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Short Communication

SARS-CoV-2 transmission dynamics in the urban-rural interface

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ABSTRACT

Objectives: As the world responds to the coronavirus outbreak, the role of public health in ensuring equitable health care that considers the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) dynamics in rural communities is still a challenge. The same suppression and mitigation measures have been implemented homogeneously, ignoring the differences between urban and rural areas. We propose an epidemiological model and simulate the dynamics of SARS-CoV-2 in urban and rural areas considering the interaction between these regions.
Study design: This was a population modeling study.
Methods: A compartmental epidemiological model was formulated to simulate the transmission of SARS-CoV-2 in urban and rural areas. We use the model to investigate the impact of control strategies focused on the urban-rural interface to contain the epidemic size of SARS-CoV-2 in rural areas.
Results: Considering five different levels for the exposition rate in urban areas and keeping intrarural and urban-rural exposition rates fixed, the preventive measures reduce the size and delay the peak for the urban infectives. The response of infected individuals and cumulative deaths in rural areas upon changes in the urban dynamics was small but not negligible. On the other hand, preventive measures focused on the urban-rural interface impact the number of infected individuals and deaths in rural areas.
Conclusions: The maintenance of SARS-CoV-2 in rural areas depends on the interaction of individuals at the urban-rural interface. Thus, restrictive measures established by the governments would not be required within rural areas. We highlight the importance of focused preventive measures on the urban-rural interface to reduce the exposure and avoid the transmission of SARS-CoV-2 to rural communities.

Introduction

Since the declaration of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) as a pandemic, different prevention and control strategies to slow the spread of this virus have been implemented worldwide.[1] These strategies have been commonly grouped into two approaches: *i*) suppression, which involves shutdowns for extended periods generating considerable social and economic costs, and *ii*) mitigation, which includes a combination of social distancing, large-scale viral testing, and symptomatic case isolation maintaining hospital burden at controllable levels.[2]

Various elements support that disease prevention measures should not be the same for urban and rural areas mainly due to the characteristics of rural communities, such as the inability to perform remote activities, lower contact rates, shortages of physicians and other healthcare providers, and a disproportionate number of older, poor, and underinsured individuals.[3] Indeed, despite the importance of rural communities and their interaction with urban areas,[4] specific SARS-CoV-2 prevention measures have not been established for these populations. Clearly, suppression measures are not feasible in rural communities, and additionally, mitigation measures would require epidemiological systems with high surveillance capacity, which seems impractical in the face of the imperfect health systems of rural areas.[5] Therefore, there is a need to understand the dynamics of SARS-CoV-2 in rural communities and establish strategic measures to avoid the transmission of the virus and the occurrence of deaths in these communities. To the best of our knowledge, there is so far little evidence of how disease control strategies should be focused to prevent cases in rural communities. To address this gap, we propose an epidemiological model describing the dynamics of SARS-CoV-2 infection in rural communities. Our model also includes the intrinsic transmission dynamics of urban areas, as well as the urban-rural interface.

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We find that due to the low interaction rate between individuals in rural communities, the maintenance of SARS-CoV-2 depends on the interaction of individuals when marketing products and carrying out activities at the urban-rural interface. Thus, preventive measures focused on the urban-rural interface reduce the size and delay the time of the peak in rural areas. In this way, the restrictive measures established by the governments would not be required within rural areas. This work can support public health decisions proposing the implementation of heterogeneous strategies focused on reducing the impacts of the SARS-CoV-2 pandemic in rural communities.

Methods

The proposed method is an adaptation of the classic homogeneous Susceptible-Exposed-Infectious-Recovered (SEIR) epidemic model to analyze infectious disease dynamics, which has a definite latent period, and has proved to be predictive for a variety of acute infectious diseases.[6] Since no realistic model will depict human populations as homogeneous,[2] in our modeling framework (Fig. 1) the population is divided into different compartments according to the residence (urban or rural) and the infection status of individuals: susceptible (S; at risk of contracting the disease), exposed (E; infected but not yet infectious), infectious (I; capable of transmitting the disease), detected (D; infectious confirmed by laboratory diagnostic test), recovered (R; those who recover from the disease), and death (F; those who die from the disease). Additionally, our model considers the interaction of people who reside in urban and rural areas and carry out commercial activities in the urban-rural interface. Given this classification, individuals are exposed to the virus and therefore become infected at different rates of exposure and infection.

The proposed urban-rural (SEIDFR) model considers that susceptible individuals can reside in urban (u) or rural (r) areas and that a proportion of these carry out activities at the urban-rural interface. Thus, susceptible individuals living in rural areas (S^r) are exposed to SARS-CoV-2 at the urban-rural interface through contact with infected individuals living in urban areas (I^u). Similarly, susceptible individuals living in urban areas (S^u) are exposed to SARS-CoV-2 through contact with other infected individuals residing in urban areas (I^u) or at the urban-rural interface through contact with infected rural individuals (I^r). Due to the low contact rate reported in rural areas,[2] the exposure rate to SARS-CoV-2 among people residing in rural areas is not considered. Once infectious, individuals can be diagnosed and detected by the national health system in both urban (D^u) and rural (D^r) areas. Additionally, these individuals can die in urban (F^u) or rural (F^r) areas or get recovered from the disease (R) (Supplementary Fig. 1).

Our model can be written as a system of differential equations following the heterogeneity associated with the activities at the

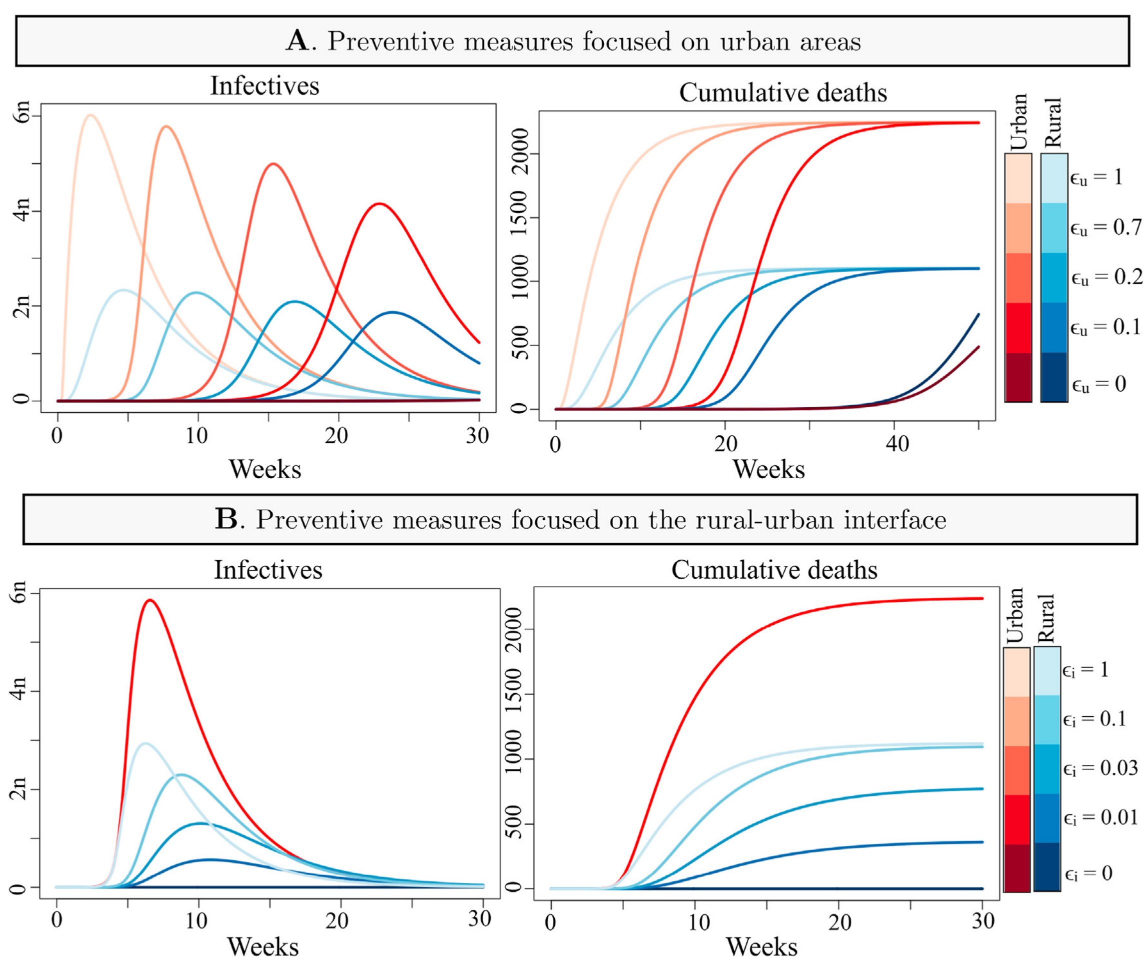

Fig. 1. Overall fraction infected (left) and death (right) individuals overtime for the rural (blue curve) and urban (red curves) structured community for five different preventive levels focused on A) urban areas and B) the urban-rural interface. The intensity of color corresponds to the intensity of the measures focused on the prevention of exposure and interaction in A) urban areas and B the urban-rural interface. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

urban-rural interface; for urban communities, the model can be written as

$$\begin{aligned} \dot{s}_u(t) &= -\varepsilon_u S_u(t) I_u(t) - \varepsilon_r S_u(t) I_r(t) \\ \dot{e}_u(t) &= \varepsilon_u S_u(t) I_u(t) + \varepsilon_r S_u(t) I_r(t) - \beta E_u(t) \\ \dot{i}_u(t) &= \beta E_u(t) - \gamma I_u(t) - \delta I_u(t) - \mu I_u(t) \\ \dot{d}_u(t) &= \delta I_u(t) \\ \dot{r}_u(t) &= \gamma I_u(t) \\ \dot{f}_u(t) &= \mu I_u(t) \end{aligned} \tag{1}$$

for rural communities, the model can be written as

$$\begin{aligned} \dot{s}_r(t) &= -\varepsilon_r S_r(t) I_u(t) \\ \dot{e}_r(t) &= \varepsilon_r S_r(t) I_u(t) - \beta E_r(t) \\ \dot{i}_r(t) &= \beta E_r(t) - \gamma I_r(t) - \delta I_r(t) - \mu I_r(t) \\ \dot{d}_r(t) &= \delta I_r(t) \\ \dot{r}_r(t) &= \gamma I_r(t) \\ \dot{f}_r(t) &= \mu I_r(t) \end{aligned} \tag{2}$$

where the initial number of susceptible individuals corresponds to all individuals who reside in rural or urban areas.

Results

Impact of control strategies focused on urban areas to contain SARS-CoV-2 in rural areas

In Fig. 1A, the community proportion that is infectious (left) and death (right) during the course of the epidemic in rural (blue) and urban (red) areas is plotted considering five different levels for the exposition rate in urban areas (ε_u) keeping intrarural and urban-rural exposition rates fixed. On week 0, preventive measures focused on urban population (at five different levels for ε_u) are put in place, and in every case, the preventive measures reduce the size and delay the time of the peak for the infectives (until 23 weeks when $\varepsilon_u = 0.1$; Fig. 1A, left), except when no preventative measures are applied (blue light and red light curves; $\varepsilon_u = 1$). For the urban infectives (Fig. 1A; left), the darkest curves ($\varepsilon = 0$) finish at $<99\%$ urban individuals getting infected or dead. When $\varepsilon = 0.1$ the urban infectives finish at $<18\%$ rural and $<4.5\%$ rural individuals getting infected. The corresponding cumulative fraction of deaths as a function of time is also shown in Fig. 1A (right), demonstrating that preventive measures focused on urban areas impact the number of deaths in urban areas (red curves). The number of deaths only changes in cases of extremes of low contact rate ($\varepsilon_u = 0$); however, in all cases, a delay in the peak is also observed. On the other hand, the response of infected individuals and cumulative deaths in rural areas (blue curves) upon changes in the dynamics is small but not negligible.

Impact of control strategies focused on the urban-rural interface to contain SARS-CoV-2 in rural areas

We then use the model to investigate the impact of control strategies focused on the urban-rural interface to contain the epidemic size of COVID-19 in rural areas. On week 0 (Fig. 1B), preventive measures (at five different levels for ε_i) are put in place, and in every case, the infectives and deaths are reduced in rural areas (blue curves) except when no preventive measures are applied (light blue curve; $\varepsilon_i = 1$). Moreover, the preventive measures reduce the size and delay the time of the peak in rural areas. For rural infectives (Fig. 1B; left), the darkest blue curve ($\varepsilon = 0$) finishes at $<100\%$ rural individuals getting infected, becoming clearer $\varepsilon = 0.01$ finishes at $<82.7\%$, $\varepsilon = 0.03$ finishes at $<55.2\%$, and $\varepsilon = 0.1$ finishes at $<24.1\%$ rural individuals getting infected. In urban areas (red curves), there is no obvious change. The corresponding cumulative fraction of deaths as a function of time is also shown in Fig. 1B (right). An interesting observation is that preventive measures focused on the urban-rural interface exclusively impact the number of deaths in rural areas (blue curves). For rural deaths (Fig. 1B; right), the darkest blue curve ($\varepsilon = 0$) finishes at $<100\%$ rural individuals dying, becoming clearer $\varepsilon = 0.01$ finishes at $<77.2\%$, $\varepsilon = 0.03$ finishes at $<36.3\%$, and $\varepsilon = 0.1$ finishes at $<4.5\%$ rural individuals dying. In urban areas (red curves), there is no either obvious change in deaths.

Discussion

In our model, we have taken social and work activity levels into account to avoid homogeneity. However, more complex infectious disease models have many other types of heterogeneities such as age,[8] place of residence,[9] or features associated with poverty in the region or country level.[10] Moreover, differences in social activity play a greater role in reducing the disease-induced herd immunity level than heterogeneous age-group mixing.[2]

When exploring the impact of control strategies focused on the urban-rural interface to contain the epidemic size of COVID-19 in rural areas, using the parameter ε_i, we indirectly consider the mobility of people between urban and rural areas and the transmission of the virus in this interface. Furthermore, SARS-CoV-2 transmission in urban areas depends primarily on the intraurban exposure rate (ε_u), since in high-contact environments such as urban regions, large households, overcrowded and poorly ventilated public transport, and large workplaces, there will be a higher infected fraction among highly active and connected individuals,[7] fundamental in the SARS-CoV-2 transmission.

When control measures focused on urban areas were investigated, the slope of the curves for rural infected individuals decreased (more than 10%) as the interaction between urban individuals decreases. This is probably because in this scenario the urban-rural interface, exposure rate is different to zero, which continues to guarantee the transmission of SARS-CoV-2 in rural areas.

In the explored scenarios, the intrarural exposure rate was close to zero due to the nature of lower contact rates in these regions.[2] In this way, from our findings, we can confirm that the dynamics of SARS-COV-2 in rural areas depend on the connectivity of these areas with urban areas.

In this work, we conclude that the maintenance of SARS-CoV-2 depends on the interaction of rural and urban individuals when marketing products and carrying out activities at the urban-rural interface. Thus, preventive measures focused on this interface reduce the size and delay the epidemic peak in rural areas. In this way, the restrictive measures established by the national government would not be required within rural areas.

These findings support public health decisions proposing the implementation of heterogeneous strategies focused on mitigating the health, economic, and social impact of the SARS-CoV-2 pandemic in rural communities.

Author statements

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Ethical approval

Not required. No human participants or their data were involved in this research.

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Competing interests

Authors declare no interests.

Data availability statement

Data supporting the findings of this study are freely available within the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2022.02.007.

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