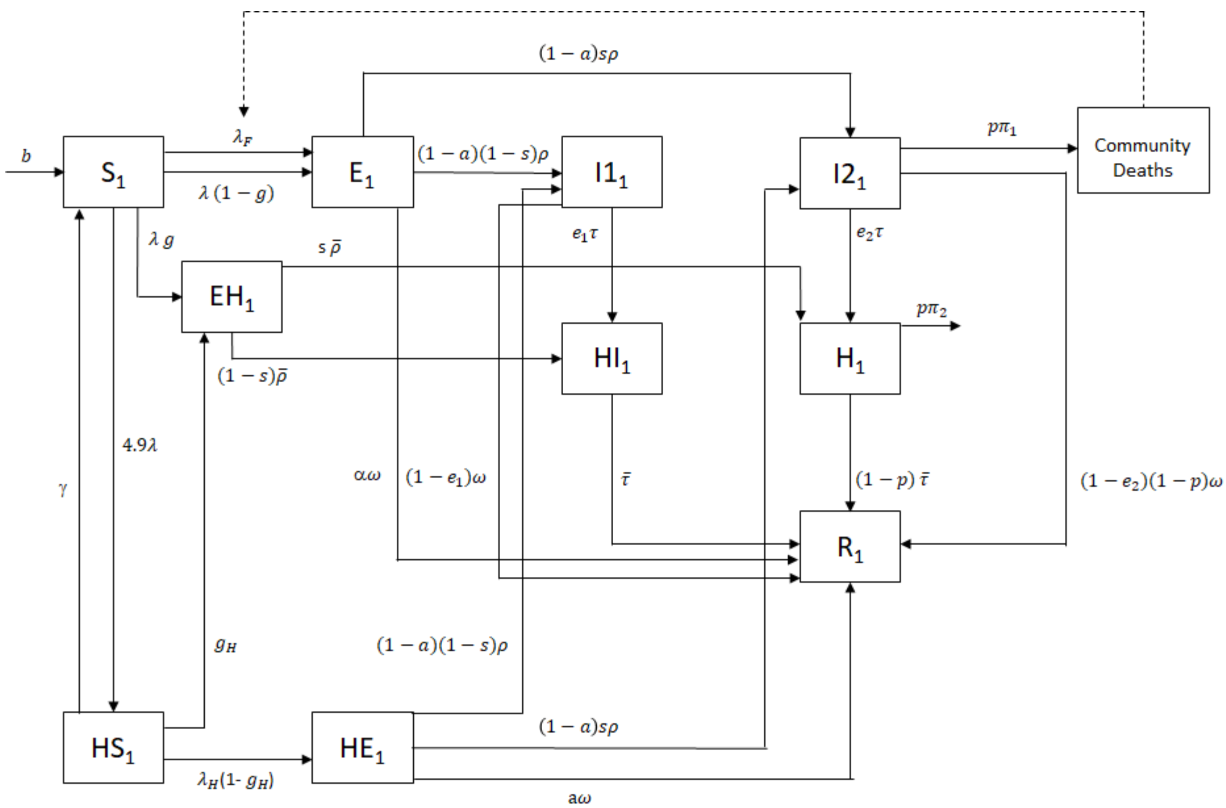
Supplementary Material for: Coordinated support for local action: A modeling study of strategies to facilitate behavior adoption in urban poor communities of Liberia for sustained COVID-19 suppression

Laura A. Skrip, Mosoka P. Fallah, Jamie Bedson, Laurent Hébert-Dufresne, Benjamin M. Althouse

Model Structure and Dynamics

A stochastic compartmental model, stratified by socioeconomic status, was developed to investigate differential effects of SARS-CoV-2 transmission and intervention in the urban slum communities versus less socioeconomically vulnerable communities of Montserrado County, Liberia. Supplementary Figure 1 displays the model structure for one stratum.



Supplementary Figure 1. Compartmental diagram of dynamic transmission model (single subpopulation stratum, labeled subscript 1). In each subpopulation (urban poor or less socioeconomically disadvantaged), susceptible individuals (S) may become infected (E) and remain asymptomatic, develop mild symptoms (I1), or develop severe symptoms (I2). Infected individuals who recover (R) may first undertake home isolation (HI) or hospitalization (H). Severely ill individuals who do not seek care may recover or die in the community. As a result of contact tracing efforts, contacts of newly infected individuals may remove themselves from the community via quarantine (EH) during the incubation period, before continuing to isolate or seek treatment if they develop symptoms. Household members (HS) of newly infected cases are expected to be at higher risk and become infected (HE) at a higher rate than community contacts.

Additional detail on select model components related to transmission dynamics and intervention implementation is provided in the following sections.

Transmission Dynamics

Force of infection. Susceptible individuals in subpopulation i are exposed to SARS-CoV-2 at a rate given by the force of infection:

$$\lambda_i = \beta_i \times \varsigma_i \times \chi_{ix} \sum_{i=1}^{2} (\sigma_1 E_i + I_{iM} + \sigma_2 I_{iS})/N_i \qquad \text{Eq. 1}$$

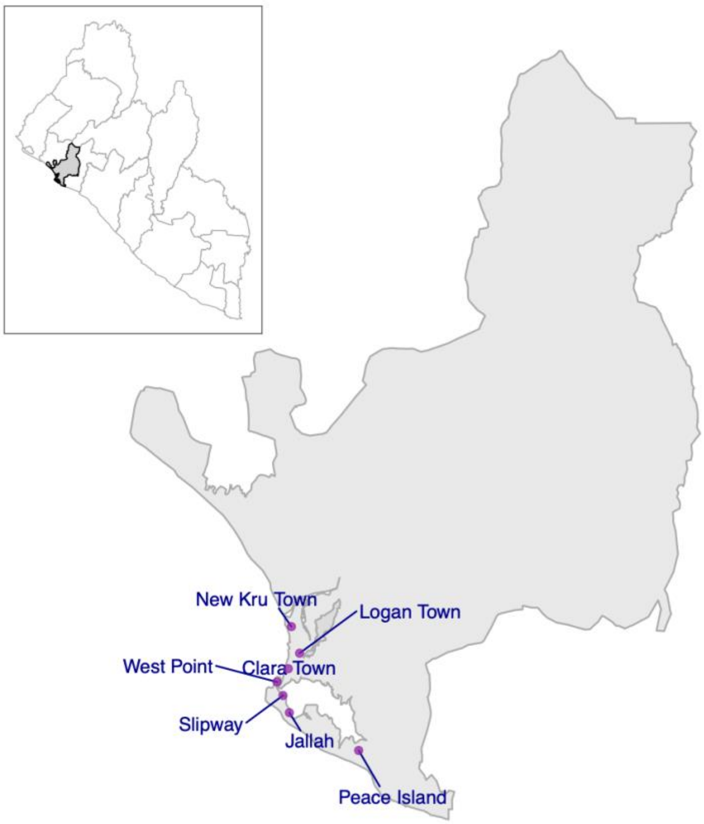
where $\beta_i$is the probability of infection upon contact with an infectious case from subpopulation *i* and $\varsigma_i$is a random draw from the distribution of contacts per person. Contact probabilities (χ_{ix}) between an individual from a community $x = 1$ in subpopulation *i* and an individual in that same community or from another community $x = 2$ in subpopulation *i* for $i = 1,2$ were derived from empirical zone-level contact matrices reported for Montserrado County in August 2014.[30] Specifically, the contact matrices reflect contacts between Ebola cases and contacts towards the beginning of the outbreak in Monrovia. Probabilities were calculated as between zones predominantly containing urban slums, as previously defined, and zones predominantly constituted by less socioeconomically vulnerable communities. The final term of the force of infection equation reflects the prevalence of infection in subpopulation i, after accounting for the relative infectiousness (σ_1) of asymptomatic to mildly symptomatic (*i.e.*, E_i is 1/1.6 times as infectious as I_{iM} [33]) and the relative infectiousness (σ_2) of severely symptomatic to mildly symptomatic (I_{iS}, 1.1 times as infectious as I_{iM}[34]) individuals.

Importation. Seeding of the outbreak in Liberia was assumed to occur via air travel until the closure of the airport with the issued state of emergency. Importation was possible for this duration among individuals leaving institutional quarantine and assumed to affect the less socioeconomically vulnerable subpopulation. Importation into the urban slum communities was expected to occur from the less socioeconomically vulnerable subpopulation and be proportional to the daily prevalence of infection (*i.e.*, the proportion of the overall population that is infected and infectious on day t) in it. For each iteration of the model, we assigned a day of introduction into each of the seven slum communities according to population-weighted probabilities and according to contact probabilities for between and within subpopulation interactions and after which community transmission would dominate. Once at least one community in the urban poor subpopulation had an importation, local transmission in that community was possible per the force of infection.

Community	Population Projection per 2008 Census	Adjusted Population**	Population-Weighted Probability
West Point	34,605	79,592	0.42
New Kru Town	5,880	13,524	0.07
Clara Town	20,976	48,245	0.26
Logan Town	6,749	15,523	0.08

Jallah	3,761	8,650	0.05
Slipway	5,418	12,461	0.07
Peace Island	4,658	10,713	0.06

* Reference: [31]
** Underreporting in the census for slum community populations has been recognized.[29] We adjusted by a factor of 2.5 to achieve population sizes more consistent with local estimates, although it is possible the adjusted populations remain underestimates.



Supplementary Figure 2. Map of Select Slum Communities in Montserrado County. Montserrado County is one of 15 counties in Liberia (insert) and includes the capital, Monrovia.

Intervention Dynamics

The status quo scenario reflects response interventions actively in place in Liberia. These have included contact tracing of high risk contacts identified by confirmed cases. According to national situation reports, the ratio of the number of contacts becoming a case to the number of newly confirmed cases has ranged from 20% to over 46% over the course of the epidemic (See attached Data File), thereby suggesting that the intervention is not covering all possible contacts.

Contact Tracing. We represented the coverage of effective contact tracing g as

$$g(t) = v(t) * c_i(t) * l * k_i$$

where ν is the effectiveness of contact tracing, which at each time step was considered as the ratio of the cumulative number of contacts becoming a case to the total number of confirmed cases, c is the coverage of contact tracing or the ratio of reported contacts per case at each time step to the number of contacts drawn from distribution ς_i, l is the probability of cooperation based on survey findings that 16% of Liberians denied the existence of COVID-19,[62] and k_i is the subpopulation-specific maximum attainable percentage of quarantine or isolation based on resource constraints.

Model Fitting

Model parameters were derived from the literature, where available, as either point estimates or distributions. Parameter sets were evaluated across ranges of probable values and the results calibrated according to predefined values for R_o using the next generation matrix approach. Specifically, the highest eigenvalue of the NGM expression was calculated for 1,000,000 randomly sampled values of the transmission parameter β across distributions for other stochastic model parameters, namely time to recovery, time to death, the incubation period, and a number of daily contacts for the less socioeconomically vulnerable subpopulation, in the R_o calculation. This was repeated for $s = 19\%$ and $s = 15\%$. We drew the parameter sets, including β, that generated R_o values within the 95% CI for R_o -- *i.e.*, 2.0 to 2.8 -- along with parameters from distributions for the urban slum subpopulation and ran the model for 180 daily timesteps. Model output was compared to cumulative reported case counts at weekly data points for 105 days post-introduction in Liberia using a likelihood-based approach based on equation:

$$L(P_j \mid parameter\ set) \propto \prod_{j=1}^{15} \binom{n_j}{x_t} P_j^{x_t} (1 - P_j)^{n_j - x_j}$$

Where x_j represents a vector of weekly cumulative cases at week j, n_j represents population size, and P_j represents model-estimated vector of cumulative incidence.

To account for underreporting of cases, we calculated the fit of cumulative counts of severely symptomatic cases from the model to reported cases for Montserrado County (See attached Data File). Parameter sets resulting in cumulative modeled case counts that exceeded the total number of confirmed cases in Montserrado County at 105-days post-introduction and resulting in fewer severe cases in the urban slum subpopulation than in the less socioeconomically vulnerable subpopulation were included for further consideration. The resulting parameter sets, consisting of those drawn from the R_o along with a number of funeral contacts and the relative value of β_1 versus β_2, were used to implement forward transmission and intervention scenarios.

Supplementary Table 1. Epidemiological parameters

Parameter Description	Symbol	Distribution or Estimate	Reference
Derived from Literature			
Birth rate	b	(31.6/1000)/365 day^{-1}	[63]
Natural death rate	μ	(7.1/1000)/365 day^{-1}	[63]
Incubation period	$1/\rho$	~lognormal($\mu = 5.1, s = 1.5$)**	[64]
Percentage of cases remaining asymptomatic	a	17.9%	[65]
Percentage of symptomatic cases with mild symptoms	$1 - s$	85.0%; 81.0%	[38–40]
Percentage of symptomatic cases with severe symptoms	s	15.0%; 19.0%	[38–40]
Time to death among severe cases	$1/\pi$	~lognormal($\mu = 16.1, s = 3.6$)	[66]
Percentage of severely symptomatic cases who die	p	13.2%	[39]
Percentage of severely symptomatic cases who recover	$1 - p$	86.8%	[39]
Time to recovery	$1/\omega$	~lognormal($\mu = 9.5, s = 2.5$)	[39]
Ratio of infectiousness of asymptomatic/presymptomatic to symptomatic in the community	σ_1	1/1.6	[33]
Ratio of infectiousness of severely symptomatic to	σ_2		

mildly symptomatic in the community			
Calculated			
Parameter	Symbol	Expression	
Probability of transmission per contact with infectious case	β_2	Calibrated to achieve $2.0 \leq R_0 \leq 2.8$ via Next Generation Matrix approach	
Ratio of transmission probabilities for subpopulation 1 versus for subpopulation 2	β_1/β_2	~uniform(min=1, max=2)	
Force of infection (community level)	λ		
Force of infection (household level)	λ_H	$\lambda_{iH} = \beta_i \times I_i(t)/N_i(t)$	
Force of infection (funeral events)	λ_F	$\lambda_{iF} = \beta_i \times I_i(t)/N_i(t)$	
Time with increased susceptibility among household members of new cases	γ	$\gamma = 1/(\rho^{-1} + \omega^{-1})$	
Time in home isolation or hospital	$\underline{\tau}$	$\underline{\tau} = 1/(\omega^{-1} - \tau^{-1})$	

** Shape and location parameters for the lognormal distribution were related to μ and s as follows: $shape = \sqrt{ln(1 + (s^2/\mu^2))}$ and $location = ln(\mu^2/\sqrt{s^2 + \mu^2})$

Supplementary Table 2. Subpopulation-Specific and Behavioral Parameters

Parameter Description	Symbol	Distribution or Estimate*	Reference
Contacts per burial	ς_f	~triangular(mode=68, min=25, max=75)	[48,67,68]
Number of contacts	ς_i	Urban poor population: ~lognormal($\mu = 10.3, s = 10.7$) Less socioeconomically vulnerable population: ~lognormal($\mu = 7.4, s = 9.5$)	[30]

Percentage of contacts within the same zone	χ_{ix}	Urban poor population: 95.8% Less socioeconomically vulnerable population: 98.2%	[30]
Percentage of contacts within the same subpopulation but different zone	χ_{ix}	Urban poor population: 2.5% Less socioeconomically vulnerable population: 0.8%	[30]
Percentage of contacts between subpopulations	χ_{ix}	Urban poor population: 1.7% General population: 0.9%	[30]
Effectiveness of contact tracing	$\nu(t)$	Calculated from situation reports	[69]
Percentage of urban poor subpopulation identifying toilets as a major concern		26.7%	[44]
Percentage of urban poor subpopulation identifying water as a major concern		20.3%	[44]
Percentage of households with 1-2 persons per sleeping room		53.4%	[44]
Percentage of respondents from Liberia indicating ease of adhering to social distancing measures		Very difficult: 14.01% Difficult: 18.21% Neither difficult nor easy: 38.94% Easy: 21.29% Very easy: 7.56%	[46]
Percentage of respondents from Liberia indicating level of confidence that the information received from State and Local authorities on COVID-19 is accurate		Not at all confident: 15.28% Slightly confident: 33.33% Moderately confident: 16.67% Very confident: 22.22% Extremely confident: 12.5%	[70]
Maximal attainable percentage of mildly symptomatic cases in home isolation, in absence of support	k_i	Urban poor population (without support): 53.4%×(1-(26.7% + 20.3%)) Urban poor population (with support): 7.56% + 21.29% + 38.94% Less socioeconomically vulnerable population: 7.56% + 21.29% + 38.94%	[44,46,70]

Time to home isolation among mildly symptomatic cases or to hospitalization among severely symptomatic cases	τ_i	Urban poor population: ~lognormal($\mu = 5.33, s = 5.97$) Less socioeconomically vulnerable population: ~lognormal($\mu = 4.58, s = 5.03$)	[30]
Proportion of mildly symptomatic cases undergoing home isolation	e_{1i}(t)	$0, 1 \le t \le 26$ $k_i \times (n/7)_{n=1}^{6}, 27 \le t \le 56$ $k_i, 57 \le t \le 180$	
Proportion of severely symptomatic cases undergoing hospitalization	e_2(t)	Step function: $0, 1 \le t \le 26$ $0.3 \times (n/7)_{n=1}^{6}, 27 \le t \le 56$ $0.3, 57 \le t \le 180$	
Time to home isolation or hospitalization among high risk contacts quarantined in presymptomatic phase	$\bar{\bar{\rho}}$	$\bar{\bar{\rho}} = 1/(\rho^{-1} + \tau^{-1})$	

Supplementary Table 3. Absolute reductions in infections, severe cases, and maximum daily incidence by intervention scenario

Please see attached file.

Supplementary Table 4. Percentage reductions in infections, severe cases, and maximum daily incidence by intervention scenario

Please see attached file.