)	20 (19-21)
Time since first paid sex (years)	6 (5-7)	7 (6-8)
Has sex with clients in public places	18% (15-22%)	19% (14-25%)
Number of sexual partners per normal week*	31 (27-34)	32 (27-36)
Number of VI/AI sex acts per week†		
Frequency of VI per normal week	32 (29-35)	32 (28-37)
Frequency of AI per normal week	1 (1-2)	2 (1-3)
Prevalence of AI†		
During a normal week	19% (15-23%)	20% (15-26%)
During last month (14 missing values)	21% (18-26%)	24% (18-30%)
During last year§	22% (18-26%)	24% (18-30%)
Proportion of weekly sex acts that are AI	3% (2-4%)	4% (2-6%)
Proportion of weekly sex acts that are AI among FSW that report weekly AI (N=86)	17% (14-21%)	21% (15-28%)
Knowledge that AI carries the highest HIV risk (1 missing value)	5% (4-8%)	6% (4-9%)
Condom use over last year†		
VI: Never used for VI	0% (0-2%)	0% (0-1%)
Almost never used for VI	1% (0-2%)	1% (0-5%)
Sometimes used for VI	8% (6-11%)	10% (6-14%)
Often used for VI	52% (47-56%)	57% (50-63%)
Always used for VI	39% (34-44%)	33% (27-39%)
AI: Never used for AI (N=100; 1 missing value)	32% (24-42%)	28% (18-41%)
Almost never used for AI	1% (0-7%)	1% (0-5%)
Sometimes used for AI	17% (11-26%)	12% (7-22%)
Often used for AI	21% (14-30%)	30% (18-45%)
Always used for AI	29% (22-38%)	29% (19-42%)
Average price charged per act (USD)‡		
VI with condom (N=464; 1 missing value)	$8 ($7-9)	$8 ($7-10)
VI without condom (N=178; 2 missing values)	$28 ($23-33)	$25 ($19-30)
AI with condom (N=73; 1 missing value)	$25 ($17-33)	$20 ($14-26)
AI without condom (N=53; 1 missing value)	$33 ($22-43)	$27 ($19-36)

AI=anal intercourse; VI=vaginal intercourse; 95%CI=95% Confidence Interval.

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*Includes new clients, regular clients, and non-paying partners with whom vaginal, anal, or oral intercourse was performed.
†With any partner types.
‡Exchange rate 1 CFA = 0.002 USD
§One women who did not report AI during last year but who did so during a normal week was recoded as having performed AI during last year since the question about AI during normal week was directly asked.

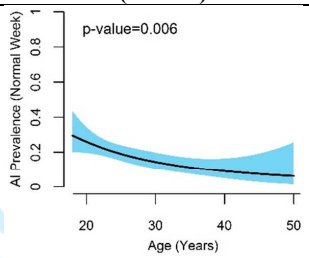
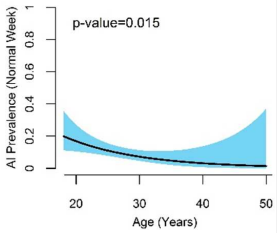
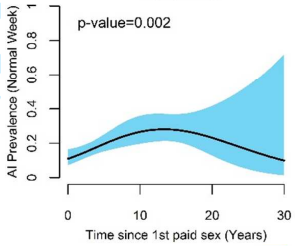
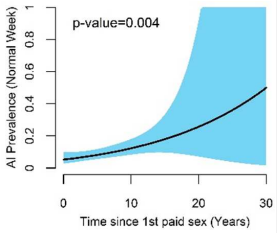
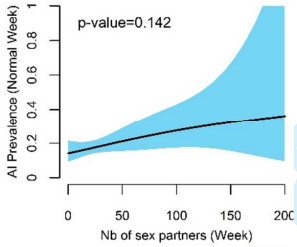
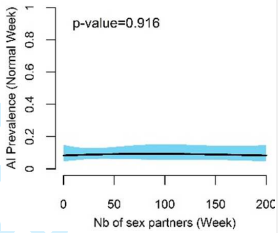
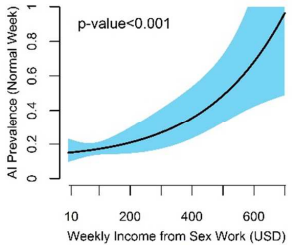
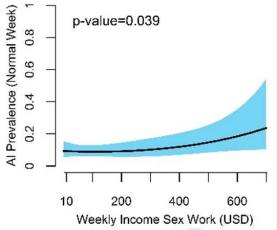
Table 2: Prevalence and frequency of vaginal/anal intercourse and consistent condom use during last month among Abidjan's female sex workers by partner type.

Characteristics	Crude Estimates (95%CI)	RDS-Adjusted Estimates (95%CI)
With new clients (N=463)		
Fraction reporting AI (5 missing value)	12% (9-15%)	13% (9-18%)
Consistent condom use for VI (7 missing values)	77% (73-81%)	75% (68-80%)
Consistent condom use for AI (N=55; 0 missing value)	49% (36-62%)	47% (30-65%)
Condom use at last VI or AI (6 missing values)	87% (84-90%)	89% (85-93%)
With regular clients (N=461)		
Fraction reporting AI (1 missing value)	14% (11-18%)	13% (10-18%)
Consistent condom use for VI (3 missing values)	67% (62-72%)	64% (57-70%)
Consistent condom use for AI (N=65; 0 missing value)	37% (27-49%)	36% (22-53%)
Condom use at last VI or AI (1 missing values)	82% (78-85%)	80% (73-85%)
With non-paying partners (N=451)		
Fraction reporting AI (5 missing values)	11% (9-14%)	14% (10-19%)
Consistent condom use for VI (36 missing values)	5% (4-8%)	4% (2-7%)
Consistent condom use for AI (N=50; 1 missing value)	8% (3-20%)	5% (1-17%)
Condom use at last VI or AI (1 missing value)	13% (10-17%)	13% (9-18%)

AI=anal intercourse; VI=vaginal intercourse; 95%CI=95% Confidence Interval.

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Table 3: Determinants of anal intercourse (during normal week) among female sex workers in Abidjan, Côte d'Ivoire in 2014 (n=461). (Poisson regression models with robust/clustered standard errors.)

Characteristics	PR (95%CI)*	aPR (95%CI)*
Age†		
Time since first paid sex†		
Weekly number of sex partners†		
Weekly income from sex work†		
Education		
No education	Referent	Referent
Some/completed primary	1.34 (0.77-2.35)	0.96 (0.57-1.60)
Secondary or higher	0.79 (0.45-1.38)	0.89 (0.54-1.49)
Foreign-born	**0.08 (0.02-0.30)**	**0.20 (0.05-0.86)**
Currently married (vs. not/formerly married)	0.15 (0.02-1.18)	0.20 (0.03-1.24)
Religion		
Muslim	Referent	Referent
Christian	1.04 (0.53-2.05)	1.17 (0.61-2.25)
Other	1.60 (0.70-3.64)	1.23 (0.58-2.61)
Has sex with clients in public places	**3.90 (2.76-5.52)**	**2.20 (1.50-3.24)**

Share earnings with someone who provides a service for sex work	**1.63 (1.10-2.42)**	0.97 (0.63-1.51)
Consumed drugs in last year	**2.38 (1.51-3.76)**	1.19 (0.74-1.92)
Consumed >6 alcoholic drinks in one occasion every week	**2.12 (1.43-3.14)**	0.96 (0.63-1.46)
Clients used violence/force to have certain types of sexual intercourse (last year)	**2.66 (1.82-3.90)**	**1.75 (1.20-2.56)**
Knows that AI carries the highest HIV risk	**1.51 (0.76-3.02)**	1.07 (0.61-1.89)
Consistently used a condom for VI during last year	**0.32 (0.18-0.56)**	0.61 (0.35-1.06)

PR=Prevalence Ratio; aPR=adjusted Prevalence Ratio; 95%CI=95% Confidence Interval.
Multivariable results are mutually adjusted for all variables listed in the table. A complete case analysis was used and 5 observations with missing values were removed.
*Estimates are adjusted for clustering of standard errors by recruiter (RDS-weights were not incorporated).
†Natural cubic spline with 2 degrees of freedom (95%CI represented by the shaded area; p-value based on Wald statistics).

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Table 4: Association between exposure to anal intercourse and HIV prevalence and reports of having diagnosed with a sexually transmitted infection (STI) in the last 12 months in a cross-sectional sample of female sex workers of Abidjan, Côte d'Ivoire. Poisson regression model with robust/clustered standard errors are used.

Anal Intercourse	Un-Matched Regressions		Matched Regressions†	
	Univariate PR (95%CI)	Multivariable* aPR (95%CI)	Matched AI/no AI	aPR (95%CI)
Outcome: HIV prevalence				
AI during normal week (n=451)	0.38 (0.14-1.01)	**0.46 (0.23-0.95)**	85 / 63	0.41 (0.13-1.25)
AI during last month (n=438)	0.51 (0.22-1.18)	0.79 (0.42-1.48)	94 / 69	1.18 (0.48-2.89)
AI during last year (n=451)	0.67 (0.33-1.35)	0.77 (0.42-1.41)	100 / 75	1.08 (0.43-2.70)
Outcome: Diagnosed by a doctor/health worker in the last 12 months with a STI				
AI during normal week (n=462)	1.28 (0.82-2.02)	0.93 (0.58-1.49)	84 / 63	1.07 (0.58-1.95)
AI during last month (n=448)	1.10 (0.69-1.76)	0.79 (0.48-1.29)	95 / 68	0.97 (0.52-1.79)
AI during last year (n=462)	1.09 (0.70-1.72)	0.85 (0.54-1.34)	99 / 75	0.99 (0.54-1.81)

PR=Prevalence Ratio; aPR=adjusted Prevalence Ratio; 95%CI=95% Confidence Interval; STI=sexually transmitted infection (includes: syphilis, gonorrhea, chlamydia, herpes, human papillomavirus, hepatitis B, hepatitis C, and other).

Estimates are adjusted for clustering of standard errors by recruiter identification (RDS-weights were not incorporated).

*Multivariable models are adjusted for the following covariates: age (natural spline with 2 degrees of freedom (dof)), time since first paid sex (natural spline 2 dof), weekly number of sexual partners (natural spline 2 dof), weekly income from sex work (natural spline with 2 dof), consistent condom use during last year for VI, country of birth (Côte d'Ivoire vs other), marital status (married vs other), having sex with clients in public spaces, and having consumed more than 6 alcoholic drinks in one occasion every week or more often.

†Women reporting AI were matched using a nearest neighbor matching algorithm based on minimizing the Mahalanobis distance to the following covariates: age, time since first paid sex, weekly number of sexual partners, weekly income from sex work, consistent condom use during last year for VI, country of birth, marital status, having sex with clients in public places, and having consumed more than 6 alcoholic drinks in one occasion every week or more often.

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Table 5: List of main parameters used in the mathematical model, elicited prior distributions, and posterior distributions following model calibration to epidemiological and intervention coverage data.

Parameters	Prior distribution	Posterior median with 95% CrI	Reference for priors
Demographics			
Proportion of FSW among females (%)*	*U*(0.8-1.7%)**U*(1.0-1.7)	1.6% (1.1-2.2%)	(51-56)
Proportion of CFSW among men (%)†	<20%	15% (10-19%)	
Turnover rate from FSW to non-FSW females ($year^{-1}$)	*U*(0.05, 0.20)	0.11 (0.07-0.18)	Assumption
Behavioral parameters			
FSW partner change rate ($year^{-1}$)	*U*(216, 360)	284 (225-348)	(40, 42, 57, 58)
CFSW partner change rate ($year^{-1}$)	*U*(23, 37)	31 (24-36)	(59)
CFSW partner change rate with women not working the sex trade ($year^{-1}$)	*U*(1.0, 6.8)	5.4 (3.6-6.5)	(56, 60, 61)
Number of sex acts per client-FSW partnership ($partnership^{-1}$ $year^{-1}$)	*U*(1, 4)	2.5 (1.7-3.4)	(61)
HIV transmission probability			
Female-to-male transmission probability (act^{-1})	*U*(0.013%, 0.141%)	0.089% (0.056-0.128%)	(5)
Male-to-female transmission probability (act^{-1})	*U*(0.060%, 0.109%)	0.089% (0.063-0.106%)	(5)
Changes in HIV transmission probability			
RR of HIV acquisition for women 15-24 years old as compared to those aged ≥25 years (act^{-1})	*U*(1.25, 2.5)	2.0 (1.5-2.5)	(35, 36)
RR of HIV transmission during acute infection (act^{-1})	*T*(9.2, 4.5, 18.8)	8.6 (5.6-12.6)	(5)
RR of HIV transmission for individuals on ART (detectable viral load) (act^{-1})	*T*(0.5, 0.3, 0.8)	0.5 (0.4-0.7)	Assumption
RR of HIV transmission for individuals on ART (virally suppressed) (act^{-1})	*T*(0.04, 0.01, 0.27)	0.12 (0.03-0.22)	(62)
RR of HIV transmission when sex act is protected by a condom (act^{-1})	*U*(0.75, 0.94)	0.83 (0.77-0.91)	Based on (63)
Condom use			
Proportion of protected sex acts by FSW with clients (selected years)	1991 = *U*(57%,68%)	62% (58-67%)	(40)
	2014 = *U*(85%,93%)	88% (86-92%)	(20, 57)
AI parameters			
Proportion of FSW that engage in AI (%)	*U*(18.3-29.9%)	25% (20-29%)	Our analysis
Proportion of sex acts that are anal for FSW that engage in AI (%)	*U*(14.8-27.6%)	21% (15-26%)	Our analysis
RR of HIV acquisition of receptive AI as compared to receptive VI (act^{-1})	*T*(10, 2, 20)	6.3 (3.0-11.1)	(4)
RR of HIV acquisition of insertive AI as compared to insertive VI (act^{-1})	2	2	(4)
Relative reduction in the proportion of protected sex acts AI versus VI§	*T*(0.75, 0.61, 0.92)	0.75 (0.66-0.85)	Our analysis

AI=anal intercourse; CFSW=clients of female sex worker; FSW=female sex workers; MSM=men who have sex with men; RR=relative risk; VI=vaginal intercourse; *T*(m,a,b)=Triangular distribution (m=mode, a=minimum, b=maximum); *U*(a,b)=Uniform distribution (a=minimum, b=maximum).

*The prior for the size of the FSW was parameterized by multiplying the size of the MSM population by a uniform prior for the ratio of FSW to MSM in order to keep the size of the former larger than the latter.

†The proportion of clients of FSW was indirectly estimated using the multiplier method, balancing the partner change rate reported by FSW and by clients of FSW. The proportion of clients of FSW was constrained to be smaller than 20%.

§In order to predict condom use at last AI/VI act, we modeled the relationships between condom use at last VI and the frequency of condom use during last year (ordinal responses). We then predict condom use at last sex for AI and VI separately based on the ordinal frequency responses and calculated their ratio.

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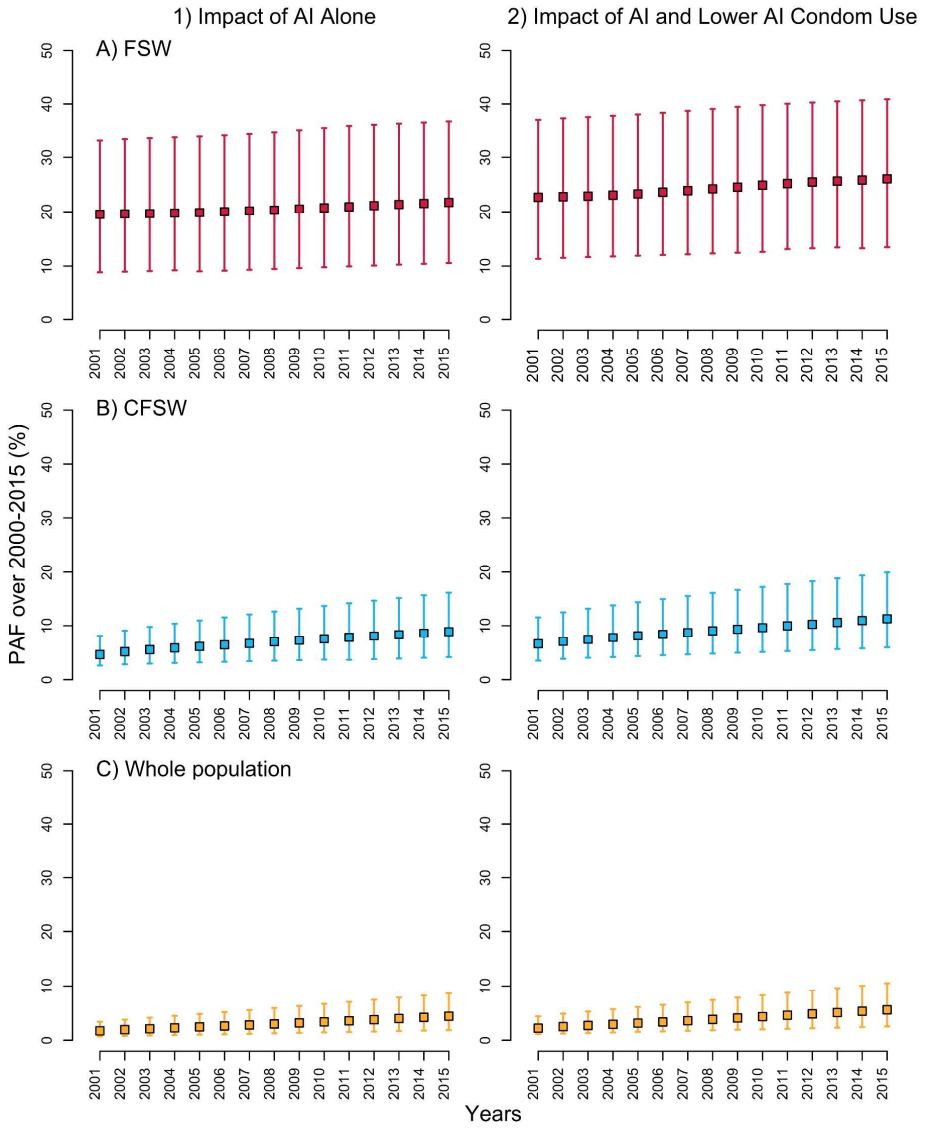


Figure 1: Population Attributable Fraction (PAF) of AI performed during sex work in Côte d'Ivoire for two scenarios: 1) we assumed that anal intercourse (AI) acts performed between female sex workers (FSW) and their clients (CFSW) were substituted by vaginal intercourse (VI) acts leaving condom use as for AI for these VI acts; 2) we assumed that AI acts were substituted with VI acts and that the proportion of sex acts protected by a condom was the same as for VI, (i.e., higher than in the previous scenario. PAF are calculated among A) FSW, B) CFSW, and C) the whole population. Median and 95% credible intervals are presented.

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