The influence of mobility among high-risk populations on HIV transmission in Western Kenya

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ABSTRACT

Western Kenya suffers a highly endemic and also very heterogeneous epidemic of human immunodeficiency virus (HIV). Although female sex workers (FSW) and their male clients are known to be at high risk for HIV, HIV prevalence across regions in Western Kenya is not strongly correlated with the fraction of women engaged in commercial sex. An agent-based network model of HIV transmission, geographically stratified at the county level, was fit to the HIV epidemic, scale-up of interventions, and populations of FSW in Western Kenya under two assumptions about the potential mobility of FSW clients. In the first, all clients were assumed to be resident in the same geographies as their interactions with FSW. In the second, some clients were considered non-resident and engaged only in interactions with FSW, but not in longer-term non-FSW partnerships in these geographies. Under both assumptions, the model successfully reconciled disparate geographic patterns of FSW and HIV prevalence. Transmission patterns in the model suggest a greater role for FSW in local transmission when clients were resident to the counties, with 30.0% of local HIV transmissions attributable to current and former FSW and clients, compared to 21.9% when mobility of clients was included. Nonetheless, the overall epidemic drivers remained similar, with risky behavior in the general population dominating transmission in high-prevalence counties. Our modeling suggests that co-location of high-risk populations and generalized epidemics can further amplify the spread of HIV, but that large numbers of formal FSW and clients are not required to observe or mechanistically explain high HIV prevalence in the general population.

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1. Introduction

Kenya is ranked among the countries with the greatest number of people living with HIV (PLHIV) in the world, with an estimated population of 1.5 million PLHIV (NASCOP, 2016). The country's most affected region is the former Nyanza province in Western Kenya, comprised of six counties – Siaya, Homa Bay, Kisumu, Migori, Nyamira, and Kisii. Of these six counties, the first four experience extremely high HIV prevalence. The 2012 AIDS Indicator Survey found that approximately 1 out 4 adults in Siaya and Homa Bay counties were living with HIV, as were 1 out of 5 adults in Kisumu and Migori counties (NASCOP, 2014a). Some studies attribute high HIV infection rates to high levels of risk in the general population (Blaizot et al., 2016; Wachira, Kimaiyo, Ndege, Mamlin, & Braitstein, 2012), especially youth (Alsallaq et al., 2017; Wachira et al., 2014) and those living in communities with historically low rates of male circumcision (Anderson et al., 2014), while others have reported that high-risk sub-populations such as female sex workers (FSW) contribute substantially to HIV transmission in this region (Gouws & Cuchi, 2012; Vandenhoudt et al., 2013).

The population of FSW has been quantified throughout Kenya using a two-stage approach with geographical mapping of locations identified by key informants, followed by enumeration of FSW at the identified locations (Odek et al., 2014). The enumeration study included street-based, home-based, venue-based, road (truck stop) based, sex den based, massage parlour based, and escort services-based FSW. In Nyanza, the highest proportion of FSW in any town or city was found in Kisii, where FSW comprised 21% of women ages 15–49 residing in Kisii town in 2012. Because Kisii County is largely rural, the proportion of FSW county-wide is similar to that of Kisumu County, where FSW comprise 4% of the population of Kisumu city, but the city itself contains a larger proportion of the county's population. Nonetheless, this remarkably high proportion of FSW was found despite Kisii having the lowest HIV prevalence in Nyanza (NASCOP, 2014a).

Mobility of high-risk populations could potentially explain the contrast between the high rates of FSW and relatively low HIV prevalence. Kisii town is situated at the intersection of two highways (Fig. 1) and experiences substantial through-migration. Since the early rise of HIV in the region, migrant populations such as long-distance truck drivers have contributed to HIV transmission in such areas (Mbugua et al., 1995). Household-based surveys may not capture populations that are not resident within the county, yet contribute to local HIV transmission.

We used an epidemiological model to investigate whether mobility of high-risk populations is necessary to explain the epidemic patterns observed in Nyanza, and the extent to which assumptions about mobility influence patterns of HIV transmission. To capture overall patterns of HIV transmission, we made use of an available agent-based HIV model, EMOD-HIV, which includes networks of relationships, HIV risk groups and risk factors such as medical male circumcision (MMC), age patterns of partnerships, and geography. By fitting the model under different assumptions about the mobility of sexual partners of FSW, we sought to gain insights into the influence of mobility on patterns of HIV transmission.
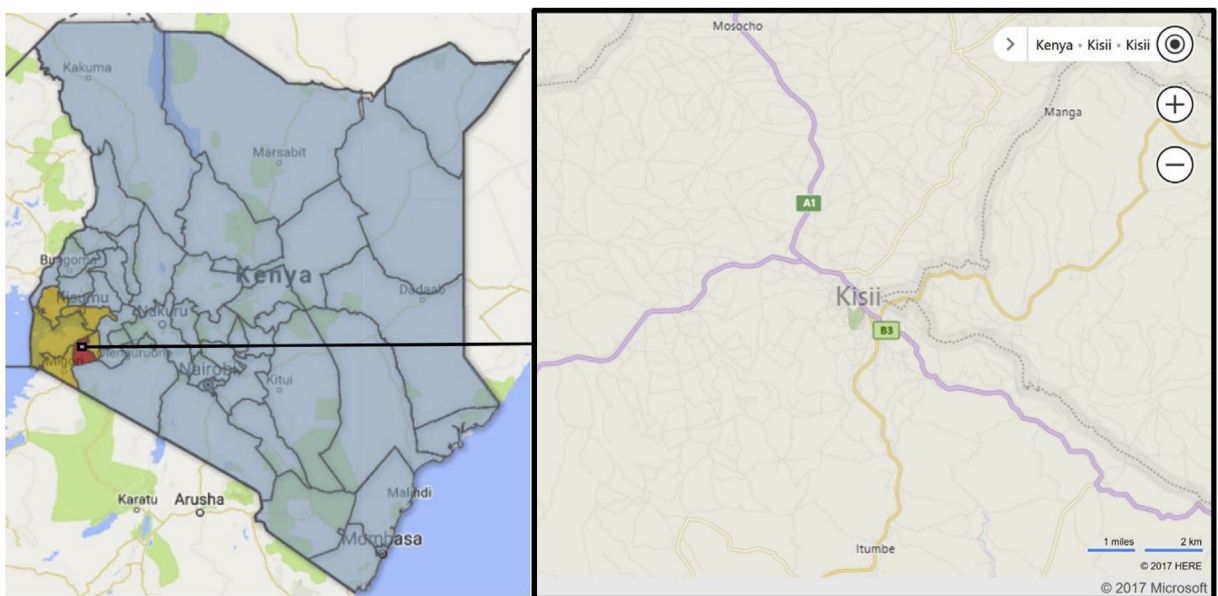
Fig. 1. Map showing Kisii County (red), the other five counties included in this modeling exercise (Homa Bay, Siaya, Kisumu, Migori, and Nyamira, orange), and the counties of Kenya not included in this modeling exercise (blue). Inset shows the location of Kisii town.

2. Methods

2.1. Epidemiological model

Modeling was conducted using the epidemiological modeling software EMOD-HIV version 2.5 (IDM EMOD, 2017), available at https://github.com/InstituteForDiseaseModeling/EMOD and described in detail at www.idmod.org/idmdoc and elsewhere (Bershteyn et al., 2012, 2013, 2016; Klein et al., 2014, 2015). A PDF snapshot of the model documentation is available with this publication as Supplementary Appendix 2, of which Section 1 describes the network assumptions, Section 2 describes the natural history and impact of treatment, Section 3 describes assumptions around transmission and interventions, and Sections 4 and 5 describe the cascade of care, cascade of prevention, and other options for simulating interventions.

Briefly, EMOD is an agent-based network model of HIV transmission that incorporates age-specific fertility and age/sex-specific non-AIDS mortality rates, four types of sexual partnerships (marital, informal, transitory, and commercial) that are remembered over time and formed according to specifiable partner age patterns, and a detailed care cascade with different modalities of HIV testing and time-variable rates of linkage, retention in care, treatment eligibility, and retention on antiretroviral therapy (ART).

2.2. Geographic stratification

EMOD was configured to model the six counties of the former Nyanza Province, including county-specific demographics, MMC and ART, and fitting to county-level HIV prevalence estimates. Counties were represented as geographic nodes (Institute for Disease Modeling, 2017) in the EMOD software. Node populations, age-specific fertility rates, and mortality rates were obtained from the UN World Population Prospects Data Query. Non-AIDS background mortality was estimated by projecting age-specific declines in mortality preceding the AIDS epidemic (Supplementary Fig. 1).

The model incorporated county-specific male circumcision rates by age and time. Baseline rates of traditional circumcision were obtained from the 2008–2009 Kenya Demographic and Health Survey (KNBS, 2010) and assumed to occur prior to sexual debut. Age-specific circumcision rates during scale-up of voluntary MMC were obtained from the PEPFAR online dashboard (PEPFAR) and the Kenya Ministry of Health. Reduction in HIV acquisition rate was assumed to be 60% for all circumcisions (Auvert et al., 2005; Bailey et al., 2007; Gray et al., 2007).

Numbers on ART per county, stratified by sex, were obtained from the Kenya Ministry of Health matching the assumptions used to configure the Spectrum software. In addition to extending life, it was assumed that ART reduced infectiousness by 92% (Donnell et al., 2010).

2.3. High-risk populations

The modeled population in EMOD was stratified into three levels of sexual risk behavior: low, medium, and high. Medium-risk individuals were assumed to be part of the general population, but to have an increased propensity to form multiple concurrent partnerships and, consequently, more lifetime partnerships. Due to the lack of reliable measurements on the proportion of the general population exhibiting medium-risk behavior, the proportion medium-risk was varied at the county level in order to fit county-level trends in HIV prevalence, and the resulting values are shown on the first six rows of Supplementary Table 1 for each of the six counties modeled.

High-risk individuals were defined as FSW and their male clients. FSW populations by county were obtained from a 2012 enumeration study (Odek et al., 2014) and aggregated by county. County populations were obtained from projections of the 2009 Kenya Population and Housing Census (Kenya National Bureau of Statistics, 2009). County-wide FSW population proportions were estimated as the ratio between the middle estimate of FSW population and the projected adult female population in the county. Women were assumed to engage in FSW beginning zero to five years after sexual debut, uniformly distributed (International Organization for Migration, 2010, p. 60; Musyoki et al., 2015). The duration of time until cessation of FSW was Weibull-distributed with a mean of 5.4 years and a 95% confidence interval of 2–9 years, so as to match the age distribution observed in FSW surveys (International Organization for Migration, 2010, p. 60; Musyoki et al., 2015; Odek et al., 2014). Further details about the modeling of FSW and clients can be found in Supplementary Appendix 1.

2.4. Mobility assumptions

Two separate fits of the model were performed under different assumptions about mobility among high-risk males, defined as clients of FSW. Under one set of assumptions, all clients were assumed to be resident to the county in which the FSW were enumerated. High-risk individuals, both FSW and their clients, had the opportunity to participate in all other forms of relationships (transitory, informal, and marital), thus mixing with the general population.

Under a second set of assumptions, a proportion of male clients of FSW were assumed to participate only in short-term commercial partnerships with other high-risk individuals, but were not permitted to participate in other relationship types (transitory, informal, or marital) within the county. The proportion of male clients considered to be resident (i.e., permitted to mix with the general population via longer-term relationships) was set to that of the county with the smallest

proportion of FSW/clients, which was Homa Bay with a FSW proportion of 0.4%. For example, in Homa Bay itself, all clients were assumed to be resident, whereas in Kisii − where the proportion of the population who are clients of FSW was three times that of Homa Bay − only one-third of clients were considered to be resident to the county.

An important limitation of this approach is that migration between counties was not included. Although the EMOD software does allow for configuration of age/sex-specific migration rates and the impact of migration on relationship stability and partner migration, in this case data were lacking on the county of residence for the population strata of interest, particularly FSW and clients in a given county. Thus, transmission of HIV across county lines was not included in the model, and the contributions of each county to the overall number of transmissions in Nyanza was simply calculated as a proportion of total transmissions in the region.

2.5. HIV prevalence

Microdata from two Demographic and Health Surveys (Central Bureau of Statistics - CBS/Kenya, 2004; KNBS, 2010) and two AIDS Indicator Surveys (NASCOP, 2014a,b) were obtained from the DHS Program (The DHS). Prevalence estimates and 95% confidence intervals by county, age, and sex were computed using the *survey* package (Lumley, 2004) in *R*. County-level estimates for the 2012 AIDS Indicator Survey (but not other surveys, which were conducted prior to the 2010 dissolution of provinces as a level of governance) were obtained from the DHS Program's StatCompiler to validate the calculations.

2.6. Model calibration

Fitting was performed using Alaeddini and Klein's parallel simultaneous perturbation optimization (PSPO) algorithm (Alaeddini and Klein, 2017a,b), a method that extends Spall's second-order stochastic optimization algorithm (SPSA) (Spall, 1992, 2000) to take greater advantage of parallel computing. The number of parallel rounds *M* was set to sixty for each of the calibrations compared in this analysis. After performing PSPO, a set of 250 model trajectories were selected using roulette resampling in proportion to likelihood. The selected parameter values are listed in Supplementary Table 1 for each of the two calibrations performed for the analysis.

2.7. Transmission patterns

To investigate the extent to which assumptions about FSW client residency influenced transmission patterns, individual transmission events in EMOD-HIV were logged using the EMOD configuration parameter "Report_Transmission." Transmission events were stratified according to the county and risk level of the transmitter and the recipient of each infection. The level of risk attributed to a transmission event was defined as the highest level of risk to date for the individuals involved. For example, if an individual became infected as a result of high-risk behavior, and later transmitted to a partner after having ceased high-risk behavior, the transmission to the partner would be considered to have originated from a high-risk individual.

3. Results

The EMOD-HIV model of Western Kenya was able to incorporate the epidemic characteristics across the six counties of Nyanza (Table 1) under two extreme assumptions about FSW client residency. Even when all FSW clients were assumed to be resident to the county where FSW were enumerated, the model was able to fit the epidemic trends (Fig. 2). For example, in Kisii, the model was able to reproduce the relatively low HIV prevalence observed in household surveys, despite a relatively high proportion of the population exhibiting high-risk behavior (FSW and clients). The seemingly disparate trends in FSW population versus HIV prevalence were offset by (1) high rates of male circumcision, especially traditionally practiced circumcision predating the start of the HIV epidemic (Table 1, middle section), and (2) the proportion of the general population with a higher propensity to have multiple concurrent partners ("medium" risk, Supplementary Table 1, first six rows). The model was also able to fit the epidemic trends when a proportion of FSW clients (any exceeding that of Homa Bay, the county with the smallest proportion of FSW) was assumed to not be resident to the county (Supplementary Fig. 2).

Although extreme assumptions about the residency of "high" risk individuals did not prevent the model from fitting epidemic trends, these assumptions did influence the relative contributions of different sub-populations to HIV transmission and acquisition (Fig. 3). High-risk individuals, defined as current and former FSW and their clients, transmitted 30.0% of new infections in the 2015−2019 time period under the assumption that all clients were resident to the county where FSW were enumerated. The proportion of new infections received by high-risk individuals was smaller than the proportion transmitted, an expected trend for a group that connects many individuals in a contact network.

Under the second set of assumptions, all clients in Homa Bay (the county with the lowest FSW proportion) were assumed to be resident, and the proportion exceeding this in other counties was assumed to be non-resident. When the model was fit under the assumption that a proportion of the clients of FSW are not resident to the county, the fraction of new infections transmitted by high-risk individuals accounted for 21.9% of new infections (Fig. 4). As with the fully-resident assumption, the fraction of new infections among high-risk individuals was 16.7%, smaller than the fraction of transmissions.

Despite both models fitting prevalence trends by county, the shift in assumptions about residency also influenced the relative contributions of each county to transmissions and new infections in Nyanza. Kisii, the lowest-prevalence county but

Table 1
Data sources and estimates used for configuration and fitting of Western Kenya model. Numbers in parentheses indicate 95% confidence intervals.

| Year	High-Prevalence Counties				Low-Prevalence Counties		Source
	Siaya	Homa Bay	Kisumu	Migori	Nyamira	Kisii	
HIV Prevalence: Female 15-49yo							
2003	24.2% (16.4−34.8%)	24.6% (13.5−42.0%)	19.1% (12.0−30.0%)	18.6% (8.9−37.2%)	7.4% (2.9−21.2%)	8.5% (4.9−15.1%)	Kenya National Bureau of Statistics, 2009
2007	21.3% (17.2−26.0%)	32.6%n(27.6−37.9%)	18.8% (12.7−25.5%)	22.0% (13.7−32.3%)		6.9% (4.8−9.6%)	Musyoki et al., 2015
2009	19.2% (10.9−32.8%)	25.2% (19.0−33.0%)	18.1% (15.8−25.3%)	22.3% (18.6−26.6%)	5.4% (2.8−11.6%)	5.7% (2.8−12.3%)	Gray et al., 2007
2012	30.0% (20.0−41.7%)	27.9% (21.1−35.6%)	20.3% (15.8−25.3%)	19.7% (7.5−38.4%)	10.5% (6.5−15.9%)	3.8% (1.4−8.2%)	NASCOP, 2014a
HIV Prevalence: Male 15-49yo							
2003	18.2% (13.4−24.6%)	11.0% (4.1−30.8%)	16.6% (9.8−27.8%)	18.0% (7.7−40.1%)	0.3% (0.1−3.3%)	1.1% (0.3−9.3%)	Kenya National Bureau of Statistics, 2009
2007	12.6% (6.8−20.7%)	24.4% (16.3−34.2%)	11.7% (6.5−18.9%)	17.2% (9.2−28.4%)		4.3% (2.2−7.3%)	Musyoki et al., 2015
2009	15.3% (11.6−20.1%)	17.4% (11.2−26.7%)	11.1% (6.2−20.1%)	19.2% (12.2−29.9%)	2.3% (0.8−10.0%)	3.3%(1.5−8.3%)	Gray et al., 2007
2012	22.1% (16.4−38.0%)	20.0% (14.5−31.8%)	19.3% (9.7−33.5%)	13.8% (5.8−28.8%)	4.9% (0.9−12.5%)	4.3% (0.9−9.7%)	NASCOP, 2014a
Proportion of 15−54yo men who are circumcised							
2003	16.0% (7.0−32.6%)	9.9% (3.5−24.5%)	32.5% (19.2−49.3%)	50.1% (24.4−75.9%)	99.2% (94.9−99.9%)	94.9% (73.3−99.2%)	Kenya National Bureau of Statistics, 2009
2007	12.5% (7.4−20.5%)	9.2% (5.2−15.8%)	19.8% (10.0−35.4%)	36.5% (20.9−55.6%)		99.1% (96.7−99.8%)	Musyoki et al., 2015
2009	17.7% (10.3−28.7%)	11.9% (5.6−23.6%)	44.8% (27.8−63.1%)	25.9% (12.8−45.3%)	100.00%	100.00%	Gray et al., 2007
2012	50.1% (42.2−58.0%)	44.3% (38.4−50.5%)	47.6% (40.1−55.2%)	60.0% (39.3−77.6%)	98.4% (94.3−99.5%)	99.1% (94.8−99.9%)	NASCOP, 2014a
Number of FSW enumerated							
2012	2149 (1687−2609)	995 (774−1216)	4041 (3228−4854)	2272 (1698−2846)	856 (665−1047)	4063 (2990−5136)	Odek et al., 2014
Female population 15-49yo							
2012	196906	225823	253728	217448	152783	290205	The DHS
Female population age 15+							
2012	254882	275155	300897	255105	183921	348132	The DHS
% of women 15−49 who are FSW							
2012	1.1%	0.4%	1.6%	1.0%	0.6%	1.4%	Odek et al., 2014, The DHS
% of women 15 + who are FSW							
2012	0.8%	0.4%	1.3%	0.9%	0.5%	1.2%	Odek et al., 2014, The DHS
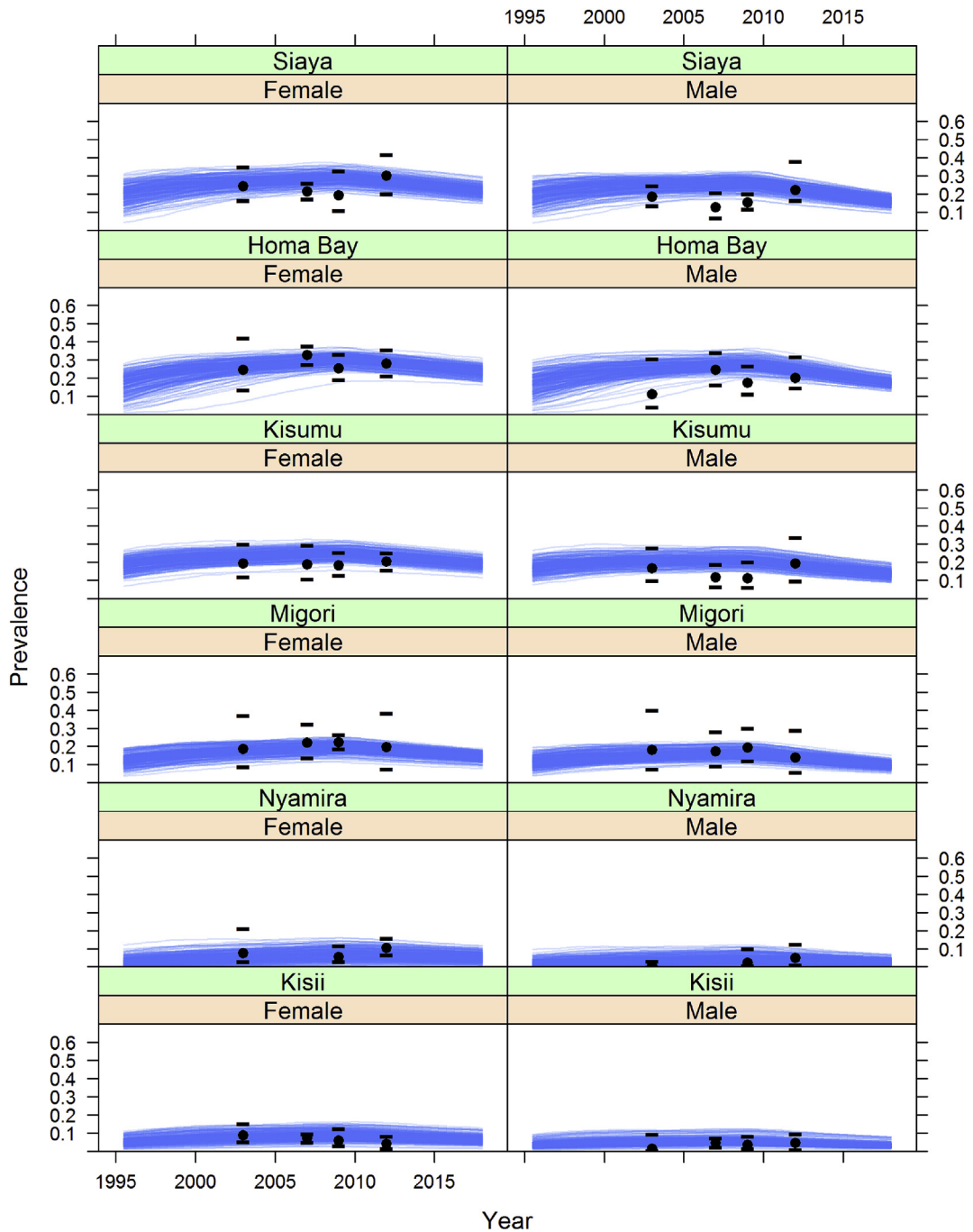
Fig. 2. HIV prevalence over time from EMOD-HIV, fit under the assumption that all clients of FSW are resident to the county in which FSW were enumerated. Panels show prevalence stratified by sex and County of Western Kenya, compared to prevalence estimates from two Demographic and Health Surveys (DHS) and two AIDS Indicator Surveys (AIS) conducted in the same counties. Blue lines show 250 stochastic runs of EMOD-HIV. Black horizontal lines show 95% confidence intervals from the surveys.

with a relatively high proportion of FSW, accounted for 10.0% of Nyanza's new infections in the 2015–2019 time period under the residency assumption, but only 5.5% under the assumption that some clients were non-resident. Regardless of the assumption about residency, the proportion of transmissions originating from FSW and their clients was very large in Kisii: 54.3% assuming full residency and 46.2% including some non-residency. In contrast, the proportion of high-risk attributable transmissions in Homa Bay was 10.5% and 9.5%, and in Siaya was 25.6% and 17.5%, under the two respective assumptions about
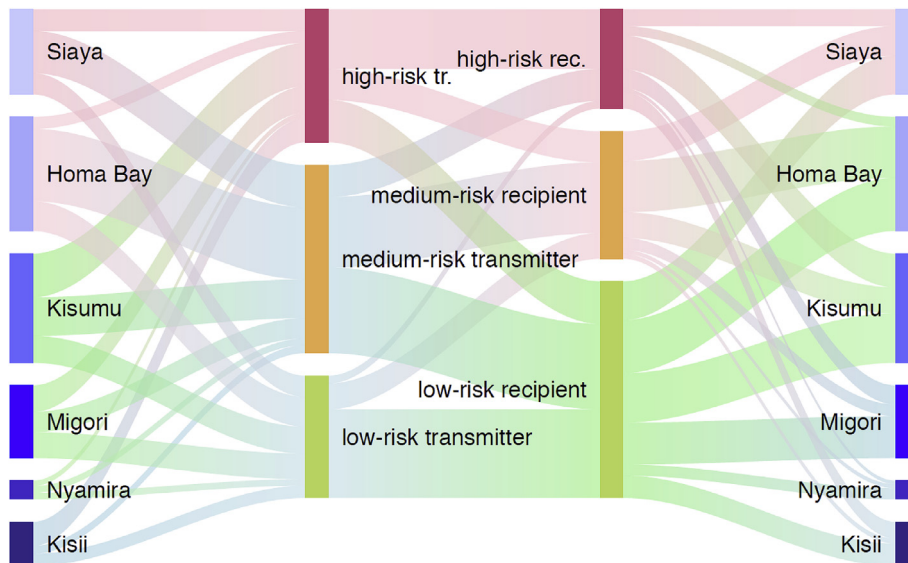
Fig. 3. Patterns of HIV transmission, shown as flows between transmitters and recipients, over the time period 2015—2019 for a model of Western Kenya in which FSW clients are assumed to be resident to the county in which FSW were enumerated.
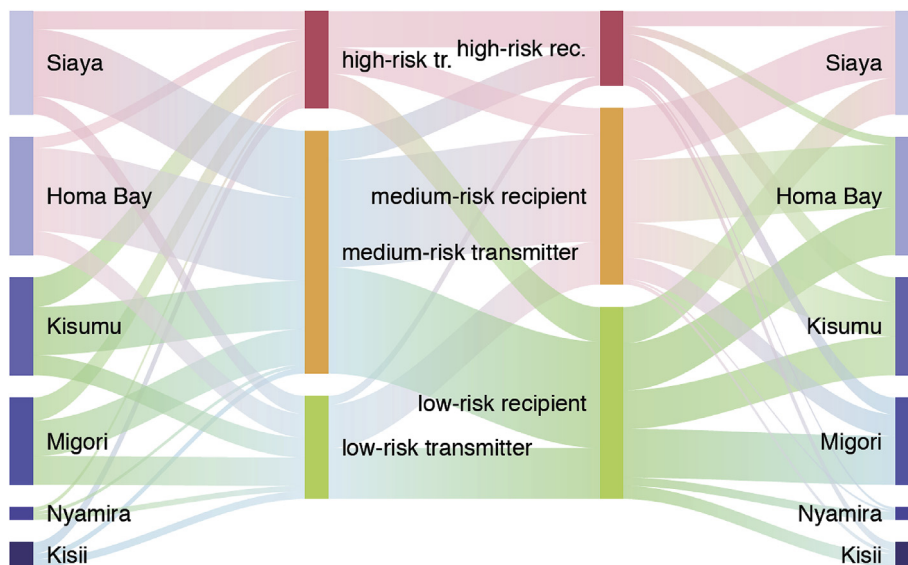
Fig. 4. Patterns of HIV transmission, shown as flows between transmitters and recipients, over the time period 2015—2019 for a model of Western Kenya fit under the assumption that a proportion of the clients of FSW are not resident to the county in which FSW were enumerated. All clients in Homa Bay (the county with the lowest FSW proportion) were assumed to be resident, and the proportion exceeding this in other counties was assumed to be non-resident.

residency, indicating that transmission in those high-prevalence counties was predominantly among the general population (See Table 2).

4. Discussion

At first glance, findings from FSW enumeration seem incongruous with the patterns of HIV prevalence in Nyanza. Kisii County has the region's lowest HIV prevalence, but among the highest proportions of women identified as FSW, with 21% of 15—49 year old women in the urban area of Kisii town identified as FSW in a recent enumeration study (Odek et al., 2014).

The enumeration of FSW as a population fraction is subject to multiple sources of uncertainty. Odek et al. (2014) estimated the uncertainty arising from the enumeration strategy. For Kisii, the estimated range on the number of FSW leads to an

Table 2
Proportion of HIV transmissions originating in each county and risk group, under two different model assumptions about residency of FSW clients.

	Resident	Non-Resident
By County		
Siaya	19.2%	23.3%
Homa Bay	25.7%	26.6%
Kisumu	24.6%	22.1%
Migori	16.4%	19.7%
Nyamira	4.2%	2.8%
Kisii	10.0%	5.5%
By Risk Group		
Low-Risk	27.5%	23.2%
Medium-Risk	42.4%	54.8%
High-Risk	30.0%	21.9%

estimated range of 15.3%–26.3% of women ages 15–49, without taking into consideration additional uncertainty in the denominator of the size of the adult female population. Denominator population estimates were based on projections of the 2009 Census of Kenya to the year of the FSW enumeration study (Kenya National Bureau of Statistics, 2009). However, likely the largest source of uncertainty about the local FSW population fraction arises from the possibility that FSW and clients are not necessarily residents of the location in which they are enumerated. This was found to be the case for other high-risk populations as well, such as fish traders in Nyanza's largest open-air market (Leidich et al., 2018).

Using a mechanistic, internally-consistent, demographically detailed model of HIV transmission in this region, we asked whether the differences in FSW patterns and HIV epidemic patterns could be reconciled in an epidemiologically consistent way. Though we hypothesized that mobility of high-risk populations would be necessary to reconcile HIV prevalence and FSW enumeration, we found that this was not the case. The residency of FSW clients was not identifiable based on overall epidemic trends. Risky behavior among the general population, as well as historic differences in male circumcision since the start of the epidemic – some of which still persist despite great success in scaling up MMC (Akullian, Onyango, Klein, Odhiambo, & Bershteyn, 2017) – appear to be the main drivers of geographic differences in HIV prevalence across Nyanza.

The potential for migration among high-risk populations introduces uncertainty as to whether HIV prevalence measured in household surveys necessarily captures the epidemic characteristics of areas with the largest FSW populations. Kisii town, for example, is located by the intersection of two highways (Fig. 1), which likely contribute to the pool of clients for the large FSW population enumerated there. Lack of client residency was compatible with the epidemic trends observed, but was not necessary for the model to fit epidemic trends.

Regardless of assumptions about residency, a majority of transmissions in Kisii originated from FSW and clients, whereas in Homa Bay and Siaya, a majority of transmissions were attributable to "medium"-risk individuals, i.e., those in the general population who have greater propensity for having multiple partners. Kisumu and Migori exhibited more mixed epidemics, with "high" and "medium" risk populations contributing about equally to HIV transmission. Further, under both sets of assumptions about residency, high-risk individuals were responsible for more transmission than acquisition of HIV. Regardless of assumptions about residency, high-risk groups were responsible for approximately four HIV transmissions for every three HIV acquisitions.

Instead of modifying the role of risk groups in HIV transmission, model assumptions about residency changed the relative contributions of each county toward overall HIV transmission in the Nyanza region. When clients were assumed to always reside in the county in which they interact with FSW, the higher-FSW counties such as Kisii contributed a larger proportion of HIV transmissions. In part, this result is a consequence of a limitation of our model: lacking information about the residency of FSW clients, the model did not account for transmissions to partners outside of the county. The finding is also symptomatic of limitations in HIV prevalence data: although HIV prevalence in the region of Nyanza is well-constrained, there is greater uncertainty in measuring HIV prevalence at the county level due to smaller sample sizes. Thus, epidemic patterns are not known with sufficient accuracy for these patterns to fully inform the role of FSW and their clients in the region's HIV epidemic, even when their populations have been enumerated at the county level.

An important limitation of this research is the lack of data on the county of residence of FSW and client populations. Although one of the modeling scenarios assumed that clients were not resident to the county where they interacted with FSW, their transmission to stable partners in their counties of residence were not included in the model.

It is important to note that the FSW enumeration used to define "high" risk populations emphasizes formal FSW identified by secondary informants. Less formal means of risky behavior, including transaction-driven behaviors such as the practice of *jaboya* in fishing communities (Njuguna et al., 2014; Opio, Muyonga, & Mulumba, 2013; Seeley et al., 2012), as well as cultural practices associated with risky behavior such as *disco matanga* (Njue, Voeten, & Remes, 2009), are broadly incorporated in the "medium" risk behavior ascribed to a proportion of the general population. Though some of these behaviors have been described qualitatively, improved quantitative understanding of their extent and geographic distribution can help identify risky behaviors associated with HIV transmission in the diverse epidemic settings across Western Kenya.

5. Conclusions

Globally, FSW populations are not necessarily co-located with highly generalized epidemics. The same is true for Western Kenya, where high population proportions of FSW are enumerated in some regions with relatively high HIV prevalence (e.g., Kisumu), and others with relatively low prevalence (e.g., Kisii). A detailed model that accounts for county-level differences in demographics, male circumcision, and risky behavior in the general population can successfully reconcile disparate patterns of FSW and HIV prevalence in Western Kenya, finding similar roles for high-risk populations in HIV transmission, regardless of assumptions about mobility of these high-risk populations. The model was able to fit an HIV epidemic either assuming that clients of FSW are resident to the county where FSW were enumerated, or assuming that they are not county residents. However, absent data about the county of residence of FSW and their clients, the model did not explicitly include inter-county migration of these key populations. Further research and modeling are required to understand the role of mobility in the contributions of key populations to highly generalized HIV epidemics such as that of Western Kenya.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.idm.2018.04.001.

References

Akullian, A., Onyango, M., Klein, D., Odhiambo, J., & Bershteyn, A. (2017 Jan 13). Geographic coverage of male circumcision in western Kenya [cited 2017 Sep 15] *Medicine (Baltimore) [Internet], 96*(2). Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC5266192/.

Alaeddini, A., & Klein, D. J. (2017 Apr 1). PSPO: Parallel simultaneous perturbation optimization. *arXiv Mathematics - Optimization and Control.* eprint arXiv: 1704.00223.

Alaeddini, A., & Klein, D. J. (2017 Aug 2). Application of a second-order stochastic optimization algorithm for fitting stochastic epidemiological models. *arXiv Mathematics - Optimization and Control.* eprint arXiv:1708.00886.

Alsallaq, R. A., Buttolph, J., Cleland, C. M., Hallett, T., Inwani, I., Agot, K., et al. (2017 Apr 12). The potential impact and cost of focusing HIV prevention on young women and men: A modeling analysis in western Kenya. *PLoS One, 12*(4), e0175447.

Anderson, S.-J., Cherutich, P., Kilonzo, N., Cremin, I., Fecht, D., Kimanga, D., et al. (2014 Jul 19). Maximising the effect of combination HIV prevention through prioritisation of the people and places in greatest need: A modelling study. *The Lancet, 384*(9939), 249—256.

Auvert, B., Taljaard, D., Lagarde, E., Sobngwi-Tambekou, J., Sitta, R., & Puren, A. (2005 Oct 25). Randomized, controlled intervention trial of male circumcision for reduction of HIV infection Risk: The ANRS 1265 trial. *PLoS Medicine, 2*(11), e298.

Bailey, R. C., Moses, S., Parker, C. B., Agot, K., Maclean, I., Krieger, J. N., et al. (2007 Feb 24). Male circumcision for HIV prevention in young men in Kisumu, Kenya: A randomised controlled trial. *The Lancet, 369*(9562), 643—656.

Bershteyn, A., Klein, D. J., & Eckhoff, P. A. (2013). Age-dependent partnering and the HIV transmission chain: A microsimulation analysis. *Journal of The Royal Society Interface, 10*(88), 20130613.

Bershteyn, A., Klein, D. J., & Eckhoff, P. A. (2016 Jul). Age-targeted HIV treatment and primary prevention as a 'ring fence' to efficiently interrupt the age patterns of transmission in generalized epidemic settings in South Africa. *International Health, 8*(4), 277—285.

Bershteyn, A., Klein, D. J., Wenger, E., & Eckhoff, P. A. (2012). Description of the EMOD-HIV model v0. 7. *arXiv Quantitative Biology — Quantitative Methods.* eprint arXiv:1206.3720.

Blaizot, S., Maman, D., Riche, B., Mukui, I., Kirubi, B., Ecochard, R., et al. (2016 Apr 29). Potential impact of multiple interventions on HIV incidence in a hyperendemic region in western Kenya: A modelling study. *BMC Infectious Diseases, 16*(189). https://doi.org/10.1186/s12879-016-1520-4.

Central Bureau of Statistics - CBS/Kenya. (2004). *Ministry of Health - MOH/Kenya, ORC Macro. Kenya demographic and Health survey 2003 [internet].* Calverton, Maryland, USA: CBS, MOH, and ORC Macro. Available from: http://dhsprogram.com/pubs/pdf/FR151/FR151.pdf.

The DHS Program [Internet]. [cited 2017 Sep 15]. Available from: http://dhsprogram.com/.

Donnell, D., Baeten, J. M., Kiarie, J., Thomas, K. K., Stevens, W., Cohen, C. R., et al. (2010 Jun 18). Heterosexual HIV-1 transmission after initiation of anti-retroviral therapy: A prospective cohort analysis. *The Lancet, 375*, 2092—2098.

Institute for Disease Modeling: Demographics parameters [Internet]. [cited 2017 Sep 16]. Available from: https://institutefordiseasemodeling.github.io/EMOD/general/parameter-demographics.html?searchText=node

Gouws, E., & Cuchi, P. (2012 Dec). Focusing the HIV response through estimating the major modes of HIV transmission: A multi-country analysis. *Sexually Transmitted Infections, 88*(Suppl. l_2), i76—i85.

Gray, R. H., Kigozi, G., Serwadda, D., Makumbi, F., Watya, S., Nalugoda, F., et al. (2007 Feb 24). Male circumcision for HIV prevention in men in rakai, Uganda: A randomised trial. *The Lancet, 369*(9562), 657—666.

International Organization for Migration. (2010). *Integrated biological and behavioural surveillance survey among migrant female sex workers in Nairobi.* Kenya. Nairobi.

Kenya National Bureau of Statistics - KNBS. (2010). *National AIDS control Council/Kenya, National AIDS/STD control Programme/Kenya, Ministry of Public Health and Sanitation/Kenya, Kenya Medical Research institute.* Kenya demographic and Health survey 2008-09 [internet]. Calverton, Maryland, USA: KNBS and ICF Macro. Available from: http://dhsprogram.com/pubs/pdf/FR229/FR229.pdf.

Kenya National Bureau of Statistics. (2009). *USAID, United Nations population fund, United States Census Bureau.* Kenya Population and Housing Census.

Klein, D. J., Bershteyn, A., & Eckhoff, P. A. (2014). Dropout and re-enrollment: Implications for epidemiological projections of treatment programs. *AIDS, 28*, S47—S59.

Klein, D. J., Eckhoff, P. A., & Bershteyn, A. (2015 Mar). Targeting HIV services to male migrant workers in southern Africa would not reverse generalized HIV epidemics in their home communities: A mathematical modeling analysis. *International Health, 7*(2), 107—113.

Leidich, A., Achiro, L., Kwena, Z. A., McFarland, W., Neilands, T. B., Cohen, C. R., et al. (2018 Jan 11). Methods for sampling geographically mobile female traders in an East African market setting. *PLoS One, 13*(1), e0190395.

Lumley, T. (2004 Apr 15). Analysis of complex survey samples. *Journal of Statistical Software, 9*(1). https://doi.org/10.18637/jss.v009.i08. pp. 1—19(19).

Mbugua, G. G., Muthami, L. N., Mutura, C. W., Oogo, S. A., Waiyaki, P. G., Lindan, C. P., et al. (1995 Aug). Epidemiology of HIV infection among long distance truck drivers in Kenya. *East African Medical Journal, 72*(8), 515—518.

Musyoki, H., Kellogg, T. A., Geibel, S., Muraguri, N., Okal, J., Tun, W., et al. (2015 Feb). Prevalence of HIV, sexually transmitted infections, and risk behaviours among female sex workers in Nairobi, Kenya: Results of a respondent driven sampling study. *AIDS and Behavior, 19*(Suppl. 1), S46—S58.

National AIDS and STI Control Programme (NASCOP). (2014a). *Kenya. Kenya AIDS indicator survey 2012.*

National AIDS and STI Control Programme (NASCOP). (2014b). *Kenya. Kenya AIDS indicator survey 2007.*

National AIDS and STI Control Programme (NASCOP). (2016 Oct). *Kenya, National AIDS control council. Kenya HIV estimates [internet]* [cited 2017 Sep 26] p. 35. Available from: http://nacc.or.ke/wp-content/uploads/2016/12/Kenya-HIV-Estimates-2015.pdf.

Njue, C., Voeten, H. A., & Remes, P. (2009 Feb 20). Disco funerals, a risk situation for HIV infection among youth in Kisumu, Kenya. *AIDS (London, England),* *23*(4), 505–509.

Njuguna, S., Kwena, Z., Ombati, E., Mburu, M., Bukusi, E., Ondondo, R., et al. (2014 Oct 1). Mobility patterns and concurrent sexual relationships among Fisher folk along lake Victoria, Kenya. *AIDS Research and Human Retroviruses, 30*(S1), A274–A275.

Odek, W. O., Githuka, G. N., Avery, L., Njoroge, P. K., Kasonde, L., Gorgens, M., et al. (2014 Mar 3). Estimating the size of the female sex worker population in Kenya to inform HIV prevention programming. *PLoS One, 9*(3), e89180.

Opio, A., Muyonga, M., & Mulumba, N. (2013 Aug 5). HIV infection in fishing communities of lake Victoria basin of Uganda – a cross-sectional sero-behavioral survey. *PLoS One, 8*(8), e70770.

PEPFAR Dashboards [Internet]. [cited 2017 Sep 15]. Available from:: https://data.pepfar.net/global

Seeley, J., Nakiyingi-Miiro, J., Kamali, A., Mpendo, J., Asiki, G., Abaasa, A., et al. (2012 Jun). High HIV incidence and socio-behavioral risk patterns in fishing communities on the shores of Lake Victoria, Uganda. *Sexually Transmitted Diseases, 39*(6), 433–439.

Source files for building the IDM EMOD disease transmission model [Internet]. (2017). *Institute for disease modeling* [cited 2017 Sep 15]. Available from: https://github.com/InstituteforDiseaseModeling/EMOD.

Spall, J. C. (1992 Mar). Multivariate stochastic approximation using a simultaneous perturbation gradient approximation. *IEEE Transactions on Automatic Control, 37*(3), 332–341.

Spall, J. C. (2000 Oct). Adaptive stochastic approximation by the simultaneous perturbation method. *IEEE Transactions on Automatic Control, 45*(10), 1839–1853.

Spectrum Models [Internet]. [cited 2017 Sep 16]. Available from:: http://www.avenirhealth.org/software-spectrummodels.php

STATcompiler [Internet]. [cited 2017 Sep 15]. Available from:: http://www.statcompiler.com/en/

Vandenhoudt, H. M., Langat, L., Menten, J., Odongo, F., Oswago, S., Luttah, G., et al. (2013 Jan 23). Prevalence of HIV and other sexually transmitted infections among female sex workers in Kisumu, western Kenya, 1997 and 2008. *PLoS One, 8*(1), e54953.

Wachira, J., Kimaiyo, S., Ndege, S., Mamlin, J., & Braitstein, P. (2012 Jan 15). What is the impact of home-based HIV counseling and testing on the clinical status of newly enrolled adults in a large HIV care Program in western Kenya? *Clinical Infectious Diseases, 54*(2), 275–281.

Wachira, J., Ndege, S., Koech, J., Vreeman, R. C., Ayuo, P., & Braitstein, P. (2014 Feb 1). HIV testing uptake and prevalence among adolescents and adults in a large home-based HIV testing Program in western Kenya. *JAIDS Journal of Acquired Immune Deficiency Syndromes, 65*(2), e58.