Modelling interventions to control COVID-19 outbreaks in a refugee camp

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Abstract

Refugee camp populations are expected to be vulnerable to COVID-19 due to overcrowding, unsanitary conditions, and inadequate medical facilities. Because there has been no COVID-19 outbreak in a refugee camp to date, the potential for nonpharmaceutical interventions to slow the spread of COVID-19 in refugee camps remains untested. We used an agent-based model to simulate COVID-19 outbreaks in the Moria refugee camp, and we studied the effects of feasible interventions. Subdividing the camp (‘sectoring’) “flattened the curve,” reducing peak infection by up to 70% and delaying peak infection by up to several months. The use of face masks coupled with efficient isolation of infected individuals reduced the overall incidence of infection and sometimes averted epidemics altogether. These interventions must be implemented quickly to be effective. Lockdowns had little effect on COVID-19 dynamics. Our findings provide an evidence base for camp managers planning intervention strategies against COVID-19 or future epidemics.
Introduction

There are more than 70 million refugees and internally displaced persons worldwide, including more than 20 million living in displacement camps.\(^1\) Displaced populations are expected to be vulnerable to COVID-19 due to poor nutrition, high rates of pre-existing disease, and inadequate access to healthcare.\(^2\)-\(^5\) COVID-19 may spread rapidly in camps due to overcrowding, poor sanitation, and frequent close contact among residents (e.g., in food lines, at shared toilets, and at shared washing facilities).\(^5\)-\(^7\) Truelove and colleagues used a computational simulation to study a potential COVID-19 outbreak in a population modelled on the Kutupalong-Balukhali refugee camp in Bangladesh, and estimated that up to 98\% of the population could become infected over a short period, overwhelming the camp’s limited medical facilities.\(^8\) Many countries have imposed interventions such as mandatory social distancing, isolation of confirmed cases, or general lockdowns to slow the spread of COVID-19, and in some cases these have been successful.\(^9\)-\(^11\) However, whether similar interventions can be effective in the uniquely challenging setting of a displacement camp is unknown.\(^7\)

The Moria refugee camp on the island of Lesbos, Greece, is Europe’s largest displacement camp. A former prison, it was converted into a refugee reception facility with the arrival of people fleeing the Syrian civil war in 2015. Designed to hold 3,000 people, it now houses nearly 20,000 in an area of less than 1 km\(^2\).\(^12\) Non-governmental organizations (NGOs) working in Moria report severe overcrowding, poor sanitation, a lack of hygiene facilities (e.g., toilets, showers, 24-hour running water), and queuing at central facilities (e.g., food lines).\(^13\),\(^14\) The population has little access to healthcare outside the camp, and there is a lack of adequate healthcare in the camp (e.g., no 24-hour service, provided only by volunteer organizations). Approximately 5\% of the camp’s population is highly vulnerable to COVID-19 infection, including people with chronic health conditions and those over 65 years of age. COVID-19 has not yet reached the camp. However, there have been cases of COVID-19 on Lesbos,\(^13\),\(^15\) and the virus is likely to reach the camp soon. Because there has not yet been an outbreak in a displacement camp, there is no empirical data to show which interventions are best able to combat the spread of COVID-19 in this setting. In the absence of empirical data, mathematical and computational models can provide an evidence base for managers planning intervention strategies, and lessons learned may be transferable to other displacement camps.
Displacement camp populations are spatially structured. In Moria, residents interact most frequently with other members of their own households. They interact with members of nearby households during daily activities or at shared toilet facilities, and they interact with residents from all parts of the camp at the camp’s single shared food line. This interaction structure will affect how COVID-19 spreads through the camp, and interventions that change the interaction structure may alter the trajectory of outbreaks. Previous modelling of COVID-19 outbreaks in displacement camps used compartmental models, which assume that populations are well-mixed. Agent-based models that track individuals through simulated daily movements are better able to capture transmission dynamics in structured populations. Furthermore, agent-based models can incorporate transmission probabilities and clinical progression rates that depend on the characteristics (e.g., age, sex, pre-existing health state) of the individuals in the population, and this is difficult to achieve with compartmental models.

We developed the first agent-based model of an epidemic in a displacement camp setting, and we applied it to evaluate potential interventions to combat the spread of COVID-19. The model tracks individuals as they undertake daily activities in a model camp (see Methods). COVID-19 can be transmitted when infected and susceptible individuals interact. The demographics and spatial structure of the model camp simulate Moria, and the parameters that control COVID-19 transmission rates and disease progression are estimated from the literature. We simulated COVID-19 outbreaks without interventions and in the presence of four interventions feasible for displacement camps: i) sectoring, ii) transmission reduction, iii) remove-and-isolate, and iv) lockdown. In sectoring, the central food line is eliminated and the camp is divided into sectors. Each sector has its own food line, and each individual uses the food line in the sector in which it lives. Thus, time spent in the food line is reduced and transmission in the food line becomes local rather than global. Transmission reduction could be any policy or behaviour that reduces the probability that infection is transmitted when individuals interact (e.g., the use of face masks, frequent hand washing, maintaining safe distances from others). Frequent hand-washing and maintaining safe distances from others are likely to be impossible in Moria, but residents have been provided with face masks. Therefore, we simulated face mask use, and we refer to this intervention as “face masks” throughout this paper. In remove-and-isolate, households with symptomatic individuals are moved to an isolation facility to prevent onward transmission of the infection. Finally, in lockdown, individuals are constrained to remain within some distance of their homes, except
when visiting shared toilets or food lines. A small proportion of the population violates the lockdown rule. For each intervention or combination of interventions, we conducted simulations in which we introduced an infected individual into the population, and we recorded the proportion of times that an epidemic was averted (i.e., fewer than 20 people became infected). If an epidemic occurred, we recorded i) the peak proportion of the population infected, ii) the time from the introduction of the first case until the peak, and iii) the total proportion of the population that became infected. For remove-and-isolate interventions, we also recorded the maximum number of individuals kept in isolation to help assess the feasibility of the intervention.

Results

The probability that COVID-19 is transmitted when individuals interact is poorly understood. Therefore, we studied both low- and high-transmission scenarios based on low- and high-end estimates from the literature. The true transmission probabilities for COVID-19 are likely to fall between these estimates. How individuals use space and interact with others in Moria or other refugee camps has not been studied. Therefore, we modelled low- and high-movement scenarios and low- and high-interaction scenarios based on estimates provided by healthcare workers in Moria. In the body of this paper we present results for the low-movement, high-interaction scenario, but results are qualitatively similar for other scenario combinations (supplementary tables S1-S11). To simulate face mask use, we reduced the odds of transmission by a factor of 0.32 in all interactions outside the home. A similar reduction has been achieved with the use of surgical masks for other respiratory viruses. The other interventions can be imposed with different intensities (e.g., more or fewer sectors, more or less efficient detection of symptoms in remove-and-isolate interventions, stricter or less strict lockdowns). In the body of the paper we present results for sectoring into 16 sectors, remove-and-isolate with a daily detection rate of 50% for symptomatic individuals, and lockdowns where individuals stay within 10 m of their homes and there is a 10% lockdown violation rate. We present qualitatively similar results for interventions with other intensities in supplementary tables S3-S8.
In the absence of interventions, the introduction of a single COVID-19 case into the model population almost always (≥98%) leads to epidemics in both the low- and high-transmission scenarios (tables 1, S1). In the low-transmission scenario, the median peak infection includes 67% of the population and occurs 55 days after the index case appears (figure 1A). In the high-transmission scenario, the median peak infection includes >99% of the population and occurs on day 20 (figure 1B). In total, 98% and >99% of the population becomes infected in the low- and high-transmission scenarios, respectively (table 1).

| Intervention                  | Total proportion infected | Epidemics averted | Total proportion infected | Epidemics averted |
|-------------------------------|---------------------------|-------------------|---------------------------|-------------------|
| Low transmission              |                           |                   |                           |                   |
| no intervention               | 0.98 (0.98-0.98)          | 0.03              | 0.87 (0.87-0.88)          | 0.17              |
| sectoring                     | 0.96 (0.96-0.96)          | 0.05              | 0.77 (0.76-0.78)          | 0.26              |
| remove-and-isolate            | 0.87 (0.86-0.87)          | 0.27              | 0.006 (0.003-0.013)       | 0.66              |
| lockdown                       | 0.98 (0.98-0.99)          | 0.04              | 0.87 (0.87-0.88)          | 0.14              |
| High transmission             |                           |                   |                           |                   |
| no intervention               |                           |                   |                           |                   |
| sectoring                     |                           |                   |                           |                   |
| remove-and-isolate            |                           |                   |                           |                   |
| lockdown                       |                           |                   |                           |                   |

All: total proportion infected >0.99 epidemics averted ≤0.01

Table 1. Total proportion of the population infected and epidemics averted without or with interventions in the low- and high-transmission scenarios. For total proportions infected, we report medians and interquartile ranges for all simulations in which epidemics occurred. For epidemics averted, we report proportions of 200 simulations. Grey cells indicate simulations without interventions.
Interventions can slow or stop the spread of COVID-19 (figure 1; tables 1, S2-S11). Sectoring reduces and delays the peak infection in both the low-transmission (median peak infection 20% on day 98) and high-transmission (median peak infection 54% on day 40) scenarios, but most individuals ultimately become infected (low-transmission scenario: total infection 96%, epidemics averted 5%; high-transmission scenario: total infection >99%, epidemics averted <1%). Face masks and remove-and-isolate interventions reduce and delay the peak infection in the low-transmission scenario (face masks: median peak infection 31% on day 96, figure 1C; remove-and-isolate: median peak infection 39% on day 70), but not in the high-transmission scenario (both interventions: median peak infection ≥97% on day ≤27). Moreover, unlike sectoring, in the low-transmission scenario, face masks and remove-and-isolate interventions can stop the epidemic.

Figure 1. Total infections over time for COVID-19 epidemics with different interventions in populations with low movement, high interaction, and (A,C) low or (B,D) high transmission probabilities. Panels (A,B) show dynamics without face mask use, and (C,D) show dynamics with face mask use. Curves show the most representative simulation (i.e., the simulation with the peak infection and peak infection date closest to the median) for the corresponding intervention. When transmission probabilities are high (B,D), only sectoring reduces or delays peak infection. When transmission probabilities are sufficiently low (i.e., low transmission with face masks, C), remove-and-isolate interventions can stop the epidemic.
isolate interventions reduce the proportion of the population that ultimately becomes infected (face masks: total infection 87%, epidemics averted 17%; remove-and-isolate: total infection 87%, epidemics averted 27%). In contrast to the other interventions, lockdowns have little effect on epidemics (low-transmission scenario: median peak infection 66% on day 57; high-transmission scenario: median peak infection >99% on day 20).

The use of face masks can augment the effects of other interventions (figure 1C,D; tables 1, S6-S8). In the low-transmission scenario, sectoring combined with face masks reduces the median peak infection to 9% on day 167, limits total infection to 77% of the population, and prevents 26% of COVID-19 introductions from becoming epidemics. In the high-transmission scenario, sectoring combined with face masks reduces the median peak infection to 39% of the population on day 53, but >99% of the population eventually becomes infected. In the low-transmission scenario, remove-and-isolate combined with face masks prevents most epidemics (median peak infection 0.2%, total infection 0.6%, 66% of epidemics averted). However, in the high-transmission scenario, remove-and-isolate combined with face masks is little better than face masks alone. Similarly, in both scenarios, lockdown combined with face masks is little better than face masks alone.
Sectoring and remove-and-isolate interventions can help control epidemics, but must be implemented early in order to be maximally effective (figure 2; tables S9, S10). If face masks are in use but sectoring is not implemented until 1% of the population shows symptoms in the low-transmission scenario, then the median peak infection increases from 9% to 19% and the proportion of epidemics averted drops from 26% to 14%. In the high-transmission scenario, sectoring after the virus is introduced to the population has little effect on the epidemic at all. If remove-and-isolate is not implemented until 1% of the population shows symptoms in the low-transmission scenario, then the median peak infection increases from 0.2% to 8.6%, the median total infection increases from 0.6% to 30%, and epidemics averted drops from 66% to 

![Figure 2](https://example.com/figure2.png)

Figure 2. Total infections over time for COVID-19 epidemics when (A,B) sectoring or (C,D) remove-and-isolate interventions start before the virus arrives, when 0.1% of the population has symptoms, when 1% of the population has symptoms, or not at all. Face masks were in use throughout all simulations. (A,C) show the low-transmission and (B,D) show the high-transmission scenario. Curves show the most representative simulation for the corresponding intervention. In all cases, a delayed start to the intervention results in higher peak infection. In the high-transmission scenario, even a slightly delayed start eliminates all gains that could be achieved by the intervention.
10%. In the high-transmission scenario, remove-and-isolate is not effective even if it is implemented early (figure 1D).

**Discussion**

Displacement camp populations are expected to be highly vulnerable to COVID-19 and other epidemics due to poor sanitation, crowded conditions, high rates of pre-existing disease, and inadequate access to healthcare.\textsuperscript{2,3,6} Without intervention, a single case of COVID-19 introduced into our model population almost always led to a severe epidemic that rapidly spread through the entire population. Sectoring, remove-and-isolate interventions, and the use of face masks slowed the spread of infection, and in some cases stopped epidemics altogether. These interventions must be implemented early to be maximally effective. Our results can help displacement camp managers choose the most effective interventions to protect vulnerable populations from COVID-19 and other epidemics.

Dividing the camp into sectors with separate food lines reduced and delayed the infection peak. Reducing the number of people that are infected at the same time may help alleviate pressure on limited medical services both in the camp and in the surrounding community.\textsuperscript{10} However, while sectoring slowed the rate at which the epidemic spread through the camp, it rarely averted epidemics altogether and had only a small effect on the total number of people that became infected. Thus, while sectoring may reduce pressure on medical services, sectoring alone is unlikely to protect vulnerable members of the population who may be at heightened risk due to COVID-19 with or without medical attention.

In contrast to sectoring, both face mask use and remove-and-isolate interventions reduced the total number of people that became infected. When infectiousness was at the low end of published estimates for COVID-19, face masks coupled with an efficient remove-and-isolate plan prevented more than 65% of COVID-19 introductions from becoming epidemics and limited the median total infection to <1% of the population. Combining these interventions with sectoring produced further gains. However, the effectiveness of face masks and remove-and-isolate interventions was sensitive to the infectiousness of the virus. If the infectiousness was at the high end of published estimates, face mask use and remove-and-isolate
interventions had little effect on epidemics. Furthermore, remove-and-isolate interventions require that managers are able to quickly and accurately detect COVID-19 cases, and may be resource-intensive, especially when they fail to completely avert epidemics. Because people must be maintained in isolation until managers are sure they are no longer infectious, the maximum number of people in isolation will usually be larger than the peak infection (supplementary tables S4, S7, S10, and S11). If managers’ capacity to remove and isolate infected individuals is overwhelmed, then remove-and-isolate interventions will fail.

In our model, requiring individuals to remain within a small radius of their homes had little effect on epidemics. Moreover, the lockdowns we studied were ambitious. For results reported in the body of the paper, we assumed that only 10% of people would violate the lockdown rule, but in the UK more than 25% of young women and more than 50% of young men admit to regularly violating lockdown rules and similar patterns have been reported in the US. Thus, it is not clear that lockdowns of the sort we modelled will be effective at combatting the spread of COVID-19 in refugee camps. However, the number of interactions that individuals engage in each day can affect the dynamics of epidemics (compare shaded to unshaded rows in supplementary tables S1-S11). Thus, encouraging camp residents to limit their daily interactions may be a viable tool for slowing epidemics.

Sectoring and remove-and-isolate interventions must be implemented from the beginning of an outbreak if they are to be maximally successful. If interventions are not in place when the virus arrives, the virus can rapidly spread to all parts of the camp. It then becomes very difficult to contain. Background rates of respiratory infection in displacement camps are high, which may make new infections difficult to detect. Thus, population managers should be prepared to impose interventions at the first threat of epidemic.

Our results provide valuable guidance to displacement camp managers, who currently lack empirical evidence to support intervention planning. However, the parameter values that underlie our results are estimated with uncertainty. The transmission probabilities for COVID-19 are estimated from the literature, which is rapidly evolving. The parameter values that describe how individuals move and interact in the camp are estimated from consultation with camp medical staff, and empirical data to confirm these estimates do not exist for Moria or any other displacement camp. Different transmission probabilities, and to a lesser extent different interaction rates, within the plausible range of values result in very different
epidemics. Until parameter values can be more accurately estimated, our model should not be used to make quantitative predictions about peak infection rates, times to peak infection, or proportions of epidemics averted. Some qualitative predictions of the model also depend on the parameter values. For example, in the low-transmission scenario, combinations of the interventions we modelled can stop the spread of COVID-19. In the high-transmission scenario, sectoring can slow the epidemic, but almost the entire population is eventually infected. Thus, in the high-transmission scenario, the removal and shielding of vulnerable individuals (i.e., those over 65 years old, or with pre-existing conditions\textsuperscript{2,19,20}) may be the only intervention that saves lives. Per interaction transmission rates are notoriously difficult to estimate empirically, and interaction rates and networks among members of vulnerable populations have rarely been studied. These are key parameters in agent-based epidemiological models, and agent-based models are better than classical compartmental models at simulating the spread of disease in structured and heterogeneous populations.\textsuperscript{16} Thus, empirical work to estimate interaction rates and per interaction transmission probabilities may be of great value. Finally, our model assumes that individuals that have recovered from COVID-19 cannot be re-infected at least for the duration of the epidemic, and evidence to support this assumption is limited.\textsuperscript{33} As more empirical data on COVID-19 becomes available, our model can be updated to provide more accurate predictions.

The model we present here is the first attempt to evaluate potential interventions to control the spread of COVID-19 in a displacement camp. We focused on Moria because severe overcrowding, poor sanitation, and frequent centralised queuing make it a particularly challenging setting for disease control,\textsuperscript{6-8} and because the recent arrival of COVID-19 on Lesbos makes intervention planning for the camp an urgent priority.\textsuperscript{13,15} However, with modified parameter values, our model can be applied to evaluate potential interventions to combat COVID-19 or other transmissible diseases in other displacements camps or vulnerable populations (e.g., urban slums\textsuperscript{7}).

Many uncertainties exist about how COVID-19 will affect refugee camp populations, and whether feasible interventions can mitigate these effects. It is not possible to evaluate interventions with well-controlled experiments, because it would be unethical to apply interventions in some populations and withhold them from others. In the absence of empirical data, agent-based simulations like those we present here may offer the best opportunity to assess potential interventions and to plan management strategies that could save human lives.
Methods

Overview

We used a spatially explicit agent-based model to track simulated COVID-19 epidemics unfolding in a refugee camp over discrete timesteps that correspond to days. The infection starts in one individual, and is transmitted probabilistically among individuals as they interact during daily activities. We modelled epidemics with no interventions, and epidemics where interventions or combinations of interventions were used to reduce disease transmission. We compared the peak number of infected individuals, the time to peak infection, and the total number of individuals infected, with or without interventions.

The parameter values that describe the population and the camp simulate the Moria refugee camp on Lesbos, Greece. The parameter values that describe disease progression and transmission are drawn from the literature. The parameter values that describe individuals’ movements about the camp are heuristic, but our qualitative predictions hold under other reasonable sets of parameter values (supplementary tables S1-S11).

Throughout these methods, we used “Moria” to refer to the Moria refugee camp, and “camp” to refer to the camp in our model. We used “person” or “people” to refer to the residents of Moria, and we used “individuals” to refer to individuals in the model population.

The population

The model population comprises 18,700 individuals. Each individual is characterised by its age, sex, condition, and disease state. Condition describes whether an individual is healthy or has a pre-existing condition that increases the risk of severe infection or mortality from COVID-19 (i.e., hypertension, diabetes, cardiovascular disease, or chronic lung disease). Each individual is assigned an age, sex and condition that matches a randomly selected
person from the medical records of the Moria camp. These characteristics do not change over time. The disease state describes the progression of a COVID-19 infection in an individual, and therefore does change over time. The initial disease state for all individuals is “susceptible.”

The camp

Each individual is a member of a household that occupies either an isobox or a tent. Isoboxes are prefabricated housing units with a mean occupancy of 10 individuals. Tents have a mean occupancy of 4 individuals. A total of 8,100 individuals occupy isoboxes and 10,600 individuals occupy tents. These correspond to the numbers of people occupying isoboxes and tents in Moria. The exact occupancy of each isobox or tent is drawn from a Poisson distribution, and individuals are assigned to isoboxes or tents randomly without regard to sex or age. This is appropriate because many people arrive at Moria travelling alone, and thus isoboxes or tents may not represent family units.

The camp covers a 1 x 1 (e.g., km) square (figure 3). Isoboxes are assigned to random locations in a central square that covers one half of the area of the camp. Tents are assigned to random locations in the camp outside of the central square. There are 144 toilets evenly distributed throughout the camp. Toilets are placed at the centres of the squares that form a 12 x 12 grid covering the camp. The camp has one food line. The position of the food line is not explicitly modelled.

In Moria, the homes of people with the same ethnic or national background are spatially clustered, and people interact more frequently with others from the same background as themselves. To simulate ethnicities or nationalities in our camp, we assigned each household to one of eight “backgrounds” in proportion to the self-reported countries of origin of people.
in the Moria medical records. For each of the eight simulated backgrounds, we randomly selected one tent or isobox to be the seed for the cluster. We assigned the $x$ nearest unassigned households to that background, where $x$ is the number of households with that background. Thus, the first background occupies an area that is roughly circular, but other backgrounds may occupy less regular shapes (figure 3).

**Disease Progression**

If an individual becomes infected, the infection progresses through a series of disease states (figure 4). The time from exposure until symptoms appear (i.e., the incubation period) is drawn from a Weibull distribution with a mean of 6.4 days and a standard deviation of 2.3 days.\textsuperscript{30} In the first half of this period, the individual is “exposed” but not infectious. In the second half, the individual is “pre-symptomatic” and infectious.\textsuperscript{26} Fractional days are rounded to the nearest whole day in discrete-time simulations. After the incubation period, the individual enters one of two states: “symptomatic” or “1\textsuperscript{st} asymptomatic.” Children under the age of 16 become asymptomatic with probability 0.836 and others become asymptomatic with probability 0.178.\textsuperscript{22,28} Individuals remain in the symptomatic or 1\textsuperscript{st} asymptomatic states for 5 days and are infectious during this period. After 5 days, individuals pass from the symptomatic to the “mild” or “severe” states with age- and condition-dependent probabilities following Verity and colleagues\textsuperscript{19} and Tuite and colleagues\textsuperscript{20}. All individuals in the 1\textsuperscript{st} asymptomatic state pass to the “2\textsuperscript{nd} asymptomatic” state. Individuals are infectious in these states. On each day, individuals in the mild or 2\textsuperscript{nd} asymptomatic state pass to the recovered

![Diagram of Disease Progression](https://example.com/diagram.png)

*Figure 4. Progression of COVID-19 infection in individuals*
state with probability 0.37, and individuals in the severe state pass to the recovered state with probability 0.071. Recovered individuals are not infectious, and are not susceptible to reinfection. We did not model deaths explicitly, but this is unlikely to affect the dynamics of the epidemic if neither recovered nor dead individuals are infectious.

### Infection Dynamics

Infection can be transmitted from infectious to susceptible individuals as they go about their daily activities. Let $p_{idw}$ denote the probability that susceptible individual $i$ becomes infected on day $d$ by transmission route $w$, where $w \in \{h, t, f, m\}$ indicates transmission within the household, at toilets, in the food line, or as individuals move about the camp, respectively. The probability that susceptible individual $i$ becomes infected on day $d$ is thus

$$p_{id} = 1 - \prod_{w \in \{h, t, f, m\}} (1 - p_{idw}). \quad (1)$$

We lack detailed information on how people use space in Moria or any other refugee camp. Therefore, we did not model movement explicitly, but instead calculated the $p_{idw}s$ for each individual given its expected activities on each day. This reduces the computational time for simulations.

**Infection within the household.** On each day, each infectious individual infects each susceptible individual in the same household with probability $p_h$. Thus, if individual $i$ shares a household with $h_{cid}$ infectious individuals on day $d$, then

$$p_{idh} = 1 - (1 - p_h)^{h_{cid}}. \quad (2)$$

**Infection at toilets.** We assumed that every individual visits the toilet nearest its household 3 times each day, and must always wait in line. If a susceptible individual is in front of or behind an infectious individual in the toilet line, the susceptible individual becomes infected with probability $p_t$. Thus, the probability that susceptible individual $i$ becomes infected in the toilet line on day $d$ is
\[ p_{idt} = 1 - \sum_{j=0}^{6} j \left( 1 - \frac{t_{cid}}{t_{id}} \right)^{6-j} \left( \frac{t_{cid}}{t_{id}} \right)^{j} (1 - p)^j, \]

where \( t_{cid} \) and \( t_{id} \) are the numbers of infectious individuals and of all individuals, respectively, that share a toilet with individual \( i \) on day \( d \).

**Infection in the food line.** The food line forms 3 times each day. We assumed that only individuals without symptoms (i.e., susceptible, exposed, pre-symptomatic, asymptomatic, or recovered) attend food lines. Food is delivered to individuals with symptoms by others, without interaction (e.g., food might be left outside homes). Each individual without symptoms attends the food line once per day on 3 out of 4 days. On other occasions, food is brought to that individual by another individual without additional interactions. For example, food might be brought by a member of the same household, or by a neighbour with whom the individual would otherwise interact (see below). If an individual attends the food line, it interacts with two individuals behind it and two individuals in front of it in the line. Because food lines in Moria are extremely dense,\textsuperscript{13,14} this may be conservative. If a susceptible individual interacts with an infectious individual in the food line, the susceptible individual becomes infected with probability \( p_f \). Thus, the probability that susceptible individual \( i \) becomes infected in the food line on day \( d \) is

\[ p_{idf} = \frac{3}{4} \left( 1 - \sum_{j=0}^{4} j \left( 1 - \frac{n_{yd}}{n_{zd}} \right)^{4-j} \left( \frac{n_{yd}}{n_{zd}} \right)^{j} (1 - p_f)^j \right), \]

where \( n_{yd} \) is the number of infectious individuals without symptoms (i.e., pre-symptomatic and asymptomatic) in the camp on day \( d \), and \( n_{zd} \) is the total number of individuals without symptoms in the camp on day \( d \).

**Infection as individuals move about the camp.** Individuals move about outside their households, and interact with individuals from other households as they move. We assumed that each individual occupies a circular home range centred on its household, and uses all parts of its home range equally. Two individuals may interact if their home ranges overlap. If individuals \( i \) and \( j \) have home ranges with radii \( r_i \) and \( r_j \), respectively, and the distance between their households is \( d_{ij} \), then the area of overlap in their home ranges is.
\[ a_{ij} = r_i^2 \cos \left( \frac{d_{ij}^2 + r_i^2 - r_j^2}{2d_{ij}r_i} \right) + r_j^2 \cos \left( \frac{d_{ij}^2 - r_i^2 + r_j^2}{2d_{ij}r_j} \right) - \frac{1}{2} \sqrt{(-d_{ij} + r_i + r_j)(d_{ij} + r_i - r_j)(d_{ij} - r_i + r_j)(d_{ij} + r_i + r_j)} \]  

(5)

The proportion of time that individuals \( i \) and \( j \) spend together in the area of overlap is

\[ s_{ij} = \frac{a_{ij}}{\pi r_i^2}, \quad s_{ij} = \frac{a_{ij}}{\pi r_j^2}, \]  

(6)

and the relative encounter rate between individuals \( i \) and \( j \) is

\[ \frac{s_{ij}}{a_{ij}} = \frac{a_{ij}}{\pi^2 r_i^2 r_j^2}. \]  

(7)

Equation (7) means that individuals encounter each other more frequently if they co-occupy a small area than if they co-occupy a large area for the same amount of time. To obtain the interaction rate between individuals \( i \) and \( j \) from the relative encounter rate, we scaled by a factor \( g_{ij} \) to account for ethnicity or country of origin. In particular, \( g_{ij} = 1 \) if individuals \( i \) and \( j \) have the same background, and \( g_{ij} = 0.2 \) otherwise. Furthermore, we scaled the interaction rate such that two individuals with the same background that share an identical home range with a radius of \( r_s \) interact on average once each day. The parameter \( r_s \) allows us to scale the mean interaction rate in the population independent of the distance that people travel around their homes. After scaling, the daily rate of interaction between individuals \( i \) and \( j \) is

\[ f_{ij} = r_s^2 \frac{a_{ij}}{\pi r_i^2 r_j^2} g_{ij}. \]  

(8)

We assumed that only individuals without symptoms interact in their home ranges. Thus, the rate at which individual \( i \) interacts with infected individuals in its home range on day \( d \) is

\[ q_{id} = \sum_j I(j, d) f_{ij}, \]  

(9)

where \( I(j, d) = 1 \) if individual \( j \) is pre-symptomatic or asymptomatic on day \( d \) and \( I(j, d) = 0 \) otherwise. The summation in equation (9) runs over all individuals in the model that do not
share a household with individual $i$. The probability that susceptible individual $i$ becomes infected on day $d$ while moving about its home range is thus

$$p_{idm} = 1 - e^{-q_idp_m},$$

(10)

where $p_m$ is the probability of transmission when a susceptible individual interacts with an infectious individual.

**Assigning parameter values.** The probabilities that COVID-19 is transmitted among individuals in different settings are not well-understood. Therefore, we studied both high- and low-transmission scenarios. In the high-transmission scenario we set $p_h = 0.33$, $p_f = 0.099$, $p_f = 0.407$, and $p_m = 0.017$, and in the low-transmission scenario we set $p_h = 0.0397$, $p_f = 0.0067$, $p_f = 0.0397$, and $p_m = 0.006$. These values are derived from the literature in the supplementary information. We also know very little about how people use space or interact in Moria or in other refugee camps. Thus, we modelled high- and low-movement and high- and low interaction scenarios. In the high-movement scenario, we assumed that males over 10 years old use home ranges with radius 0.2 (i.e., 200 m), and that males under 10 years old and all females use home ranges with radius 0.05. In the low movement scenario, we assumed that males over 10 years old use home ranges with radius 0.1, and all others use home ranges with radius 0.02. In the high-interaction scenario, we set $r_s$ so that the average individual in the camp interacts with 20 others per day (i.e., $r_s = 0.0226$ and $r_s = 0.0202$ in high- the low-movement scenarios, respectively). In the low-interaction scenario, we set $r_s$ so that the average individual in the camp interacts with 5 others per day (i.e., $r_s = 0.0113$ and $r_s = 0.0101$ in high- the low-movement scenarios, respectively).

**Interventions**

We modelled four different interventions that might be imposed on the baseline model, alone and in combinations: sectoring, face mask use, remove-and-isolate, and lockdown.

**Sectoring.** The camp in our baseline model has a single food line where transmission can occur among individuals from any parts of the camp. This facilitates the rapid spread of infection. A plausible intervention would be to divide the camp into sectors with separate food lines, and require individuals to use the food line closest to their homes. To simulate
such an intervention, we divided the camp into $n$ sectors, each with its own food line. These sectors form a $\sqrt{n} \times \sqrt{n}$ grid over the camp. We replaced equation (4) with

$$p_{idf} = \frac{3}{4} \left( 1 - \sum_{j=0}^{4} \left( 1 - \frac{n_{iyd}}{n_{izd}} \right)^{4-j} \left( \frac{n_{iyd}}{n_{izd}} \right)^{j} \left( 1 - \frac{p_{f}}{\sqrt{n}} \right)^{j} \right).$$

(11)

Here $n_{iyd}$ is the number of infectious individuals without symptoms (i.e., pre-symptomatic and asymptomatic) served by the same food line as individual $i$ on day $d$, and $n_{izd}$ is the total number of individuals without symptoms served by the same food line as individual $i$ on day $d$. Rescaling the transmission probability by $1/\sqrt{n}$ accounts for the fact that shorter lines have shorter waiting times. We conducted simulations with $n \in \{4, 16, 144\}$ to study how the number of sectors affects COVID-19 epidemics.

**Face mask use.** Behavioral changes such as using personal protective equipment, frequent handwashing, and maintaining safe distances from others may reduce the risk of COVID-19 transmission. In Moria, there is approximately one tap per 42 people, so frequent handwashing (e.g., greater than 10x per day, as in$^{25}$) may be impossible. Due to the high population density ($\sim$20,000 people km$^{-2}$), maintaining safe distances from others may also be difficult or impossible.$^{5}$ However, people in Moria have been provided with face masks. To simulate the use of face masks, we scaled the odds of transmission per interaction in food lines, in toilet lines, and during movement about the camp by a factor of 0.32 following Jefferson and colleagues.$^{25}$

**Remove-and-isolate.** Managers of some populations, including Moria, have planned interventions in which people with COVID-19 infections and their households will be removed from populations and kept in isolation until the infected people have recovered. To simulate a remove-and-isolate intervention, we conducted simulations in which in each individual with symptoms (i.e., symptomatic, mild case, or severe case) is detected with probability $b$ on each day. If an individual with symptoms is detected, that individual and its household are removed from the camp. Individuals removed from the camp can infect or become infected by others in their household following equation (2), but cannot infect or become infected by individuals in other households by any transmission route. We assumed that individuals are returned to the camp 7 days after they have recovered, or if they do not
become infected, 7 days after the last infected person in their household has recovered. We simulated remove-and-isolate interventions with $b \in \{1, 0.5, 0.25\}$. These capture interventions in which symptomatic individuals and their households are removed on average on the 1st, 2nd, or 4th day of symptoms.

**Lockdown.** Some countries have attempted to limit the spread of COVID-19 by requiring people to stay in or close to their homes.\(^1\) This intervention has sometimes been called "lockdown." We simulated a lockdown in which most individuals are restricted to a home range with radius $r_l$ around their households, except when visiting shared toilets or food lines. We assumed that a proportion $v_l$ of the population violates the lockdown. Thus, for each individual in the population, we set their home range to $r_l$ with probability $(1 - v_l)$. Otherwise, we set their home range to 0.2 in the high-movement scenario or to 0.1 in the low movement scenario. We simulated interventions with \((r_l, v_l) \in \{(0.005, 0.05), (0.01, 0.1), (0.02, 0.2)\}\) to study lockdowns that are more or less restrictive and strictly enforced.

**Simulations**

In each simulation, we initialised the model population and camp structure as described above, and we randomly selected one individual to enter the exposed state. We simulated the epidemic by iterating days, and we tracked the disease state of each individual over time. We ran each simulation until all individuals in the population were either susceptible or recovered, at which point the epidemic had ended. If fewer than 20 individuals became infected, we recorded that an epidemic had been averted. If the epidemic was not averted, then we recorded the maximum number of infected individuals, the time to peak infection, and the proportion of the population that became infected in each simulation. For remove-and-isolate, we also recorded the peak number of individuals in isolation to help assess the feasibility of the intervention.
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Competing interests

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Supplementary Materials

Estimating transmission probabilities for the high- and low-transmission scenarios

High-transmission scenario

For the high-transmission scenario, we estimated the daily transmission probability within households, $p_h$, using data from Danis and colleagues.\textsuperscript{27} Danis and colleagues reported that 8 of 10 people who shared an apartment in a French chalet for four days with one infectious individual subsequently became infected. Thus, we estimated $p_h = 0.33$ by solving $1 - (1 - p_h)^4 = 8/10$.

We estimated transmission rates per interaction using data from Liu and colleagues.\textsuperscript{23} Liu and colleagues reported a total of 43 secondary infections among 126 attendees at 8 meals, each with one infectious individual present. We assumed that meals lasted 2 h and that the transmission rate was constant over time. Thus, the probability of transmission in an interaction lasting $m$ minutes is

$$p(m) = 1 - \left(1 - \frac{43}{126}\right)^{\frac{m}{120}}.$$  

We assumed that interactions in food lines, toilet lines, and while moving about the camp lasted for 150 min, 30 min, and 5 min respectively. Therefore, $p_f = p(150) = 0.407$, $p_t = p(30) = 0.099$, and $p_f = p(5) = 0.017$. These estimates are at the high end of those found in the empirical literature, and may represent an upper bound for the infectiousness of COVID-19.

Low-transmission scenario

For the low-transmission scenario, we estimated the daily transmission probability within households using data from Li and colleagues.\textsuperscript{24} Li and colleagues studied the households of 105 COVID-19 patients who were hospitalised in China between 1 January and 20 February 2020. Household members were exposed to infection until patients were hospitalised, and Li and colleagues recorded the proportion of household members that became infected.
Members of households occupying isoboxes or tents in the Moria refugee camp may be in closer contact for longer periods than members of Chinese households. Therefore, we assumed that the transmission rates among household members in Moria would be similar to the transmission rates between spouses in Chinese households, who may be in closer contact than other household members.

Li and colleagues reported that 25 of 90 spouses of infectious individuals became infected. However, spouses in Li and colleagues’ data were exposed to their infectious partners for multiple days, and our model is parameterised on daily transmission probabilities. Therefore, we estimated the days of exposure for spouses in Li and colleagues’ data set, and used this and the total infection rate to estimate the daily transmission probability. Li and colleagues reported that 12 patients were hospitalised on days 0 or 1 of symptoms, 34 were hospitalised on days 2-5 of symptoms, and 59 were hospitalised on days 7-11 of symptoms. Fourteen patients self-isolated in their homes from the onset of symptoms and there was no transmission from these patients to their households. We do not know on which days the patients that self-isolated were hospitalised, so we assumed that they were divided proportionally between the group that was hospitalised on days 2-5 and the group that was hospitalised on days 7-11. We assumed that every patient became infectious three days before the appearance of symptoms and remained infectious until hospitalisation. We do not know the exact day on which patients were hospitalised, so we assumed that all patients were hospitalised on the middle day for their groups. We solved

$$12(1 - (1 - p_h)^3) + 14(1 - (1 - p_h)^3) + 34 \frac{79}{93} (1 - (1 - p_h)^6) + 59 \frac{79}{93} (1 - (1 - p_h)^{12}) = \frac{25}{90}$$

for $p_h$ to obtain an estimated daily transmission probability within households of 0.0397.

Because the Moria population has smaller homes, less sanitary conditions (e.g., no washing facilities in homes), and poorer background health than the population Li and colleagues studied, this estimate may be conservative.

We set the transmission probability between individuals that interact in food lines, $p_f$, equal to $p_h$. This is reasonable because food lines in Moria are dense and people wait in food lines for up to 3 h per visit. We set the transmission probability between individuals that interact in toilet lines to $1 - (1 - p_t)^{1/6} = 0.0067$ to reflect an estimated 30 min waiting time in toilet.
lines. We set the transmission rate per interaction during movement about the camp to $p_m = 0.006$ following Shen and colleagues.\textsuperscript{21} Shen and colleagues reported that 3 of 473 of attendees at three parties with 2 infectious individuals became infected. It is unlikely that the 2 infectious individuals interacted with all of the other attendees at each party. Thus, Shen and colleagues’ estimate may be conservative as a per-interaction transmission probability.
Supplementary Tables

Supplementary tables report summary statistics for 200 COVID-19 introductions into the model population in each of 8 scenarios without (S1) or with (S2-S11) interventions. The peak and total proportions of individuals infected, time to peak infection, and peak population in isolation are reported as medians with interquartile ranges. The proportion of epidemics averted is the proportion out of the 200 COVID-19 introductions. Parameter values for the low- and high-transmission, low- and high-movement, and low- and high-interaction scenarios are presented in the Methods.

### Table S1

| Interventions | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|---------------|--------------|----------|-------------|--------------------------|------------------------|---------------------------|-------------------------------|------------------------------|
| No intervention | Low Low | 0.57 (0.57-0.58) | 64 (60-70) | 0.97 (0.97-0.97) | 0.05 |
| | Low High | 0.67 (0.66-0.67) | 55 (52-59) | 0.98 (0.98-0.98) | 0.03 |
| | High Low | 0.58 (0.57-0.58) | 65 (61-71) | 0.97 (0.97-0.97) | 0.05 |
| | High High | 0.68 (0.67-0.68) | 55 (51-59) | 0.98 (0.98-0.98) | 0.02 |
| | Low >0.99 | 21 (20-22) | >0.99 | <0.01 |
| | High >0.99 | 20 (19-21) | >0.99 | <0.01 |
| Face masks | Low Low | 0.23 (0.22-0.23) | 119 (111-129) | 0.80 (0.80-0.81) | 0.22 |
| | Low High | 0.31 (0.31-0.32) | 96 (89-106) | 0.87 (0.87-0.88) | 0.17 |
| | High Low | 0.23 (0.23-0.24) | 116 (108-126) | 0.80 (0.80-0.81) | 0.21 |
| | High High | 0.32 (0.32-0.33) | 92 (84-101) | 0.87 (0.87-0.88) | 0.20 |
| | Low >0.99 | 27 (26-29) | >0.99 | <0.01 |
| | High >0.99 | 27 (26-29) | >0.99 | <0.01 |
| | Low 0.97 (0.97-0.97) | 27 (26-29) | >0.99 | <0.01 |
| | High 0.97 (0.97-0.97) | 27 (26-29) | >0.99 | <0.01 |

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Table S3

| Interventions | Transmission Low | Movement Low | Interaction Peak proportion infected (95% CI) | Time to peak infection (days) | Total proportion infected (95% CI) | Proportion epidemics averted | Peak population in isolation |
|---------------|-----------------|--------------|-----------------------------------------------|-------------------------------|-----------------------------------|-------------------------------|------------------------------|
| 4 sectors     | Low             | Low          | Low                                           | 0.25 (0.24-0.27)              | 80 (75-85)                       | 0.94 (0.94-0.94)              | 0.08                         |
|               |                 | High         | Low                                           | 0.34 (0.32-0.37)              | 76 (73-84)                       | 0.97 (0.97-0.97)              | 0.08                         |
|               |                 | High         | High                                          | 0.30 (0.28-0.32)              | 91 (83-101)                      | 0.94 (0.94-0.94)              | 0.07                         |
|               | High            | Low          | Low                                           | 0.43 (0.40-0.46)              | 68 (62-73)                       | 0.97 (0.97-0.97)              | 0.05                         |
|               |                 | High         | High                                          | 0.73 (0.68-0.77)              | 33 (32-36)                       | >0.99                        | <0.01                        |
|               | High            | Low          | Low                                           | 0.83 (0.79-0.86)              | 30 (28-31)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | 0.83 (0.78-0.86)              | 31 (29-32)                       | >0.99                        | <0.01                        |
|               |                 | Low          | Low                                           | 0.91 (0.89-0.93)              | 27 (26-28)                       | >0.99                        | <0.01                        |

Table S4

| Interventions | Transmission Low | Movement Low | Interaction Peak proportion infected (95% CI) | Time to peak infection (days) | Total proportion infected (95% CI) | Proportion epidemics averted | Peak population in isolation |
|---------------|-----------------|--------------|-----------------------------------------------|-------------------------------|-----------------------------------|-------------------------------|------------------------------|
| Remove and isolate on ~day 4 | Low             | Low          | Low                                           | 0.31 (0.30-0.32)              | 84 (79-91)                       | 0.83 (0.83-0.84)              | 0.28                         |
|               |                 | High         | Low                                           | 0.46 (0.45-0.47)              | 65 (61-70)                       | 0.90 (0.90-0.90)              | 0.20                         |
|               |                 | High         | High                                          | 0.31 (0.30-0.33)              | 82 (77-90)                       | 0.83 (0.83-0.84)              | 0.26                         |
|               | High            | Low          | Low                                           | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |
|               |                 | Low          | Low                                           | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |

Remove and isolate on ~day 2

| Interventions | Transmission Low | Movement Low | Interaction Peak proportion infected (95% CI) | Time to peak infection (days) | Total proportion infected (95% CI) | Proportion epidemics averted | Peak population in isolation |
|---------------|-----------------|--------------|-----------------------------------------------|-------------------------------|-----------------------------------|-------------------------------|------------------------------|
| Remove and isolate on ~day 2 | Low             | Low          | Low                                           | 0.23 (0.22-0.24)              | 94 (85-104)                      | 0.77 (0.76-0.78)              | 0.43                         |
|               |                 | High         | Low                                           | 0.39 (0.38-0.40)              | 70 (65-76)                       | 0.87 (0.86-0.87)              | 0.27                         |
|               |                 | High         | High                                          | 0.23 (0.22-0.24)              | 92 (83-103)                      | 0.77 (0.76-0.78)              | 0.43                         |
|               | High            | Low          | Low                                           | >0.99                        | 22 (21-23)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |
|               |                 | Low          | Low                                           | >0.99                        | 22 (21-23)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |

Remove and isolate on ~day 1

| Interventions | Transmission Low | Movement Low | Interaction Peak proportion infected (95% CI) | Time to peak infection (days) | Total proportion infected (95% CI) | Proportion epidemics averted | Peak population in isolation |
|---------------|-----------------|--------------|-----------------------------------------------|-------------------------------|-----------------------------------|-------------------------------|------------------------------|
| Remove and isolate on ~day 1 | Low             | Low          | Low                                           | 0.18 (0.16-0.20)              | 104 (93-111)                     | 0.71 (0.70-0.73)              | 0.40                         |
|               |                 | High         | Low                                           | 0.35 (0.34-0.36)              | 72 (67-81)                       | 0.85 (0.84-0.85)              | 0.40                         |
|               |                 | High         | High                                          | 0.19 (0.17-0.20)              | 102 (91-110)                     | 0.72 (0.70-0.73)              | 0.47                         |
|               | High            | Low          | Low                                           | >0.99                        | 22 (21-23)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (21-22)                       | >0.99                        | <0.01                        |
|               |                 | Low          | Low                                           | >0.99                        | 22 (21-23)                       | >0.99                        | <0.01                        |
|               |                 | High         | High                                          | >0.99                        | 21 (20-22)                       | >0.99                        | <0.01                        |
### Table S5

| Interventions | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|---------------|--------------|----------|-------------|--------------------------|------------------------|---------------------------|----------------------------|-----------------------------|
| **Loose lockdown** | Low | Low | 0.58 (0.57-0.58) | 65 (61-69) | 0.97 (0.97-0.97) | 0.02 | | |
| | Low | High | 0.67 (0.67-0.68) | 55 (53-60) | 0.99 (0.98-0.99) | 0.02 | | |
| | High | Low | 0.58 (0.58-0.59) | 64 (61-67) | 0.97 (0.97-0.97) | 0.06 | | |
| | High | High | 0.69 (0.68-0.69) | 54 (52-58) | 0.99 (0.99-0.99) | 0.03 | | |
| **Moderate lockdown** | Low | Low | 0.57 (0.57-0.58) | 65 (61-68) | 0.97 (0.97-0.97) | 0.04 | | |
| | Low | High | 0.66 (0.65-0.66) | 57 (54-61) | 0.98 (0.98-0.99) | 0.04 | | |
| | High | Low | 0.58 (0.58-0.59) | 64 (61-68) | 0.97 (0.97-0.97) | 0.06 | | |
| | High | High | 0.68 (0.67-0.68) | 55 (53-59) | 0.99 (0.99-0.99) | 0.02 | | |
| **Tight lockdown** | Low | Low | 0.57 (0.56-0.57) | 66 (63-70) | 0.97 (0.97-0.97) | 0.06 | | |
| | Low | High | 0.63 (0.62-0.63) | 59 (56-63) | 0.98 (0.98-0.98) | 0.04 | | |
| | High | Low | 0.58 (0.57-0.58) | 66 (63-71) | 0.97 (0.97-0.97) | 0.04 | | |
| | High | High | 0.64 (0.63-0.64) | 58 (55-63) | 0.98 (0.98-0.98) | 0.02 | | |

### Table S6

| Interventions | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|---------------|--------------|----------|-------------|--------------------------|------------------------|---------------------------|----------------------------|-----------------------------|
| **4 sectors with face masks** | Low | Low | 0.073 (0.067-0.084) | 217 (190-244) | 0.68 (0.68-0.69) | 0.37 | | |
| | Low | High | 0.14 (0.13-0.15) | 145 (130-165) | 0.82 (0.82-0.82) | 0.23 | | |
| | High | Low | 0.098 (0.088-0.11) | 180 (159-198) | 0.68 (0.68-0.69) | 0.31 | | |
| | High | High | 0.19 (0.18-0.21) | 119 (106-133) | 0.82 (0.82-0.83) | 0.22 | | |
| **16 sectors with face masks** | Low | Low | 0.037 (0.030-0.043) | 277 (195-341) | 0.50 (0.47-0.52) | 0.42 | | |
| | Low | High | 0.090 (0.082-0.10) | 167 (137-207) | 0.77 (0.76-0.78) | 0.26 | | |
| | High | Low | 0.054 (0.049-0.060) | 199 (166-247) | 0.54 (0.53-0.56) | 0.42 | | |
| | High | High | 0.13 (0.13-0.14) | 129 (108-149) | 0.78 (0.77-0.78) | 0.25 | | |
| **144 sectors with face masks** | Low | Low | 0.009 (0.002-0.014) | 177 (91-294) | 0.15 (0.01-0.23) | 0.60 | | |
| | Low | High | 0.063 (0.056-0.068) | 218 (176-260) | 0.71 (0.70-0.72) | 0.28 | | |
| | High | Low | 0.032 (0.025-0.035) | 228 (164-288) | 0.38 (0.34-0.40) | 0.60 | | |
| | High | High | 0.11 (0.11-0.12) | 135 (114-166) | 0.73 (0.72-0.74) | 0.29 | | |
| | Low | Low | 0.17 (0.15-0.19) | 108 (92-130) | >0.99 <0.01 | | | |
| | Low | High | 0.25 (0.23-0.27) | 76 (62-88) | >0.99 <0.01 | | | |
| | High | Low | 0.29 (0.26-0.32) | 70 (62-84) | >0.99 <0.01 | | | |
| | High | High | 0.43 (0.40-0.47) | 51 (45-58) | >0.99 <0.01 | | | |
Table S7

| Interventions | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Prop’n epid’ics averted | Peak population in isolation |
|---------------|--------------|----------|-------------|--------------------------|------------------------|--------------------------|--------------------------|----------------------------|
| Remove and isolate on ~day 4 with face masks | Low | Low | 0.002 (0.001-0.003) | 44 (33-62) | 0.005 (0.003-0.011) | 0.76 | 0.002 (0.002-0.005) |
| | High | 0.010 (0.002-0.026) | 87 (36-169) | 0.064 (0.005-0.28) | 0.60 | 0.016 (0.003-0.039) |
| | Low | 0.002 (0.001-0.002) | 33 (26-47) | 0.004 (0.002-0.006) | 0.76 | 0.003 (0.002-0.004) |
| | High | 0.016 (0.003-0.032) | 124 (48-189) | 0.20 (0.008-0.32) | 0.66 | 0.026 (0.004-0.048) |
| | Low | 0.96 (0.96-0.96) | 29 (28-30) | >0.99 | 0.03 | 0.91 (0.91-0.91) |
| | High | 0.96 (0.96-0.96) | 28 (27-29) | >0.99 | <0.01 | 0.92 (0.92-0.92) |
| | Low | 0.96 (0.96-0.96) | 29 (28-30) | >0.99 | <0.01 | 0.91 (0.91-0.91) |
| | High | 0.96 (0.96-0.96) | 28 (27-29) | >0.99 | 0.02 | 0.92 (0.92-0.92) |

Table S8

| Interventions | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|---------------|--------------|----------|-------------|--------------------------|------------------------|--------------------------|--------------------------|----------------------------|
| Loose lockdown with face masks | Low | Low | 0.23 (0.22-0.23) | 120 (110-132) | 0.80 (0.80-0.81) | 0.24 |
| | High | 0.31 (0.31-0.32) | 97 (90-104) | 0.88 (0.87-0.88) | 0.14 |
| | Low | 0.23 (0.23-0.24) | 119 (108-129) | 0.81 (0.81-0.82) | 0.22 |
| | High | 0.33 (0.32-0.33) | 95 (87-104) | 0.89 (0.88-0.89) | 0.14 |
| | Low | 0.97 (0.97-0.97) | 27 (26-28) | >0.99 | <0.01 |
| | High | 0.97 (0.97-0.97) | 27 (26-28) | >0.99 | <0.01 |
| Moderate lockdown with face masks | Low | Low | 0.22 (0.22-0.23) | 122 (112-135) | 0.80 (0.80-0.81) | 0.19 |
| | High | 0.30 (0.29-0.30) | 102 (95-112) | 0.87 (0.87-0.88) | 0.14 |
| | Low | 0.23 (0.22-0.24) | 118 (108-125) | 0.81 (0.81-0.82) | 0.22 |
| | High | 0.31 (0.31-0.32) | 99 (92-108) | 0.88 (0.88-0.89) | 0.14 |
| | Low | 0.97 (0.97-0.97) | 27 (26-28) | >0.99 | <0.01 |
| | High | 0.97 (0.97-0.97) | 26 (26-28) | >0.99 | <0.01 |
| Tight lockdown with face masks | Low | Low | 0.21 (0.21-0.22) | 124 (115-137) | 0.80 (0.79-0.80) | 0.24 |
| | High | 0.26 (0.26-0.27) | 112 (102-122) | 0.85 (0.85-0.86) | 0.22 |
| | Low | 0.22 (0.22-0.23) | 121 (113-134) | 0.81 (0.80-0.81) | 0.16 |
| | High | 0.27 (0.27-0.28) | 107 (100-119) | 0.86 (0.86-0.86) | 0.27 |
| | Low | 0.97 (0.97-0.97) | 27 (26-28) | >0.99 | <0.01 |
| | High | 0.97 (0.97-0.97) | 26 (26-28) | >0.99 | <0.01 |
Table S9

| Interventions                                      | Transmission Movement Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|----------------------------------------------------|----------------------------------|--------------------------|------------------------|---------------------------|-------------------------------|-----------------------------|
| Face masks with 16 sectors imposed when 1% of population is symptomatic | Low                              | Low                      | 0.10 (0.095-0.10)      | 121 (110-136)             | 0.56 (0.55-0.58)             | 0.24                        |
|                                                    | High                              | Low                      | 0.19 (0.18-0.20)       | 97 (90-105)               | 0.78 (0.77-0.78)             | 0.14                        |
|                                                    |                                    | High                      | 0.11 (0.10-0.11)       | 118 (109-128)             | 0.58 (0.57-0.59)             | 0.23                        |
|                                                    |                                    | Low                      | 0.21 (0.21-0.22)       | 94 (87-104)               | 0.78 (0.77-0.79)             | 0.14                        |
|                                                    |                                    | High                      | 0.92 (0.92-0.93)       | 29 (28-30)                | >0.99                       | <0.01                       |
|                                                    |                                    | Low                      | 0.94 (0.94-0.94)       | 28 (27-29)                | >0.99                       | <0.01                       |
|                                                    |                                    | High                      | 0.94 (0.94-0.94)       | 28 (27-29)                | >0.99                       | <0.01                       |

Table S10

| Interventions                                      | Transmission Movement Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Proportion epidemics averted | Peak population in isolation |
|----------------------------------------------------|----------------------------------|--------------------------|------------------------|---------------------------|-------------------------------|-----------------------------|
| Face masks with remove-and-isolate on day 2 starting when 1% of population is symptomatic | Low                              | Low                      | 0.059 (0.056-0.064)    | 89 (82-104)               | 0.17 (0.16-0.19)             | 0.24                        |
|                                                    | High                              | Low                      | 0.086 (0.082-0.093)    | 76 (69-88)               | 0.30 (0.28-0.31)             | 0.10                        |
|                                                    |                                    | High                      | 0.061 (0.057-0.066)    | 87 (77-97)               | 0.17 (0.16-0.19)             | 0.26                        |
|                                                    |                                    | Low                      | 0.097 (0.091-0.10)     | 74 (68-83)               | 0.34 (0.31-0.35)             | 0.18                        |
|                                                    |                                    | High                      | 0.96 (0.96-0.97)       | 27 (26-28)               | >0.99                       | <0.01                       |
|                                                    |                                    | Low                      | 0.96 (0.96-0.96)       | 28 (27-29)               | >0.99                       | <0.01                       |
|                                                    |                                    | High                      | 0.97 (0.96-0.97)       | 27 (26-28)               | >0.99                       | <0.01                       |

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Table S11

| Interventions                                      | Transmission | Movement | Interaction | Peak proportion infected | Time to peak infection | Total proportion infected | Prop’n epid’cs averted | Peak population in isolation |
|----------------------------------------------------|--------------|----------|-------------|--------------------------|------------------------|---------------------------|------------------------|-----------------------------|
| Face masks, sectoring, remove-and-isolate          | Low          | Low      | Low         | 0.001 (0.001-0.001)      | 24 (22-27)             | 0.002 (0.002-0.002)       | 0.93                   | 0.002 (0.002-0.002)       |
|                                                    | High         | Low      | Low         | 0.002 (0.001-0.002)      | 32 (19-49)             | 0.003 (0.002-0.04)        | 0.87                   | 0.002 (0.002-0.003)       |
|                                                    | Low          | High     | Low         | 0.001 (0.001-0.002)      | 22 (20-23)             | 0.001 (0.001-0.003)       | 0.94                   | 0.002 (0.001-0.002)       |
|                                                    | High         | Low      | High        | 0.002 (0.001-0.003)      | 30 (24-40)             | 0.003 (0.002-0.008)       | 0.86                   | 0.003 (0.002-0.004)       |
|                                                    | Low          | High     | High        | 0.25 (0.23-0.29)         | 79 (69-96)             | >0.99                     | 0.08                   | 0.29 (0.26-0.33)          |
|                                                    | High         | Low      | High        | 0.33 (0.31-0.37)         | 62 (53-70)             | >0.99                     | 0.04                   | 0.38 (0.36-0.42)          |
|                                                    | High         | High     | High        | 0.32 (0.30-0.36)         | 68 (57-78)             | >0.99                     | 0.07                   | 0.37 (0.33-0.40)          |
|                                                    | Low          | 0.44 (0.41-0.50) | 48 (45-55)  | >0.99 | <0.01 | 0.50 (0.47-0.56) |
| Face masks, sectoring, lockdown                    | Low          | Low      | Low         | 0.020 (0.008-0.026)      | 234 (156-311)          | 0.32 (0.091-0.40)         | 0.52                   |                            |
|                                                    | High         | Low      | Low         | 0.060 (0.053-0.065)      | 242 (194-294)          | 0.75 (0.74-0.76)          | 0.26                   |                            |
|                                                    | Low          | High     | Low         | 0.031 (0.026-0.036)      | 269 (184-351)          | 0.46 (0.42-0.50)          | 0.46                   |                            |
|                                                    | High         | High     | Low         | 0.082 (0.076-0.090)      | 182 (150-212)          | 0.78 (0.77-0.78)          | 0.26                   |                            |
|                                                    | Low          | Low      | High        | 0.27 (0.24-0.30)         | 77 (66-90)             | >0.99                     | <0.01                  |                            |
|                                                    | High         | Low      | High        | 0.33 (0.31-0.37)         | 62 (53-70)             | >0.99                     | <0.01                  |                            |
|                                                    | Low          | Low      | High        | 0.33 (0.30-0.37)         | 65 (58-77)             | >0.99                     | <0.01                  |                            |
|                                                    | High         | Low      | High        | 0.40 (0.37-0.45)         | 55 (48-62)             | >0.99                     | <0.01                  |                            |
| Face masks, remove-and-isolate, lockdown           | Low          | Low      | Low         | 0.002 (0.001-0.002)      | 32 (26-43)             | 0.003 (0.002-0.004)       | 0.80                   | 0.003 (0.002-0.003)       |
|                                                    | High         | Low      | Low         | 0.002 (0.001-0.003)      | 31 (25-50)             | 0.004 (0.002-0.007)       | 0.73                   | 0.003 (0.002-0.005)       |
|                                                    | Low          | High     | Low         | 0.002 (0.001-0.002)      | 32 (24-38)             | 0.003 (0.002-0.005)       | 0.85                   | 0.003 (0.002-0.004)       |
|                                                    | High         | Low      | High        | 0.002 (0.001-0.004)      | 29 (23-52)             | 0.004 (0.002-0.011)       | 0.70                   | 0.003 (0.002-0.006)       |
|                                                    | High         | High     | High        | 0.95 (0.95-0.95)         | 30 (28-31)             | >0.99                     | 0.04                   | 0.94 (0.93-0.94)          |
|                                                    | Low          | Low      | Low         | 0.96 (0.95-0.96)         | 29 (28-30)             | >0.99                     | 0.02                   | 0.94 (0.94-0.94)          |
|                                                    | High         | Low      | High        | 0.95 (0.95-0.96)         | 29 (38-31)             | >0.99                     | <0.01                  | 0.94 (0.93-0.94)          |
|                                                    | High         | High     | High        | 0.96 (0.96-0.96)         | 28 (27-30)             | >0.99                     | 0.02                   | 0.94 (0.94-0.94)          |
| Face masks, sectoring, remove-and-isolate, lockdown| Low          | Low      | Low         | 0.001 (0.001-0.002)      | 23 (19-28)             | 0.002 (0.002-0.003)       | 0.92                   | 0.002 (0.002-0.002)       |
|                                                    | High         | Low      | Low         | 0.002 (0.001-0.002)      | 26 (20-43)             | 0.003 (0.002-0.005)       | 0.88                   | 0.002 (0.002-0.003)       |
|                                                    | Low          | High     | Low         | 0.002 (0.001-0.002)      | 26 (21-32)             | 0.002 (0.002-0.004)       | 0.94                   | 0.002 (0.002-0.003)       |
|                                                    | High         | Low      | High        | 0.002 (0.001-0.002)      | 30 (25-43)             | 0.003 (0.002-0.006)       | 0.84                   | 0.002 (0.002-0.004)       |
|                                                    | Low          | Low      | High        | 0.17 (0.14-0.21)         | 97 (75-124)            | >0.99                     | 0.07                   | 0.19 (0.15-0.23)          |
|                                                    | High         | Low      | High        | 0.27 (0.24-0.30)         | 77 (65-86)             | >0.99                     | 0.04                   | 0.30 (0.28-0.34)          |
|                                                    | Low          | Low      | High        | 0.24 (0.21-0.27)         | 84 (73-98)             | >0.99                     | 0.08                   | 0.27 (0.24-0.30)          |
|                                                    | High         | Low      | High        | 0.34 (0.31-0.38)         | 63 (55-71)             | >0.99                     | 0.06                   | 0.36 (0.35-0.42)          |

In table S11, the camp is divided into 16 sectors \(n = 16\), remove-and-isolate occurs on average on day 2 \(b = 2\), and lockdown is moderate \(r_7 = 0.01, v_7 = 0.1\).