# Empowering the crowd: Feasible strategies to minimize the spread of COVID-19 in high-density informal settlements

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**Abstract**

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# Introduction

COVID-19 pandemic is deepening on low-income countries [Guardian: https://www.theguardian.com/world/2020/aug/06/tota confirmed-coronavirus-cases-in-africa-pass-1-million]. In Africa, it is being observed that the virus is slowly spreading from urban areas to informal settlements, from which will likely reach rural areas [https://www.afro.who.int/news/africa-marks-six-months-covid-19]. With more than 1 billion people living in informal settlements [Sattherwaite], considering actions to contain the spread of the virus is an urgent task, which necessarily involves the engagement of local communities [Wilkinson].

The need for action is even more pressing in regions immerse in procrasted armed conflicts, in which a large portion of their populations become displaced. When the displaced population exceeds official resettlement and refugee camp capacity, Internally Displaced Persons (IDPs) must live in informal settlements (hereafter named "camps"). These regions must contend with the public health challenges resulting from violence [Ref], the deterioration of health-systems [Ref], especially of critical care [Ref], and the breakdown of essential infrastructure such as water and sanitation systems [Ref].

This research focuses on a worse-case situation, the North West region of Syria (NWS): a relatively small geographical area hosting 4.2 million persons, including 1.15 million IDPs living in camps. 27.4% of NWS population is currently living in camps, and this proportion raises to 34.4% for the area of Idlib province [Refs].

A high proportion of the population in this region suffers from comorbidities. In NW Syria, 10% of the population has a chronic disease, with 17% of them having no access to medicines [REF Reach doc], often entirely reliant on humanitarian assistance for their healthcare needs [data?]. As in other conflict regions, the political instability in NW Syria hinders coordinated public health actions, and the ongoing movements of IDPs creates ample opportunity for infectious disease transmission, while making contact tracing interventions infeasible.

To investigate feasible COVID-19 prevention interventions in the camps, we considered a Susceptible-Exposed-Infectious-Recovered model in which the camps' populations are divided into classes, reflecting their estimated age-structures and comorbidity prevalences [Ref]. We use this model to propose a number of interventions aimed at reducing the number of contacts within and between population classes in general, and with symptomatic individuals in particular. We paid special attention to how the living conditions in informal camps inform the assumptions underlying our proposed interventions. We modelled interventions previously proposed for African cities [Zandvoort], such as self-distancing, isolation of symptomatic individuals and the creation of a 'safety zone' in which more vulnerable members of the population are protected from exposure to the virus.

Building upon the approach used to model the impact of these interventiosn in African cities, our model includes a parametrization of the contacts that each individual has per day [Zandvoort]. We further elaborate upon this approach by making a more explicit representation of contacts and other parameters in the model. We consider the micro-dynamics of contacts, the time that individuals take to recognize their symptoms before self-isolating, the effect of having care-givers to attend isolated individuals, and the existence of a buffer zone in which exposed and protected population classes can interact under certain rules, among other details. We examine a potential worst-case scenario in which there is no access to any health-care facility. Since empowering local communities in conflict regions to understand how to control COVID-19 is possibly the most (and perhaps only) effective way to minimize its spread, our models are of utmost importance for informing the implementation of realistic interventions in these regions.

# Methods

## The model

We considered a discrete-time stochastic model simulating the spread of the virus in a single camp. The model is divided in compartments, containing individuals at different possible epidemiological stages along the progression of the disease (see Supplementary Material). The model additionally considers that the population is split in classes, dependent on the age-structure and comorbidities. The simulation starts with a population of susceptible individuals and then one individual becomes exposed. The progression of the disease in the individual goes through a series of infectious stages: a preclinical infectious stage, and then either a clinical (symptomatic) or subclinical (asymptomatic) infectiousnessstage. Susceptible individuals may become infected if they have a contact with infectious individuals. Individuals are no longer infectious if they recover or if they die. The model simulates the development of the disease for a period of 12 months. We verified that a steady state was always reached before the limit of the simulation was achieved. We did not considered any additional entry of infectious individuals in the camp during the simulation. Births and deaths due to other causes were not considered in the model, since populations changes due to the disease are much larger than those related to these processes, provided that there are no conflicts during the period simulated.

## Population structure

We considered data from the NW of Syria as a reference to parametrize the models [SOURCE]. The population size of informal camps was log-normally distributed, with a mean size of 600 individuals. We simulated population sizes of 500, 1000 and 2000 individuals. Unless stated otherwise, the results presented refer to populations of 2000 individuals, because interventions tend to be less effective in larger camps. The original data was structured in three population ages: age 1 (0-12 years old), age 2 (13-50 yrs.) and age 3 (>50 yrs). For the classes correspondent to age 2 and 3, we additionally considered two subclasses comprising health individuals and individuals with comorbidities, respectively. Therefore, in the absence of interventions, we considered 5 population classes, whose proportions are shown in Table [create Table].

## Epidemiological severity assumptions

An important question to consider in the model is the access to health care. In the NW of Syria, there are available XXX beds in hospitals (XXX UCIs) and XX ventilators for 4.5 million people [Ref]. Basic estimations predicted a collapse of the health facilities after 8 weeks of the outbreak []. Hence, we considered a worst-case scenario in which individuals will not have access to health care. As a consequence, we assumed that symptomatic individuals requiring an ICU would die. More problematic is to estimate the fate of those individuals that would have symptoms with a severity requiring hospitalization but not necessarily ICU care, since in the absence of hospitalization their fate is uncertain. To address this point, and departing from previous models [Refs], we considered a hospitalization compartment. The role of this compartment is to account for a longer infectious period for these individuals that, since there is no access to hospitals, will stay in the camp. This compartment will also help us to model more realistically some interventions, for example noting that the severity of the symptoms for these individuals is incompatible with self-isolation. From this compartment, we simulated two possible extreme scenarios, one in which all of these individuals would recover, and another in which these individuals will all die. This strategy allowed us to estimate upper and lower bounds for the different variables. In the simulations presented in the Main Text, we considered a worst-case scenario, namely the one in which all individuals die.

Another consideration comes from the estimation of the fraction of the population that will suffer severe or very severe symptoms (parameters $h_i$ and $g_i$, see Table [Table]). These parameters are class-specific, but we gathered this data from wealthy countries [Refs], with access to health care. Following previous work [Zandvoort], we considered that severity in the camps would correspond to the one observed in these countries for a population 10 years older.

## Transmissibility assumptions

In our model, individuals from the presymptomatic, asymptomatic, symptomatic and hospitalized compartments are equally infectious. Although asymptomatic individuals are often considered less infectious [Ref], the fraction of asymptomatic we considered was of 16% [Ref], which might be an underestimation after recent findings reporting up to 49% [Ref], and hence we opt to considered them equally infectious than symptomatic ones. The length of the time intervals that individuals spend in each compartment was retrieved from literature (see Table [Table] and Supplementary Material).

We modelled contacts between individuals considering that the number of contacts between individuals belonging to different classes was the product of the mean number of contacts that an individual has per day ($\bar{c}_i$, see Supplementary Materia) times the probability of randomly interact with an individual of a given class. We estimated that this probability is proportional to the fraction of the population that the class represents. The $\bar{c}_i$ values were estimated from direct conversations with camp's managers in NW Syria. We estimated that individuals of age 1 have 25 contacts per day on average, those of age 2 have 15 contacts per day, and we fix to 10 contacts per day those of age 3.

The probability of getting infected after a contact with an infectious individual, $\tau$, was estimated considering a Gaussian distribution of the basic reproduction number $R_0$ with mean 4 and 99% CI=(3–5). These values were a compromise between values reported in the literature from cities including favelas, ranging from $R_0$=2.77, 3.44 in Abuja and Lagos, respectively (Nigeria, [Ref]); $R_0$ =3.3 in Buenos Aires (Argentina, [Ref]), to Rohinya's refugee camps that were estimated to be as high as $R_0$=5 [Ref]. The probability distribution for $\tau$ was estimated randomly generating a value for $R_0$, and dividing the value by the real part of the main eigenvalue of the Next Generation Matrix (see Supplementary Material).

## Interventions

### Self-distancing

We considered a situation in which the whole population reduce the mean number of contacts per day by a certain amount (20% or 50%). Since the mean number of people per tent in a camp is 7 [verify], we considered that the number of contacts per day cannot be reduced by more than a 50%. Note that, for an adult, this would mean having 7.5 contacts per day.

### Buffering zone

When individual self-distancing cannot be achieved, a possible solution is the split of the population in groups, and to apply self-distancing measures between individuals belonging to different groups. The interaction between groups is then limited to certain zones named "buffering zones". We assumed that these zones are open spaces, not occupied by more than 4 individuals wearing masks, and in which 2 meters of distance between individuals of different groups is guaranteed. This setting could completely reduce the probability of infection per contact, but we considered that its actual efficiency will be of an 80%. An additional intervention we considered in some simulations, is that symptomatic individuals cannot access the buffering zones.

### Safety zone

In this intervention, the camp is divided in two areas: a safety zone, in which more vulnerable people lives (that we will refer to as "green" zone following previous studies [Ref]), and an exposed (orange) zone with the remainder population. In the simulations, it is always considered that the first exposed individual belongs to the orange zone. We avoided the use of the term "shielding" for this intervention as in other studies, since it may lead to a (misleading) picture in which it is believed that the vulnerable population is isolated into a closed space, such as a separated building. Such intervention would require additional assumptions on how contacts occur in a closed space . In our simulations, we assumed that the camp is split in two separated areas instead. The number of contacts between individuals living in different areas is reduced, while the living conditions within both areas remain otherwise the same. Therefore, the number of contacts per day and individual does not change unless self-distancing is implemented. In practice, this means that, for every individual, reducing the number of contacts with individuals living in the other zone, implies an increase in the number of contacts with the individuals in their own zone (see Supplementary Material). This is important to investigate undesired side-effects that the split may have.

We also considered that individuals living in the green zone cannot leave it, which means that supplies for this population should be provided by individuals in the orange zone, and hence the contacts between both populations never vanishes. However, we considered that this interaction will always occur in a buffering zone, and we assumed that each individual in the green zone can have a maximum number of contacts per week with individuals of the orange zone: either 10 or 2 contacts per week for each individual.

An important social question to be addressed in this intervention is how population will be distributed in the two zones, since different partitionings may have a different reception in the population. We considered the following isolation scenarios: i) elderly population only (age 3); ii) elderly population and adults (age 2) with comorbidities; and iii) elderly, adults with comorbidities, and other adults (e.g. spouses or care-givers) and their young kids ($<$ 13 yrs. and not exceeding 40% of the population in the green zone). For the scenario iii) we considered, in turn, three additional possibilities, in which the total population in the green zone represent 20%, 25% or a maximum of 30% of the total population.

### Lockdown of the safety zone

An additional measure that can incorporated once the safety zone is implemented, is a further reduction in the number of contacts occuring in the buffering zone. This occurs only after the first symptomatic case in the orange zone is identified. We refer to this reduction as "lockdown" (of the safety zone). Again, since supplies for people living in the green zone cannot be disrupted, we assumed that the number of contacts per week and individual is reduced by a 50% or a maximum of a 90% (see Table XXX)

### Self-isolation

A challenge in informal settlements is how self-isolation can be implemented when households consist of a single, and often small, space. Moreover, water should be collected at specific locations, there are communal latrines and the scarcity of food supplies do not allow for the complete isolation of whole families. We considered the possibility that individuals showing symptoms self-isolate in individual tents in dedicated spaces of the camps, or next to the tents of their relatives.We modelled this intervention for an increasing number of tents from 10 to an unlimited number (see Table XXX). We also considered that there is a minimum time for an individual to recognize his/her own symptoms. We considered three possible time intervals with means of 12, 24 or 48 hours (see Table XXX). In addition, we considered that there are a number of care-givers dedicated to supply food and water to isolated individuals, interacting via a buffering zone. In Supplementary Material, we show that considering one carer per individual having one contact per day, we account for both the positive effects of isolation and the negative effects derived from the contact with care-givers, since the probability of infection with the rest of the population cannot be neglected. In this respect, we considered that people moving to a severely symptomatic stage (hospitalized compartment) becomes fully infectious. The rationale behind this choice is that these individuals require a more intensive care, and hence it is expected that the rules imposed for a buffering zone cannot be longer fulfilled.

### Evacuation

The last intervention refers to the possibility of evacuating severely symptomatic individuals, i.e. those in the hospitalization compartment. This measure does not change the fate of the evacuated individuals. Hence, we assume that the evacuation will not be to a hospital but to isolation centers [REF] . In this way, the only effect of the intervention is a reduction of the infectiousness of these individuals to zero.

## Analysis of the interventions

For each implementation of the interventions, we run 500 simulations, analysing results arising from the incorporation of an intervention with respect to a set of simulations in which the intervention was absent. The main variables we considered in the comparisons were the fraction of casualties in the population, the case fatality rates (CFR), the fraction of population recovered and the time at which it is observed a peak in the symptomatic population, which is the most informative population in settings in which there is no access to other tests. We additionally considered the fraction of simulations in which at least one death is observed, as a proxy for the probability of outbreak. For consistency, when we compared the statistics of a given variable between two interventions, only simulations in which there was an outbreak were considered. When it was needed to individuate if differences between interventions were significant, we conducted statistical analysis: t– or Welch–tests for pairwise comparisons depending on whether normality is fulfilled, and Tukey tests for multiple comparisons among non-orthogonal variables.

## Results

When interventions are absent, the CFR takes values around 2% when we consider that individuals that would require hospitalization (but not ICU) are recovered (Suppl. Fig. ), raising up to ~11% when we considered that all would die . In the following and unless otherwise stated, we consider the latter scenario to evaluate the interventions. In such scenario, the probability of observing an outbreak is close to 0.85, having that 10% of the population in the camp would die, with the number of symptomatic cases peaking after 55 days.

Self-distancing has a notable effect in reducing the probability of outbreak, with a 10% decrease when just a reduction of a 20% in the number of contacts was considered (Fig. 1A). It was, however, needed a reduction of up to 50% to observe a more nuanced decrease in the fraction of population dying, that could be reduced as much as a 35% (Fig. 1B). The same occurs for the time to the peak of symptomatics (Fig. 1C), which increases up to 110 days, hence doubling the values when there are no interventions in place. As a counterpart, the proportion of population recovered is reduced a 35% (Suppl. Fig. )

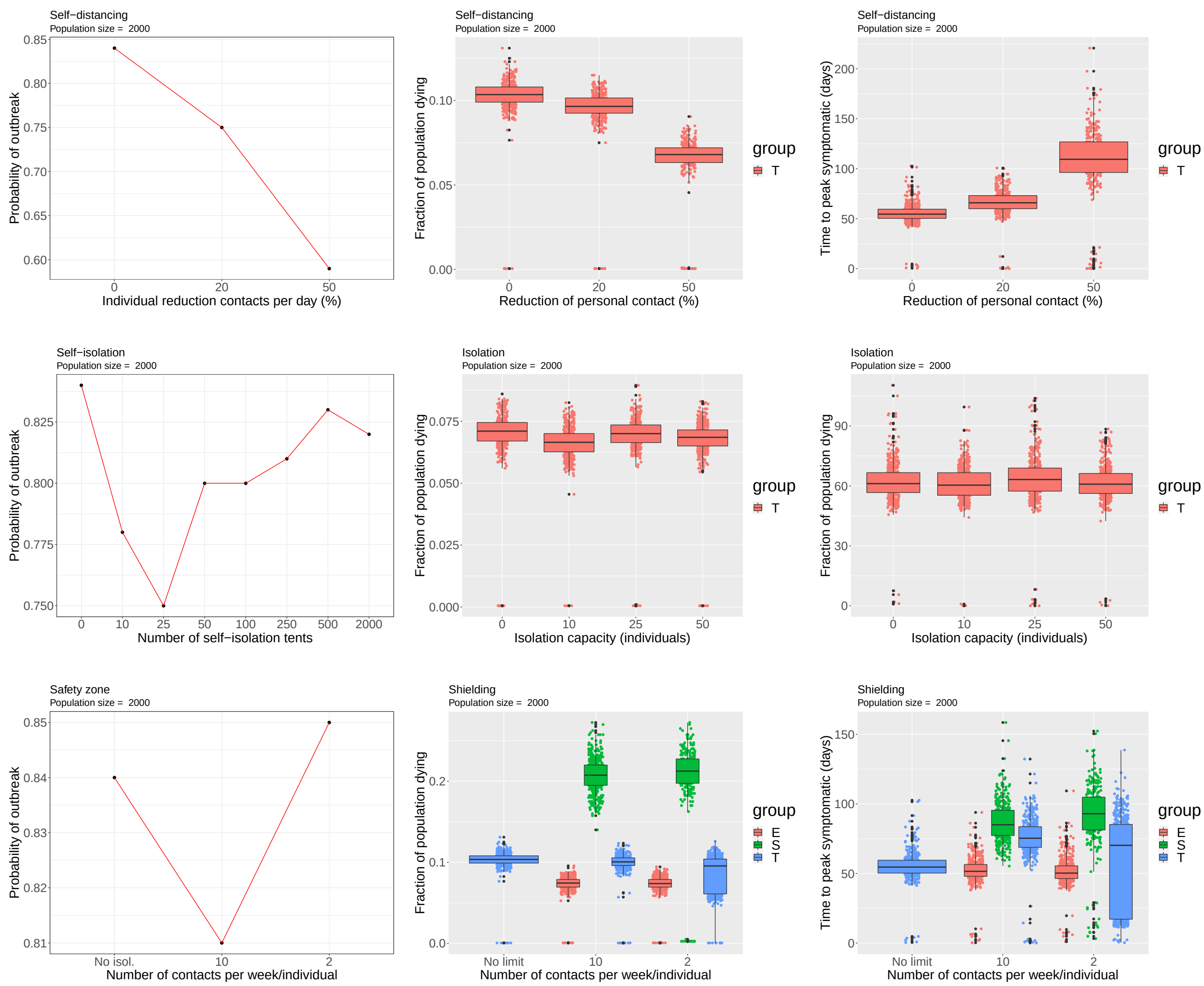



Figure 1: **Lower and upper bounds when interventions are absent.** Probability of outbreak (left-column), fraction of casualties (middle-column) and time in which the number of symptomatic cases peaks (right-column) for the interventions incorporating self-distancing (top-row) self-isolation (middle-row) and for the implementation of a safety-zone (bottom-row).

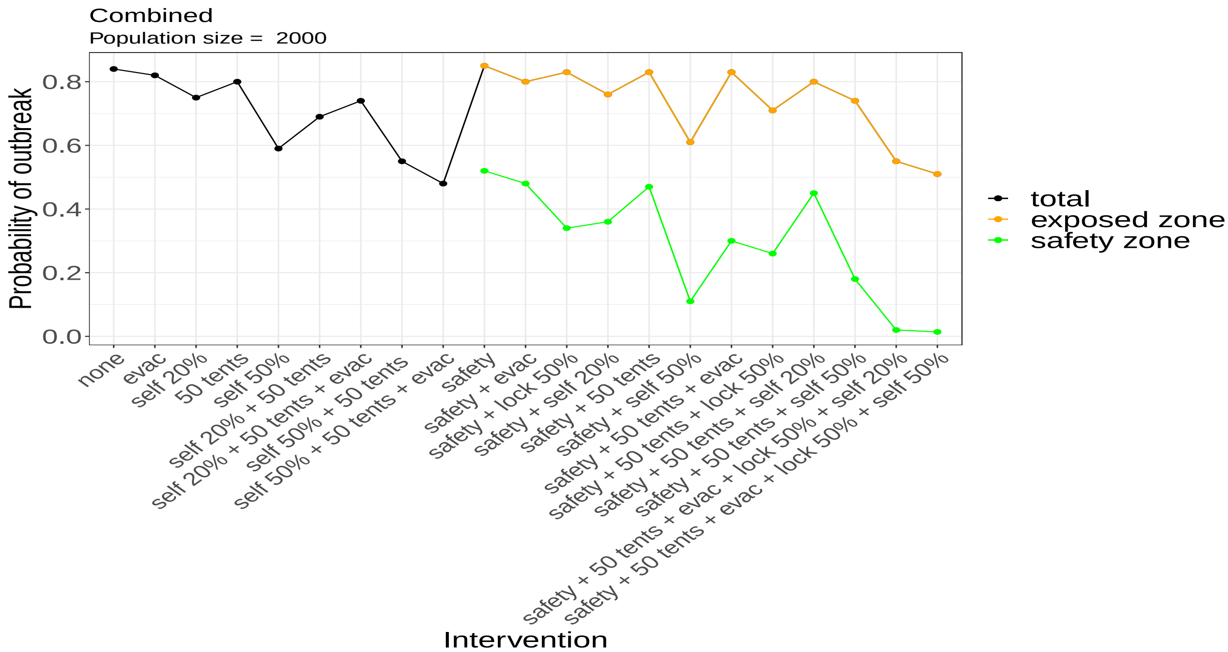
Self-isolation brings a modest decrease in the probability of observing an outbreak (Fig. 1D), but it provides a strong reduction in the fraction of population dying (~30%), when only 10 tents are available for a population of 2000 individuals, i.e. a 0.5% of the total population (Fig. 1E). Interestingly, increasing the number of tents does not significantly[?] enhance this reduction and, when the number of tents represent a 10% of the population, the fraction of deaths even increases. This effect is a consquence of having one carer per individual isolated (see Supplementary Material), whose side effect is that, when the number of isolated population increases, it also increases the number of adult healthy individuals in contact with the infected population. Still, the Case Fatality Rate experience a continuous, albeit small, reduction with an increasing number of tents (Supplementary Fig. XX).

Importantly, these results hold when the time required for individuals to recognize their symptoms is of 24h on average, and the intervention becomes less effective when this time increases (Supplementary Fig. XX). On the other hand, reducing this time to 12h does not significantly reduce the fraction of people dying , but it does increase the time in which the number of symptomatic cases peak (Supplementary Figs. XX and XX). If we additionally consider that the symptomatic cases that would require hospitalization are evacuated, it is only observed a 2% reduction in the fraction of individuals dying (Supplementary Fig. XXX). Since we assumed that the evacuation does not change their fate, the intervention only affects their infectivity. Although the period between developing more important symptoms and dying is relatively long (~10 days), the number of individuals under these conditions is small, when compared to the rest of the infected population.

Creating a safety zone overall improves the effect of previous interventions, but sometimes with different outcomes for the exposed and protected populations. For instance, the probability of outbreak strongly decreases (almost 40%) for the protected population (see Fig. 1G). Notably, approximately 16% of this reduction is due to the health checks performed to get into the buffering zone, which exclude symptomatic individuals (Supplementary Fig. XX). On the other hand, the probability of outbreak may increase for the exposed population if the contacts per week and per individual occuring in the buffering zone are reduced to 2. This is a consequence of an increased number of contacts within subpopulations, which may also explain the increase in the CFR of the protected population (Supplementary Fig. XX), . Despite of this side-effect, the fraction of individuals dying for the protected subpopulation and, in turn, globally, is reduced (Fig. 1H). Another important outcome of this intervention is the notable increase of the time to peak of symptomatics, raising up to 35% globally, and to 70% for the protected population (Fig. 1I). Regarding the population moving to the safety zone, having only elderly or at most elderly and adults with comorbidities, guarantee a low probability of outbreak, which would otherwise increase the global fraction of population dying (Supplementary Fig. XX and XX). Positive effects of the safety zone are even more marked for smaller population sizes, except for the time to peak of symptomatic, which has a weaker effect for smaller populations (Supplementary Fig. XXX and XXX).

The incorporation of a lockdown again shows the side-effect in which, if there is an outbreak in the safety zone, it has a negative effect due to the increased number of contacts of individuals within the zone (Supplementary Fig. XXX). However, the probability of outbreak is very strongly reduced to a barely 10% and, consequently, when there is an outbreak in the camp (which in most of the cases will not reach the safe zone) the fraction of deaths decreases overall (Supplementary Fig. XXX).

Finally, the combination of interventions add their effects approximately behave as they were shown when incorporated individually (Fig. XXX and Supplementary Fig. XXX). In particular, the creation of a safety zone improves the benefits of the other interventions, and there are not noticeable side effects beyond those previously described.


Combined
Population size = 2000
Probability of outbreak
0.0
0.2
0.4
0.6
0.8
none
evac
self 20%
50 tents
self 50%
self 20% + 50 tents
self 20% + 50 tents + evac
self 50% + 50 tents
self 50% + 50 tents + evac
safety
safety + evac
safety + lock 50%
safety + self 20%
safety + 50 tents
safety + self 50%
safety + 50 tents + evac
safety + 50 tents + lock 50%
safety + 50 tents + self 20%
safety + 50 tents + self 50%
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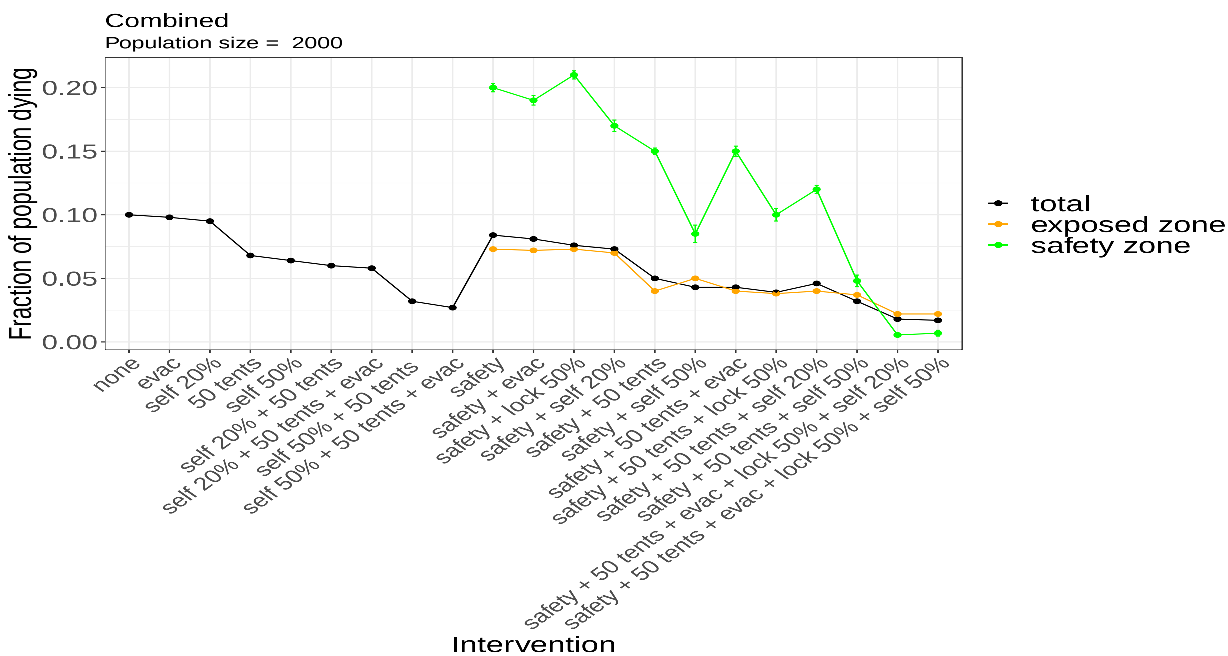
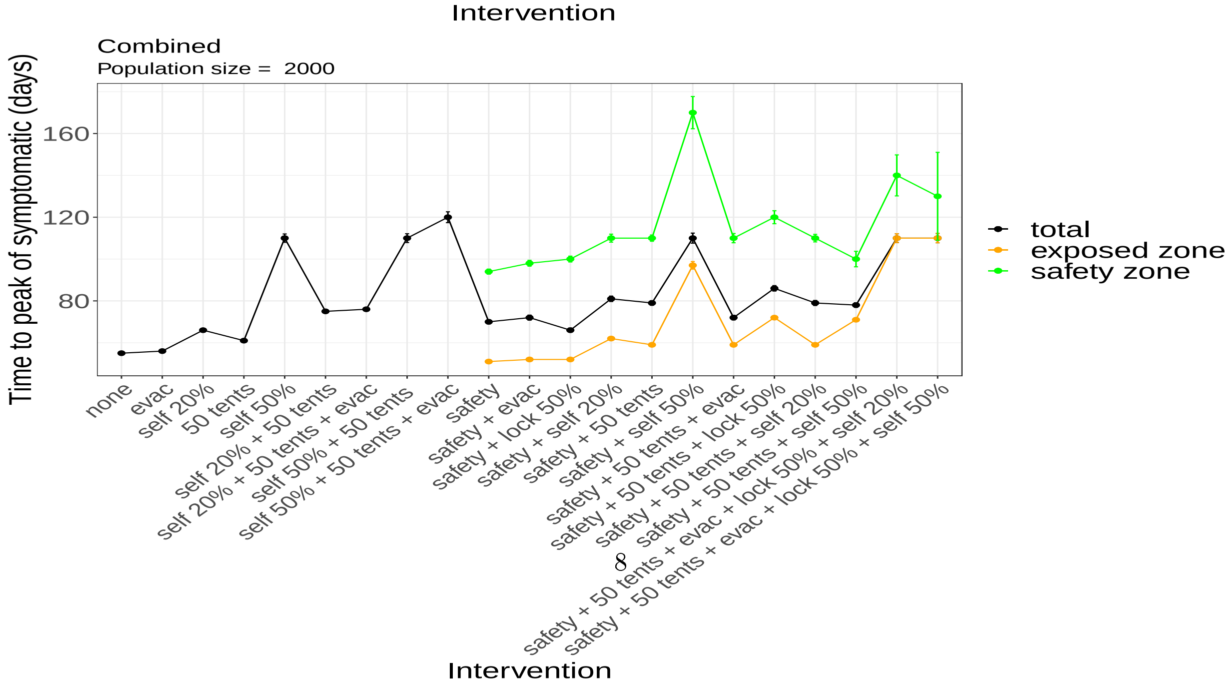
safety + 50 tents + evac + lock 50% + self 50%
Intervention
total
exposed zone
safety zone


Combined
Population size = 2000
Fraction of population dying
0.00
0.05
0.10
0.15
0.20
none
evac
self 20%
50 tents
self 50%
self 20% + 50 tents
self 20% + 50 tents + evac
self 50% + 50 tents
self 50% + 50 tents + evac
safety
safety + evac
safety + lock 50%
safety + self 20%
safety + 50 tents
safety + self 50%
safety + 50 tents + evac
safety + 50 tents + lock 50%
safety + 50 tents + self 20%
safety + 50 tents + self 50%
safety + 50 tents + evac + lock 50% + self 20%
safety + 50 tents + evac + lock 50% + self 50%
Intervention
total
exposed zone
safety zone


Combined
Population size = 2000
Time to peak of symptomatic (days)
80
120
160
none
evac
self 20%
50 tents
self 50%
self 20% + 50 tents
self 20% + 50 tents + evac
self 50% + 50 tents
self 50% + 50 tents + evac
safety
safety + evac
safety + lock 50%
safety + self 20%
safety + 50 tents
safety + self 50%
safety + 50 tents + evac
safety + 50 tents + lock 50%
safety + 50 tents + self 20%
safety + 50 tents + self 50%
safety + 50 tents + evac + lock 50% + self 20%
safety + 50 tents + evac + lock 50% + self 50%
Intervention
total
exposed zone
safety zone

## Discussion

In this research, we proposed a number of feasible interventions of immediate applicability, for informal settlements. We took as reference settlements of IDPs in the NW of Syria, and took into account the feasibility of the different interventions, their cultural acceptance and the need for low-cost solutions. In general, we considered worst case scenarios, leading to a probable overestimation of the number of casualties but making more apparent the potential effects of the interventions. Our results are aligned with previous works XXX

Self-distancing proves to be an efficient measure, and reducing the number of contacts to a 50% has the most important effect among all the interventions. Such a reduction may, however, be difficult to achieve, due to the large 6-13 year's old fraction of the population which may have high motility within the settlements and little control.

We proposed the implementation of self-isolation using individual tents, that could be located either in a dedicated zone in the camp or next to the tents of relatives, with a buffering zone ($\sim 2\ m^2$) in-between. We think this intervention is more likely to be accepted in NW Syria than the evacuation to community-based isolation wards which poses cultural challenges and whose minimum set-up requirements are hardly fulfilled [WHOsetupWards]. The use of individual isolation tents is effective even for a number of individual tents as low as 5 to 10 per 1000 capita in the settlement.

One of the parameters that we assessed is the need for care-givers for individually isolated individuals. Altough, in many cases it will be impossible to discern Covid-19 from other affections by the community, an increase in the contacts between individually isolated individuals and their care-givers may increase the infectivity. We considered that there is one care-giver per individual isolated with a daily contact in a buffering zone, and this choice shows that increasing the number of isolated individuals over xx cases increases the infectivity, due to the consequent increase of exposed care-givers. This could be circumvented with a more organized group of care-givers, which would reduce the number of total contacts with infectious individuals. The intervention is effective even though we assumed that individuals requiring hospitalization should leave the tents due to their need of care, and hence they become fully infectious.

The intervention consisting in separating the settlement in two zones, one of which is a safety zone, does not modify the composition of the settlement, not the number of people per tent and distance between tents. This would mitigate side-effects derived from an increase in the number of contacts between vulnerable population. In our modelization, we considered that contacts between the individuals within the safety zone are not reduced as compared to the exposed zone, and we observed in some cases an increase in the fraction of deaths in the protected population. However, these side-effects are compensated by the strong reduction in the probability of outbreak in the safety zone that this intervention provides, which leads to an overall reduction in the fraction of deaths in the whole camp. Moreover, in NWS Syria there are about 1000 camps, which will statistically justify such an intervention. Most importantly, it is unrealistic to think that the level of contacts will be maintained in the safety zone if an outbreak occurs in the camp, which would lower the chances of such side-effects.

An important question for the success of this intervention comes from the efficiency of the buffering zone. The reduction in the number of contacts per week in the buffering zone between individuals living in the safety zone and individuals from the exposed zone, the implementation of basic health checks to identify symptomatic individuals, and the eventual lockdown, have notable effects. Also important is which population should be shielded. Protecting only elderly and at most adults with comorbidities have the most beneficial effects, and the intervention becomes less effective when healthy adults and kids are included. However, the elderly and individuals with comorbidities need care-givers, and leaving them alone might have more deleterious effects than allowing accompanying persons. This also allows to preserve the social cohesion of the population. Another relevant consideration is the fraction of population recovered, that may help to reach herd immunity. We observed that unless a self-distancing of 50% is considered, the fraction of population recovered is close to a 75%, which is quite promising to prevent future outbreaks.

Decisions on which population should be protected are one example of social challenges that may become more complex in practice. Another example we did not address is that it is unlikely that a kid under 13 is individually isolated. Altough the number of of exceptions to the cases proposed are possibly endless, our results demonstrate that a community-based approach can be effective, much more than health-based responses which may take years to reach the needed level of response. In this respect, this modelization research demonstrates that in an extreme environment like NW Syria alternative responses can be efficient if the dynamics of the virus are well understood by the local communities and if they can implement at least some of the interventions proposed in this research. Given the highly dynamic environment existing in the camps and the slow reaction of the local and international authorities, empowering the local population is possibly the best, if not the only way, to help these communities, not only for the IDP camps of NW Syria, but in many other cases: slums in India, Africa and South America, isolated rural villages in Africa, South America and east Asia and in areas with large numbers of IDPs such as South Sudan or Colombia.