SUPPLEMENTAL DIGITAL CONTENT

Note: Reference numbers in this document are different from those in the main text

S1. Model equations

A schematic diagram of the model is shown in Fig. S1. The population includes all sexually active heterosexuals, 15–69 years old, and is stratified according to gender, ethnicity, and state of HIV infection. Let Y_{ski} be the number of individuals of gender $k=m$, f (male, female), ethnicity $i=1,2,3$ (Dutch natives, Africans, and Caribbeans), and HIV state $s=0,1,2,3,4$ (uninfected, acute, chronic, pre-AIDS, treated). Let $Y_i=\Sigma_{s,k}\ Y_{ski}$ be the total size of the ethnic group i. The model is described by the following differential equations, for $i=1,2,3$ and $k=m, f$:

$$\frac{dY_{0ki}}{dt}=\frac{1}{2}(1-b_ie_i)\mu Y_i-\mu Y_{0ki}-(\lambda_{ki}+\tilde{\lambda}_{ki})Y_{0ki},$$

$$\frac{dY_{1ki}}{dt}=(\lambda_{ki}+\tilde{\lambda}_{ki})Y_{0ki}-(\gamma+\mu)Y_{1ki},$$

$$\frac{dY_{2ki}}{dt}=\frac{1}{2}b_ie_i\mu Y_i+\gamma Y_{1ki}-[(1-\tau_{ki})\delta+\tau_{ki}\theta_i+\mu]Y_{2ki}+\varepsilon Y_{4ki},$$

$$\frac{dY_{3ki}}{dt}=(1-\tau_{ki})\delta Y_{2ki}-(\zeta+\mu+\mu_3)Y_{3ki},$$

$$\frac{dY_{4ki}}{dt}=\tau_{ki}\theta_iY_{2ki}+\zeta Y_{3ki}-(\varepsilon+\mu+\mu_4)Y_{4ki}.$$

The definitions of the parameters are summarised in Tables S1–S3 and in Table 1 in the main text. The removal rate out of the population for causes not related to HIV/AIDS is μ; this is also the rate at which individuals enter the population, such that the total population remains constant in the absence of the infection. A fraction b_i of migrants is born in their own country (first generation migrants), while a fraction $1-b_i$ is born in the Netherlands (second generation migrants). Among first generation migrants, a fraction e_i is infected when entering the country. Therefore, in total, a fraction b_ie_i of migrants entering the population is infected at the time of entry (for simplicity assumed all with chronic infection), while a fraction $1-b_ie_i$ is uninfected. Dutch natives enter the population uninfected. The ratio of men to women among those entering the population (uninfected or infected) is 1:1. The rates at which uninfected individuals get infected from sexual contacts in the Netherlands and abroad are λ_{ki} and $\tilde{\lambda}_{ki}$, respectively (see following paragraphs). The rate of progression from acute to chronic HIV is γ, from chronic to pre-AIDS δ, and from pre-AIDS to AIDS and death μ_3. Those progressing to AIDS flow out of the population, to account for the fact that those with AIDS are not sexually active or refrain from unsafe sexual practices. Individuals with chronic HIV infection initiate treatment before progressing to pre-AIDS (after $1/\theta_i$ years with chronic infection) with probability τ_{ki} or progress to pre-AIDS (without being treated) with probability $1-\tau_{ki}$. Also, a fraction of pre-AIDS cases is treated, at a rate ζ. The treatment failure rate is ε; cART usually achieves a reduction in viral load, hence, those failing cART 'move' to the chronic phase (and not to pre-AIDS).

S2. Infection from sexual contacts in the Netherlands

The per capita rate of acquiring infection via sexual contacts in the Netherlands, λ_{ki}, with $k=m, f$ and $i=1,2,3$, is defined apart for contacts with main partners ($\lambda_{ki}^{\text{main}}$) and for contacts with secondary partners ($\lambda_{ki}^{\text{sec}}$) from the formulas

$$\lambda_{ki}=\lambda_{ki}^{main}+\lambda_{ki}^{\text{sec}},$$

$$\lambda_{ki}^{main}=\sigma_{ki}\sum_{j=1}^{3}\pi_{kij}\frac{\sum_{s=1}^{4}[1-(1-\beta_s)^{\psi_{ji}\alpha_{ji}}]Y_{sk'j}}{\sum_{s=0}^{4}Y_{sk'j}},$$

$$\lambda_{ki}^{\text{sec}}=\phi_{ki}\sum_{j=1}^{3}\rho_{kij}\frac{\sum_{s=1}^{4}[1-(1-\beta_s)^{\xi_{ji}\hat{\alpha}_{ji}}]Y_{sk'j}}{\sum_{s=0}^{4}Y_{sk'j}}.$$

Here, k' denotes the gender opposite to k and β_s is the per contact transmission probability from an individual at the $s>0$ state of infection. For main partnerships, we define the following parameters for individuals of gender k and ethnicity i: σ_{ki} is the average number of main partners per year; π_{kij} is the fraction of these partners with individuals of ethnicity j; α_{ij} is the frequency of sexual contacts between main partners (of ethnicity i and j) in the Netherlands; and ψ_{ij} is the proportion of these contacts that are unprotected. For secondary partnerships, the following parameters are used, for individuals of gender k and ethnicity i: ϕ_{ki} is the average number of secondary partners per year; ρ_{kij} is the fraction of these partners with individuals of ethnicity j; $\hat{\alpha}_{ij}$ is the frequency of sexual contacts between secondary partners (of ethnicity i and j) in the Netherlands; and ξ_{ij} is the proportion of these contacts that are unprotected.

At each moment, the total number of partnerships formed by all men of ethnicity i with women of ethnicity j must be equal to the number of partnerships formed by all women of ethnicity j with men of ethnicity i:

$$\pi_{kij}\sigma_{ki}\sum_{s=0}^{4}Y_{ski}=\pi_{k'ji}\sigma_{k'j}\sum_{s=0}^{4}Y_{sk'j}\quad\text{and}\quad\rho_{kij}\phi_{ki}\sum_{s=0}^{4}Y_{ski}=\rho_{k'ji}\phi_{k'j}\sum_{s=0}^{4}Y_{sk'i},$$

for main and secondary partnerships, respectively. To ensure that this holds, we calculate the "imbalance"

$$D_{kij}=\frac{\pi_{kij}\sigma_{ki}\sum_{s=0}^{4}Y_{ski}}{\pi_{k'ji}\sigma_{k'j}\sum_{s=0}^{4}Y_{sk'j}},\quad\text{for main partnerships,}$$

$$F_{kij}=\frac{\rho_{kij}\phi_{ki}\sum_{s=0}^{4}Y_{ski}}{\rho_{k'ji}\phi_{k'j}\sum_{s=0}^{4}Y_{sk'j}},\quad\text{for secondary partnerships,}$$

and adjust the rates of partner change as follows

$$\sigma_{ki}\text{ becomes }\sigma_{kij}=\sigma_{ki}D_{kij}^{\upsilon_1-1}\quad\text{and}\quad\sigma_{k'j}\text{ becomes }\sigma_{k'ji}=\sigma_{k'j}D_{kij}^{\upsilon_1},$$
$$\phi_{ki}\text{ becomes }\phi_{kij}=\phi_{ki}F_{kij}^{\upsilon_2-1}\quad\text{and}\quad\phi_{k'j}\text{ becomes }\phi_{k'ji}=\phi_{k'j}F_{kij}^{\upsilon_2}.$$

The parameters υ_1 and υ_2 determine how much of the imbalance (in the reported partner change rates between men and women) is determined by men or by women; the first one is for main partnerships and the second one for secondary partnerships. In the numerical results we used the values $\upsilon_1=\upsilon_2=0.5$; this assumes that the imbalance in the reported partner change rates can be equally attributed to 'overreporting' by men and 'underreporting' by women.

S3. Infection from sexual contacts while visiting country of origin

For migrants the per capita rate of acquiring infection via sexual contacts during visits to their country of origin is defined from the following formula:

$$\tilde{\lambda}_{ki} = h_{ki}(M_{ki} + S_{ki})P_i, \quad k = m,f; \quad i = 2,3,$$

where h_{ki} is the frequency of travelling to the country of origin of the migrants; P_i is the prevalence of HIV infection in the specific country; $M_{ki} = \theta_{1ki}[1 - (1 - \beta)^{\tilde{\psi}_{ki}\tilde{\alpha}_{ki}}]$ is the transmission probability from main partners per trip; and $S_{ki} = \theta_{2ki}\tilde{\xi}_{ki}\tilde{\phi}_{ki}\beta$ is the transmission probability from secondary partners per trip. In the last formulas, θ_{1ki} and θ_{2ki} are the fractions of migrants who engage in sexual intercourse with main and secondary partners respectively during their trips to their home country; $\tilde{\xi}_{ki}$ is the fraction of sexual contacts with secondary partners that is unprotected and $\tilde{\psi}_{ki}$ the fraction of contacts with main partners that is unprotected; $\tilde{\phi}_{ki}$ is the average number of secondary partners per trip; $\tilde{\alpha}_{ki}$ is the number of sexual acts between main partners per trip. The transmission probability per sexual act, β, is the average probability over the whole duration of HIV infection. Infection of Dutch heterosexuals while they are abroad has been shown to be limited [1,2]; therefore, we took $\tilde{\lambda}_{k1} = 0$.

S4. Parameter estimates

Data sources: The "HIV survey among migrants in Amsterdam" is a cross-sectional community-based survey, carried out in 2003–2004 [3]. Participants were included in the survey if they or one of their parents were born in Surinam, the Netherlands Antilles, Aruba, or Ghana, if they were 18–55 years old and living in the Netherlands. Participants were interviewed face-to-face with a questionnaire covering demographic characteristics, sexual behaviour, ethnicity of their sexual partners, and travelling to the country of origin. Data from the participants originating from Surinam, Antilles, and Aruba were used for the parameters relating to the Caribbean subpopulation in the model; data from migrants from Ghana were used to inform the parameters for the African subpopulation. The study on "Sexual Health in the Netherlands" was carried out by the Rutgers-NISSO Group in 2006 [4]. This was a population study with two phases of recruitment via internet panel. For the first phase the respondents were randomly selected. For the second phase respondents were selected non-randomly to achieve a representative sample with regard to demographics: age, gender, education, and ethnicity. The 4170 respondents completed an internet-based questionnaire about demographic characteristics and sexual behaviour. Also behavioural data from the second PIENTER study were used [5]. This is a study aiming to evaluate the effectivity of the current National Immunization Program in the Netherlands. During 2006 and 2007, individuals living in the Netherlands aged up to 80 years old were randomly selected. Blood samples were tested for the presence of several antibodies for infectious diseases. Also a self-completed questionnaire was given; from this questionnaire, data on sexual behaviour were obtained and used in our study for the participants who were at least 15 years old.

Parameters relating to sexual behaviour of migrants in the Netherlands: These parameters were estimated from data from the "HIV survey among migrants in Amsterdam" [3]. The migrants participating in this survey were asked about their sexual partners in the Netherlands: whether they have 'steady' partners, how many 'other' partners they have (if any), frequency of condom use with these partners, and the ethnicity of these partners. The frequency of intercourse between main partners was estimated from data from the study 'Sexual health in the Netherlands' [4]. Among individuals with a main relation, 19% reported having sex at most once per month, 40% reported at most once per week, and 40% reported a few times per week up to daily [6]. These data result in an average of 8.9 sexual contacts per month (106.8 contacts per year).

Parameters relating to sexual behaviour of Dutch natives: The rate of change of main partners for Dutch natives was estimated from the study 'Sexual Health in the Netherlands' [4]. When asked about their main or steady relationship, 8% of Dutch heterosexuals reported a duration of less than one year, 22% reported a duration of 1–5 years, and 70% reported a duration of more than five years [4]. From these data we calculated an average rate of partner change of 0.32 per year. The other parameters relating to sexual behaviour of Dutch natives were estimated from data from the second PIENTER study [5]. The participants were asked how many sex partners they had in the previous six months; if they had a 'steady' partner; the country of origin of the partners; and frequency of condom use with these partners. Two hundred of the Dutch participants reported having casual partners in the preceding year. Among them, only one had a partner from sub-Saharan Africa or the Caribbean, resulting in 0% mixing of Dutch women with Africans and with Caribbeans, 0% mixing of Dutch men with Caribbeans, and 1.2% mixing of Dutch men with Africans. In addition, 31% of men and 34% of women reported not knowing the ethnicity of their casual partner. Hence, these data were insufficient to assess the ethnicity of the secondary partners of Dutch natives. Other data were not available, to inform these parameters, therefore the mixing of Dutch natives in secondary partnerships was taken equal to that in main partnerships. Other levels of mixing were examined in the sensitivity analysis and the results were robust.

Condom use and frequency of intercourse with secondary partners: For the parameters relating to condom use, we had data on condom use reported by Dutch natives, by Africans, and by Caribbeans (ξ_{ii} and ψ_{ii}, for $i = 1,2,3$, respectively). For mixed partnerships, we took the maximum of the two rates, giving a sort of upper bound for the parameter:

$\xi_{ij} = \xi_{ji} = \max\{\xi_{ii}, \xi_{jj}\}$ and $\psi_{ij} = \psi_{ji} = \max\{\psi_{ii}, \psi_{jj}\}$, for $i,j = 1,2,3$. For the frequency of intercourse with secondary partners, we could not find any data. Therefore we used the arbitrary value of $\hat{\alpha}_{ij} = 10$ contacts per partner per year for all i, $j = 1,2,3$, assuming that these frequencies must be much lower than the respective frequencies for main partners (due to the sorter duration of the relations). Other values for this parameter were examined in sensitivity analysis.

Parameters relating to imported transmissions: The prevalence of HIV in the Netherlands Antilles in 2004 was estimated at 0.8% [7]. In 2007, the prevalence of HIV in Surinam was estimated at 2.4% and in the Caribbean in total at 1.1% [8]. In Ghana the prevalence of HIV was 1.9% in 2007 and the whole sub-Saharan Africa 5.0% [8]. Based on these estimates, we assumed an

aggregate prevalence of 5% in sub-Sahara Africa and 1% in the Caribbean region ($P_2 = 5\%$, $P_3 = 1\%$). The prevalence of HIV among those migrating to the Netherlands was taken equal to the prevalence among migrants living in the Netherlands ($e_2 = 3.5\%$, $e_3 = 0.5\%$), in order to avoid creating an increasing or decreasing trend in prevalence due to the prevalence among entrants being higher or lower, respectively, than the prevalence among those already in the country. The other parameters were estimated from the "HIV survey among migrants in Amsterdam". Participants were asked how many times they travelled to their home country in the last five years and from these data we estimated the number of trips per year per gender. Participants were also asked if they have sexual partners in their home country (a 'main' partner and how many 'other' partners), and how frequently they used condoms with these partners. Frequency of intercourse between main partners was not asked. Therefore, we calculated the average duration of trips and assumed that individuals having a main partner in their home country have intercourse with this partner twice a week. Hence, the number of sexual acts per trip is equal to twice the average duration (in weeks) of each trip. For instance, Caribbean men reported an average duration of 5.79 weeks per trip to their home country; the number of sexual contacts per trip is then estimated at 2×5.79.

Effect of cART: Combining data from several European and American Cohorts of individuals on cART, it was estimated that for those on cART aged 20 years, the average life expectancy is 49.4 years [9]. This gives a total life expectancy of at least as long as the sexual lifespan. Also, in the Netherlands it has been shown that for successfully treated individuals, the mortality rates approach those of uninfected individuals [10]. Hence we used a zero excess mortality rate for those on cART ($\mu_4 = 0$).

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