Under What Conditions Can Vaccination Control the COVID-19 Pandemic in Brazil?

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Summary

In the context of the COVID-19 pandemic in Brazil, vaccines have enormous potential to control the transmission of the coronavirus when combined with preventive measures such as mask use, isolation, and social distancing. However, most states have faced growing case numbers and vaccine shortages, highlighting the urgent need to prioritize vaccine distribution to regions in more critical situations.

In this study, we developed a method to estimate the approximate proportion of the population that must be vaccinated to bring the spread of COVID-19 under control across different Brazilian states over time. To achieve this, we calculated the basic reproduction number (R_0) and conducted two analytical exercises using the CoronaVac vaccine as a reference.

In the **first exercise**, we examined the vaccination needs of each state under a hypothetical scenario in which vaccination campaigns had begun in December 2020, January 2021, or February 2021. Our findings showed that in December 2020, no state would have required more than 50% vaccine coverage to initiate a decline in case numbers. However, by January 2021, states such as Amazonas and Rondônia would already have needed nearly 100% of their populations vaccinated, reflecting the worsening national situation. In February, although some states experienced a drop in cases, the minimum vaccination rates needed to curb viral transmission remained higher than in December. For example, Rio Grande do Sul would have needed to vaccinate approximately 62.5% of its population.

In the **second exercise**, to complement our understanding of how vaccines should be distributed more efficiently among states, we calculated the number of people still needing immunization to control the pandemic, based on our model and vaccination data collected between February 22 and March 22, 2021. The results revealed strong regional disparities: Tocantins had achieved only 2.16% of its vaccination target, while São Paulo had reached 5.62%.

Ultimately, the simplicity and adaptability of our methodology make it a valuable tool for public policy design. It enables the identification of priority regions and supports the efficient allocation of vaccines to the most affected states at each stage of the pandemic. By guiding evidence-based decisions, this approach contributes directly to controlling the spread of the coronavirus in Brazil.

Methodology

To develop our methodology, we first calculated the basic reproduction number, denoted as R_0, which represents the average number of secondary infections generated by a single infected individual in a fully susceptible population. The value of R_0 indicates whether the coronavirus transmission is expanding ($R_0 > 1$) or declining ($R_0 < 1$). It is important to emphasize that an R_0 below 1 does not mean the pandemic is fully controlled, but rather that the number of new cases is trending downward.

To calculate R_0, we applied a classical epidemiological model—the **SIR model**—which divides the population into three compartments according to disease status: *Susceptible* (S), *Infected* (I), and *Recovered* (R). Additionally, we employed the ordinary differential equation (ODE) function `ode` from the **deSolve** package (v1.28; Soetaert et al., 2010) in the R software environment to estimate the optimal values of two key parameters in the SIR model, β (infection rate) and γ (recovery rate). Thus, the basic reproduction number is given by:

$$R_0 = \frac{\beta}{\gamma}.$$

Using the calculated R_0, we can approximately determine the proportion of the population, p, that must be immunized at a given point in time (year, month, or day) to bring R_0 below the threshold of 1. In other words, this allows us to estimate the number of vaccine doses required to prevent further epidemic expansion. Based on the relation described by Fine, Eames, and Heymann (2011), Bello and Egea (2020), and Anderson et al. (2020), we apply the following inequality:

$$R_0(1 - p) < 1,$$

which can be rearranged as:

$$p > 1 - \frac{1}{R_0}. \tag{1}$$

This relationship defines the minimum proportion of individuals that must be vaccinated over time, given a momentary R_0, to prevent an increase in coronavirus transmission.

Since vaccines vary in their efficacy—that is, their ability to prevent infection—we incorporated the effect of vaccine efficacy, denoted by ε, into our calculation of the required proportion of immunized individuals (Bello and Egea, 2020; Anderson et al., 2020). The modified inequality is:

$$p > 1 - \frac{1}{R_0 \varepsilon} \tag{2}$$

To estimate the proportion of the population that needs to be immunized, we computed R_0 across different periods using official COVID-19 data from Brazilian states, including confirmed cases, recoveries, and deaths (BRASIL, 2021). Furthermore, for both analytical exercises conducted in this study, we focused on cases where $R_0 > 1$ and used the efficacy value of the **CoronaVac** vaccine (Sinovac/Butantan), which has the lowest reported efficacy among approved vaccines (50.38%). This choice reflects the most challenging scenario for reducing COVID-19 case numbers in Brazil.

Application

Exercise 1

In the first exercise, we investigated the percentage of the population that would need to be vaccinated in each Brazilian state to contain the spread of the pandemic during December 2020, January, and February 2021. We considered a hypothetical scenario in which mass vaccination was already underway across the country, without vaccine shortages.

For this purpose, we applied Equation (2) to calculate the proportion of the population that should be vaccinated, taking into account the efficacy of the CoronaVac vaccine (50.38%), in order to achieve $R_0 < 1$ (Figure 1). The results reflect the expansion or reduction of the pandemic across states during the analyzed months.

Figure 1. Estimated percentage of each state's population that must be vaccinated to reduce coronavirus transmission ($R_0 < 1$). Calculations were performed for December 2020, January, and February 2021, assuming that vaccination was ongoing nationwide.

Our findings show that in December 2020—if vaccination had already been underway, as in several other countries—no state would have needed to vaccinate more than 50% of its population to initiate a decline in COVID-19 cases. The most critical situation was observed in Espírito Santo (ES), which would have required approximately 49% coverage, whereas Maranhão (MA) presented the most favorable scenario, requiring vaccination of only around 13% of its population.

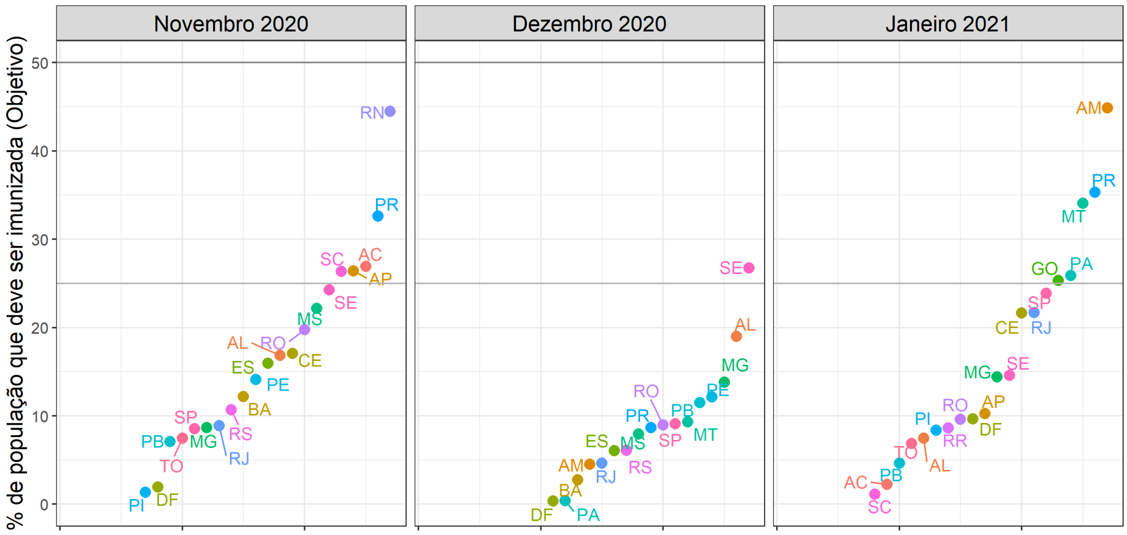

Figure 1: Estimated percentage of each state's population that must be vaccinated to reduce coronavirus transmission ($R_0 < 1$)

By January 2021, however, several states with $R_0 > 2$ would have needed almost 100% of their populations vaccinated, such as Amazonas (AM) and Rondônia (RO). Severe scenarios were also observed in Bahia (BA) and Minas Gerais (MG), which would have required vaccination coverage of 75% and 62.5%, respectively.

In February, Rio Grande do Sul (RS) stood out for its increase in cases, requiring vaccination of approximately 62.5% of its population. Conversely, Rio de Janeiro (RJ) and Maranhão (MA) showed less critical situations—consistent with their lower urgency levels observed in the following exercise.

Exercise 2

In the second exercise, we incorporated data on the proportion of the population already vaccinated in each state (PAINEL COVID-19 NO BRASIL, 2021) and the current average expansion rate of the pandemic (R_0) to determine the percentage of the population that would need to be immunized to bring R_0 below 1.

Table 1. Numerical optimization of the SIR model using state-level COVID-19 data between February 22 and March 22, 2021. Columns represent: estimated reproduction rate (R_0); percentage of the population that must be immunized (% Target Population); percentage of the target population already vaccinated with two doses (% Vaccinated of Target); and Urgency, which reflects the states with the highest R_0 values.

Results indicate that Tocantins (TO), the state most affected during the previous 30 days, would have needed to vaccinate 83.23% of its population to control the pandemic (i.e., to reduce R_0 below 1). However, as of March 22, 2021, only 1.8% of its population

Table 1. SIR Model Results

Estado	R0 estimado	% pop objetivo	urgência	% de vacinados para controle	% da população já vacinada
TO	1.72	83.23	1	2.16	1.80
AP	1.59	73.72	2	2.27	1.67
AC	1.30	45.47	15	2.55	1.16
AL	1.39	55.61	7	2.68	1.49
MT	1.45	61.24	6	2.69	1.65
PI	1.31	46.51	14	2.90	1.35
SC	1.37	53.84	11	3.01	1.62
MG	1.46	62.86	3	3.04	1.91
PR	1.38	54.14	9	3.12	1.69
SE	1.32	47.72	12	3.14	1.50
ES	1.38	54.97	8	3.22	1.77
PA	1.19	31.43	22	3.28	1.03
GO	1.30	45.45	16	3.30	1.50
DF	1.46	62.70	5	3.64	2.28
RS	1.46	62.72	4	3.75	2.35
RR	1.37	53.99	10	4.69	2.53
PB	1.24	38.21	18	4.76	1.82
RN	1.19	31.62	21	5.12	1.62
SP	1.31	46.98	13	5.62	2.64
MA	1.13	22.91	24	5.63	1.29
BA	1.21	34.18	20	5.76	1.97
MS	1.29	44.77	17	6.48	2.90
PE	1.18	30.27	23	6.54	1.98
AM	1.23	36.83	19	7.52	2.77
RJ	1.13	22.45	25	8.28	1.86

had been vaccinated, reaching just 2.16% of this goal.

Amapá (AP), the second-highest state in the urgency ranking, would have needed 73.72% coverage but had vaccinated only 1.67% of its population, achieving 2.27% of the target. São Paulo (SP), the most populous state in Brazil, should have vaccinated approximately 46.98% of its population within 30 days to control the pandemic but had reached only 2.64%, fulfilling 5.62% of its goal. Nonetheless, São Paulo performed better than many other states, ranking 13th among 27 in the urgency index.

Discussion

This study presents a methodology for estimating the vaccination coverage required in each Brazilian state to significantly reduce the impact of the COVID-19 pandemic. The two exercises demonstrate that pandemic control varies across time and space, as infection dynamics are inherently fluid. Consequently, this approach enables the identification of states requiring greater vaccine allocation and supports the development of tools for prioritizing distribution in scenarios of limited supply.

To better contextualize the findings, it is useful to interpret results in absolute numbers. For example, in São Paulo—the country's most populous state—the necessary vaccination coverage to begin a significant case reduction was estimated at 28%, corresponding to roughly 12.3 million people. Comparing this to the 4.2 million individuals who had received a second vaccine dose nationwide by March 23, 2021 (G1, 2021) highlights the scale of the challenge given Brazil's vaccine shortage at the time.

Exercise 1 also underscores the importance of both vaccine access and coverage. Although Amazonas suffered heavily in January, it was closer to achieving its vaccination target than Pará, due to better vaccine access. The Federal District, Roraima, and Paraíba also showed better relative progress, having reached over 20% of their target vaccination coverage. Nevertheless, full control requires reaching 100% of the estimated target, meaning these states still faced major challenges similar to the rest of the country.

Some states, such as Minas Gerais, exhibited unrealistically high vaccination targets—up to 60% of the population within one month—highlighting the crucial role of vaccination speed in curbing viral spread. Similarly, Exercise 2 revealed that states previously more stable, such as Santa Catarina, Acre, and Paraíba, experienced renewed increases in transmission due to the lack of restrictive containment measures and limited vaccine access.

Although Rio de Janeiro and Maranhão appeared lower on the urgency scale with smaller R_0 estimates, they still required faster vaccination rates to reach target coverage. Notably, the case of Santa Catarina illustrates the limitations of the model: despite showing instability in March 2021, the model suggested near-equilibrium due to an R_t close to 1. Future refinements should therefore include R_t instead of R_0, incorporating variables such as social isolation, immunity, reinfection risk, and vaccine-induced immunity delays (e.g., 14 days after the second CoronaVac dose).

The advantage of this model lies in its simplicity and adaptability—it can be expanded to integrate parameters such as pre-existing immunity, socio-demographic factors (e.g., population density, the COVID Protection Index—IPC, Ação Covid-19 Collective, 2020), and updated scientific insights on vaccine efficacy against severe disease and viral transmission. However, it is important to note that while the model offers a snapshot, the pandemic itself is dynamic. Therefore, an $R_0 < 1$ at a given moment does not guarantee long-term control unless sustained over time.

Overall, the model reveals a worsening of the pandemic control situation in Brazil, as indicated by the rise in required vaccination coverage from December 2020 to January 2021, with February levels remaining above December's. Nonetheless, our findings show that if Brazil had secured vaccine contracts and launched mass immunization in December—as initially announced by the federal government—the country could have achieved a sustained decline in cases.

Finally, this study reinforces the need for continuous pandemic monitoring and a coordinated federal system to prioritize the most affected states. Since urgency levels evolve monthly, targeted and adaptive vaccine distribution policies are essential, particularly in the context of limited supply and increasing relaxation of containment measures.