Assessing the effectiveness of quarantine measures during the COVID-19 pandemic in Chile using Bayesian structural time series models

Claudia Barría-Sandoval [a, b], Guillermo Ferreira [c, *], Bernardo Lagos [c, d], Carola Montecino Bacigalupo [e]

[a] Nursing School, Faculty of Health and Social Sciences, Universidad de las Américas, Concepción, Chile
[b] Faculty of Nursing, Universidad de Concepción, Concepción, Chile
[c] Department of Statistics, Universidad de Concepción, Concepción, Chile
[d] Applied Mathematics Group (GMA) Faculty of Sciences, Universidad del Biobío, Concepción, Chile
[e] Nursing School, Faculty of Health and Social Sciences, Universidad de las Américas, Santiago, Chile

ARTICLE INFO

ABSTRACT

Background: With the emergence of the COVID-19 pandemic, all existing health protocols were tested under the worst health crisis humanity has experienced since the Black Death in the 14th century. Countries in Latin America have been the epicenter of the COVID-19 pandemic, with more than 1.5 million people killed. Worldwide health measures have included quarantines, border closures, social distancing, and mask use, among others. In particular, Chile implemented total or partial quarantine measures depending on the number of infections in each region of the country. Therefore, it is necessary to study the effectiveness of these quarantines in relation to the public health measures implemented by government entities at the national level.

Objective: The main objective of this study is to analyze the effectiveness of national- and region-level quarantines in Chile during the pandemic based on information published by the Chilean Ministry of Health, and answers to the following question are sought: Were quarantine measures in Chile effective during the COVID-19 pandemic?

Methods: The causal effect between the rates of COVID-19 infections and the population rates in Phase 1 and Phase 2 quarantines in the period from March 2020 to March 2021 in different regions of Chile were evaluated using intervention analyses obtained through Bayesian structural time series models. In addition, the Kendall correlation coefficient obtained through the copula approach was used to evaluate the comovement between these rates.

Results: In 75% of the Chilean regions under study (12 regions out of a total of 16), an effective Phase 1 quarantine, which was implemented to control and reduce the number of cases of COVID-19 infection, was observed. The main regions that experienced a decrease in cases were those located in the north and center of Chile. Regarding Phase 2, the COVID-19 pandemic was effectively managed in 31% (5 out of 16) of the regions. In the south-central and extreme southern regions of Chile, the effectiveness of these phases was null.

Conclusion: The findings indicate that in the northern and central regions of Chile, the Phase 1 quarantine application period was an effective strategy to prevent an increase in

---

* Corresponding author.
E-mail addresses: cbarria@udla.cl (C. Barría-Sandoval), gferreir@udec.cl (G. Ferreira), bla@udec.cl (B. Lagos), cmontecino@udla.cl (C. Montecino Bacigalupo).

COVID-19 infections. The same observation was made with respect to Phase 2, which was effective in five regions of northern Chile; in the rest of the regions, the effectiveness of these phases was weak or null.

1. Introduction

In the Chinese city of Wuhan, a new infectious disease caused by coronavirus (COVID-19) began to spread during December 2019 and was subsequently dispersed rapidly throughout the world. On March 11, 2020, the World Health Organization (WHO) declared COVID-19 a pandemic (World Health Organization, 2020a, 2020b, 2020c). From an epidemiological perspective, the WHO has adjusted the concept of a pandemic ((Observatorio de Medicina UC, 2020), (Kaffure, 2010), (World Health Organization, 2020a, 2020b, 2020c)) and has repeatedly modified the Pandemic Preparedness Plan ((W. H. Organization, 1999), (W. H. Organization, 2011), (W. H. Organization, 2017)). Currently, the WHO indicates that a pandemic is the global spread of a new disease. Based on the Pandemic Preparedness Plan, a pandemic is now managed based on four phases: the interpandemic phase, a period in which there is no pandemic and there are no cases; the pandemic alert phase, when an outbreak or sporadic cases are locally detected; the pandemic phase, when there are cases grouped in areas, territories or countries due to common exposure; and the transition phase, where large outbreaks or cases are grouped together but with local transmission. Therefore, the epidemiological approach carried out by different countries under the WHO guidelines in the context of a pandemic has become relevant. Among the various strategies applied to limit the spread of infection and reduce the probability of contagion, the main strategies have attracted attention: strengthening the hospital network (increasing the number of health teams, converting highly complex beds, etc.) and blocking outbreaks (quarantines or confinement and physical distancing)World Health Organization, 2020a, 2020b, 2020c).

Within the blockade of outbreaks and for the purposes of this study, it is necessary to determine the concept of quarantine. It can be noted that the term quarantine is derived from the Latin quarantum, which means forty. Originally, it applied to the 40-day period of isolation of ships that arrived from countries with disease epidemics, such as bubonic plague and cholera, to allow latent cases of the disease to develop and be detected in ship crews before they were allowed to disembark. The literature indicates that the first quarantine of this type was imposed in 1374 in Venice, Italy (Mathys EA et al., 1980). In general, the term quarantine has been applied as self-quarantine or quarantine of selective individuals suspected of being carriers of infection. However, the term mass quarantine, which refers to the forced quarantine of a population by government entities to prevent the spread of a disease outbreak (Bergstresser), is currently being applied. One of the objectives of mass quarantine is to flatten the spread curve or the projected number of people who could be infected during a period of time (Courtney). In February 2020, the WHO indicated that a quarantine represents the restriction of activities or the separation of people who are not sick but who may be exposed to an infectious agent or disease, with the aim of monitoring symptoms and early detection of cases. Quarantine should be differentiated from isolation, the latter being the separation of sick or infected people from others to avoid the spread of infection or contamination (Organization, 2020). In the context of the COVID-19 pandemic, different governments worldwide implemented strategies to limit the spread of the infection. It is pertinent that these strategies be continuously reviewed to verify their effectiveness; therefore, in this context, it is of great relevance to analyze in some depth the application and effectiveness of the quarantines in Chile.

1.1. Quarantine implementation and its effectiveness

China was the first government to impose mass quarantines and travel bans to Wuhan on January 23, 2020, and then across the country (Taghrir et al., 2020). Several studies carried out to evaluate the effectiveness of quarantines have used the Susceptible-Exposed-Infected-Recovery (SEIR) model, which represents the rate of which individuals are considered susceptible, exposed, infected and recovered, and the findings demonstrated that the strict quarantine strategies in China, such as home confinement, traffic restrictions, travel bans and stoppage of face-to-face work activities, had a significant effect on the transmission of the infection in the community and were highly successful in controlling the initial stages of the spread of the pandemic (Jia et al., 2003). Other studies used the same SEIR model, and it was predicted that the application of a rigorous quarantine at the optimal rate of 100% participation will decrease the number of cases by 89.7% ((Gao et al., 2019), (Li et al., Wei)). Although the optimal rate of quarantine enforcement is not easily achievable, these analyses illustrate the likely effectiveness of mass quarantine. Previous investigations have also indicated that the timely implementation of quarantines is relevant since the number of cases increases by approximately 10% when a quarantine is implemented one week late and that an early quarantine from 1 to 2 weeks could decrease the case rate by 25%−57.3% ((Li et al., Wei) (Yang et al., 2020),). A study conducted by (Qiu and Xiao) using the real-time status dynamic model of SEIO (MH) to model the Wuhan population in terms of the susceptible (S), exposed (E), infected with symptoms (I), under medical care (M) and out of the system (O) classes on a daily basis revealed that the Wuhan blockade lowered R0 from 2.65 to 1.98, and it was predicted that if the quarantine had been implemented in the city seven days earlier, the total number of infected people would have been reduced by 72%.

Moreover, delaying the quarantine from 1 to 6 days would have expanded the size of the pandemic 5 times, while delaying by 7 days would have led to an uncontrolled pandemic. Another tool used to investigate the chance impacts of interventions is Bayesian structural time series (BSTS) models. In this context, (Feroze, 2020), (Feroze, 2021), (Navas Thorakkattle Farhin et al., 2022), and (Xie, 2022) implemented BSTS models to predict future trends of COVID-19 and investigated the chance impacts of lifting the blockades in the countries under study. Unlike these studies, in this study, evaluating the causal impact of the implementation of quarantines, i.e., the beginning and end of the blockades in all regions of Chile have been considered as the period of intervention, is proposed.

In Chile, the government has limited the activities and mobility or circulation of people, organizations and companies under the concept of dynamic quarantine as of July 2020, and it implemented a step-by-step strategy as a gradual measure to face the pandemic according to the health situation of each commune in the country under the guidelines of the Ministry of Health (Gobierno de Chile, 2020). This strategy considers 5 phases to overcome the COVID-19 pandemic, ranging from quarantine to advanced opening (Ministerio de Salud de Chile, 2020).

- Phase 1 (Quarantine). Involves total and permanent confinement, with restricted mobility and special permits for essential activities. There is a permanent and mandatory quarantine for adults over 75 years of age. Social and recreational activities are prohibited, as are the operations of restaurants, cinemas and theatres, to minimize the interaction and spread of the virus.
- Phase 2 (Transition). Decreases the degree of confinement. There is a permanent and mandatory quarantine for adults over 75 years of age. Displacement is allowed from Monday to Friday for the population under 75 years of age, and social and recreational activities can take place during the week, with a maximum number of 10 people. The operation of restaurants, cinemas and theatres is prohibited to avoid sudden mobility and minimize the risks of contagion.
- Phase 3 (Preparation). Confinement ends for the population under 75 years of age, and permanent and mandatory quarantine is applied only for adults over 75 years of age. Displacement is allowed from Monday to Sunday, except during the hours restricted by curfew. Social and recreational activities can take place any day of the week, with a maximum number of 50 people. The operation of restaurants, cinemas and theatres is prohibited.
- Phase 4 (Initial Opening). Quarantine is applied only for adults over 75 years of age, with permission to go out once per day. Displacement is allowed from Monday to Sunday, except during the hours restricted by curfew. Social and recreational activities can take place any day of the week, with a maximum number of 50 people. Restaurants, cinemas and theatres are allowed to operate at 25% of their capacity. This phase makes it possible to resume certain activities with a lower risk of contagion, minimizing crowds.
- Phase 5 (Advanced Opening). Establishes the end of the quarantine for the entire population. Displacement is allowed from Monday to Sunday, except during the hours restricted by curfew. Social and recreational activities can take place any day of the week, with a maximum number of 150 people. Restaurants, cinemas and theatres are allowed to operate at 75% of their capacity. This phase allows the number of people in activities to be increased compared to the previous phase, always considering self-care measures (use of masks, physical distancing and hand washing).

In the aforementioned context, the purpose of this research is to analyze the effectiveness of quarantines in Chile during the COVID-19 pandemic at the national level and by region based on the information published by the Ministry of Health from Chile. Therefore, it seeks to answer the following question: Were the quarantine measures effective during the COVID-19 pandemic in Chile?

2. Materials and methods

2.1. Data sources and variable definitions

To determine whether the quarantines decreed in Chile were effective in relation to the number of daily infections in each region, we propose an intervention analysis and a comovement study between these two time series; that is, some techniques will be used that provide the direction of the trend between the number of infections and the quarantines in Phase 1 and Phase 2.

In this study, the daily record of the COVID-19 pandemic in Chile and variables such as the percentage of confirmed COVID-19 cases and the percentage of the region's population in Phase 1 and Phase 2 in the 16 regions of Chile from March 3, 2020 to March 15, 2021, are used. The data on the variables regarding the severity of COVID-19 were obtained from the Ministry of Science and Technology website https://www.minciencia.gob.cl/covid19. Fig. 1 shows a map of Chile with integer numbers identifying each region where data recording was possible. Additionally, Fig. 2 shows curves of the percentage of confirmed COVID-19 cases (black line) by region, denoted by $Y_{r,t}$, and the percentage of the population in quarantine in Phase 1 (red line) by region, denoted by $X_{r,t}^{(1)}$. The intervention periods that were analyzed are located below the curve $X_{r,t}^{(1)}$ and denoted by the letters a, b and c. Figure (3) shows the percentage of the population per region in Phase 2 (orange line), denoted by $X_{r,t}^{(2)}$, and the intervention periods. It is observed that the time series $Y_{r,t}$ is a series that takes values in the interval (0, 1), which is
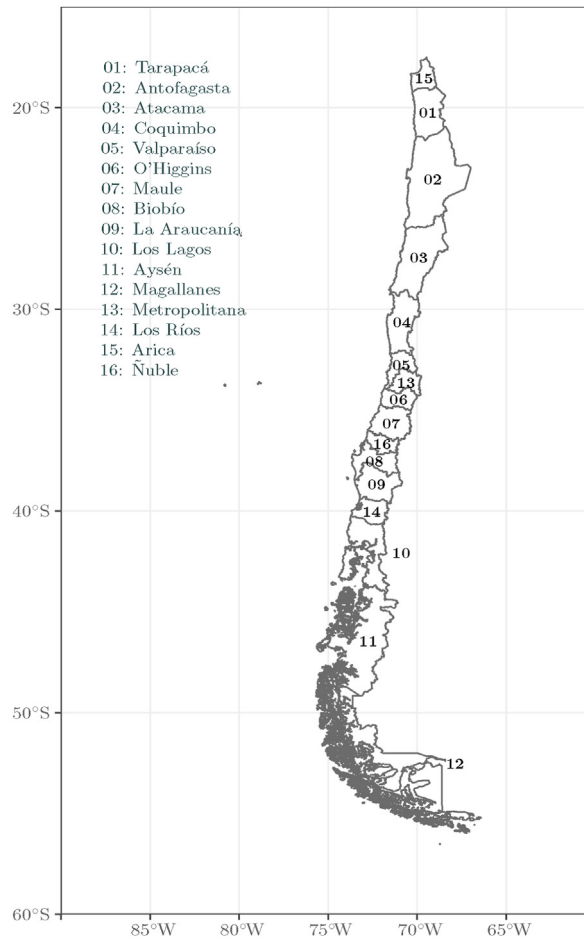
Fig. 1. Regions of Chile from north to south and the number identifying regions.

obtained through the following transformation: $Y_t = \frac{\tilde{Y}_t - a}{b - a}$, where $a = \min\{\tilde{Y}_t\}$, $b = \max\{\tilde{Y}_t\}$ and $\{\tilde{Y}_t\}$ is the number of confirmed COVID-19 cases, where $t = 1.2, \ldots T$. However, $X_{r,t}^{(j)}$ is calculated as follows:

$$X_{r,t}^{(j)} = \sum_{c \in r} \frac{P_c}{\sum_{c \in r} P_c} \mathbb{1}(F_{c,t} = j), \; j = 1, 2,$$

where P_c represents the number of inhabitants in commune c, $\sum_{c \in r} P_c$ is the number of inhabitants of region r, $F_{c,t}$ represents the phase of the step-by-step plan for commune c at time t and $\mathbb{1}(\cdot)$ is an indicator function, where

$$\mathbb{1}(F_{c,t} = j) := \begin{cases} & \text{if } F_{c,t} = j \text{ ,} \\ 0 & \text{if } F_{c,t} \neq j. \end{cases}$$

In the next section, different methodologies for measuring the degree of effectiveness of quarantine measures in Chile during the pandemic are presented.

2.2. Bayesian structural time series models

The causal impact of a treatment is the difference between the observed series and a simulated time series that would have occurred had the intervention not taken place. To measure this impact, structural time series models (STSMs) or state space models are used. In general, these models can be defined by:
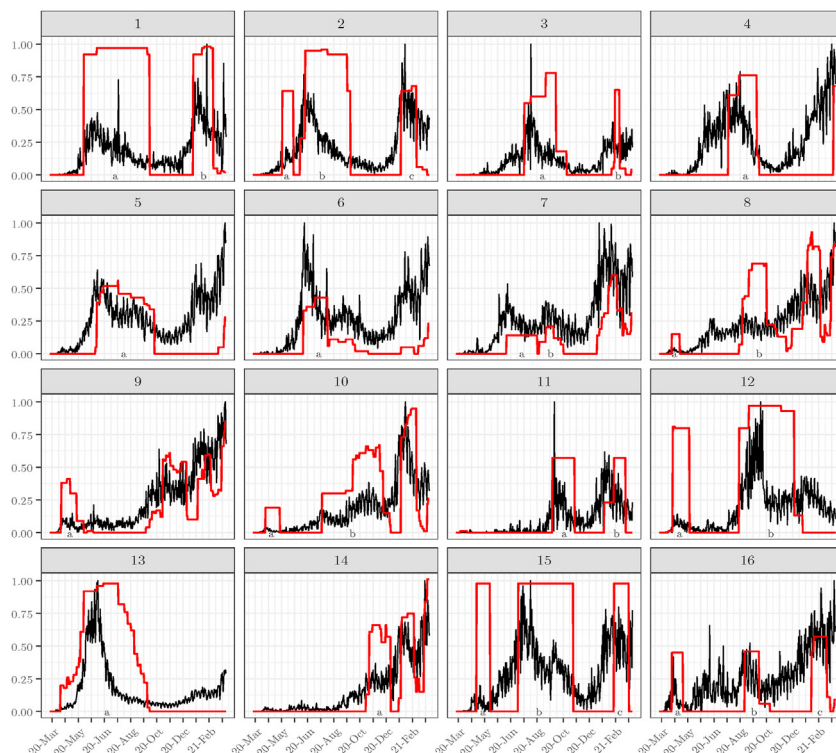
Fig. 2. The percentage of confirmed COVID-19 cases (black line) and the percentage of people in Phase 1 (red line) by region.
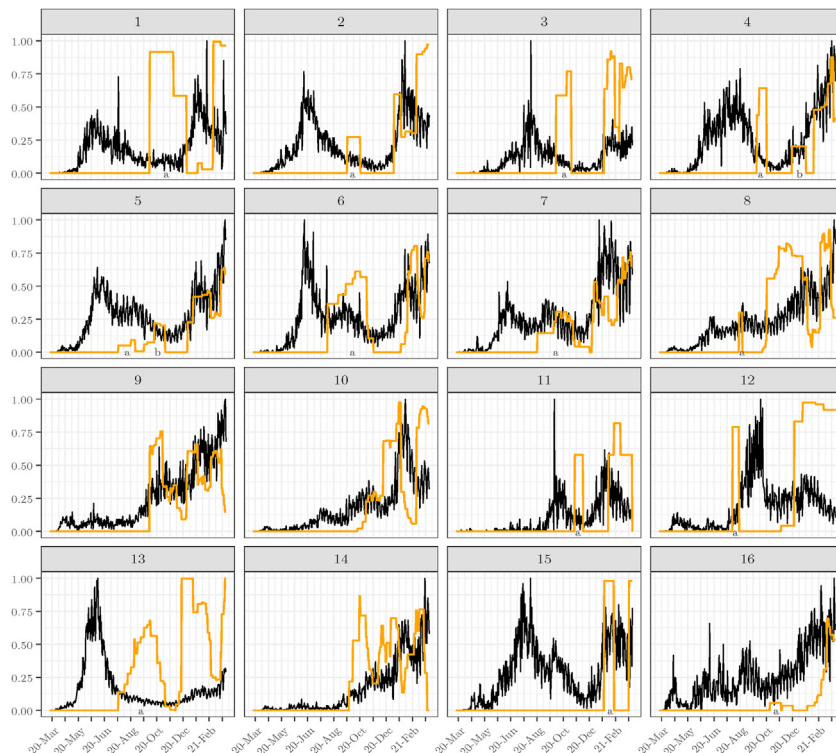

Fig. 3. The percentage of confirmed COVID-19 cases (black line) and the percentage of people in phase 2 (orange line) by region.

$$
\begin{aligned}
Y_t &= G_t \alpha_t + \omega_t, \\
\alpha_{t+1} &= F_t \alpha_t + \eta_t,
\end{aligned}
\tag{1}
$$

where Y_t is the observation, G_t is the observation operator, α_t is the unobserved state vector, F_t is the transition operator, η_t is state noise with variance Q_t and ω_t is observation noise with variance R_t such that $\mathrm{Cov}(\omega_t, \eta_s) = 0$ for all $s, t \in Z$. Based on this definition, different representations of the state vector α are implemented in the ARIMA-type linear time series analysis. (Brodersen et al., 2015) proposed a Bayesian version of the STSM models and are known as BSTS models. These authors used the representation given in (1) with an equation of state following a diffusion regression, which allows counterfactual predictions to be obtained by constructing a synthetic control based on a combination of phenomena that were not treated. This methodology is freely available through the CausalImpact package developed by the authors (Brodersen et al., 2017) for the R statistical software (R. C. Team et al.), which can be downloaded at https://www.r-project.org. BSTS models can be used to conduct intervention analysis for a time series. These models can estimate the postintervention difference between the observed series and a simulated time series that would have occurred had the intervention not taken place. These calculations help assess the causal impacts of lockdowns through the following steps:

- In the first step, the BSTS model uses the data up to the first day of the quarantine. The data used for this purpose are referred to as preintervention data.
- In the next step, the previously estimated model with preintervention data is used to predict the value observed in the postquarantine period (postintervention) considering the absence of intervention. This prediction will be denoted by $\hat{y}^*$.
- In the last step, to estimate the causal impact of lockdowns, the difference between the real observations and the predicted observations obtained in the postlockdown period is calculated, that is,

$$
D = y - \hat{y}^*,
$$

where y represents the actual postintervention observations.

The criteria to consider whether the quarantine was effective are as follows: First, the number of cases decreases considerably once Phases 1–2 are completed, that is, the observed value is less than the predicted value obtained in the absence of intervention, i.e., $D < 0$. Second, the quarantine curves follow the sinusoid-like behavior of the percentage of those infected by COVID-19. For this, the Kendall Tau coefficient τ_{xy} defined below will be used.

2.3. Statistical methods of comovement

In this section, the methodology of comovement is used as defined by Baur (2003), who maintains that there is no explicit definition of the term comovement in the literature, which is why he defines it as common movement or correlated movement. To quantify the comovement of two sequences, two different approaches can be found in the literature. In one approach, comovement coefficients have been suggested to have properties similar to the correlation coefficient (see, for example (Vallejos, 2008),). Alternatively, comovement has been approached from a hypothesis testing approach ((Li, 2014)). Since hypothesis tests require fairly strong distributive assumptions, the methodology belonging to the first category is considered in this paper.

There are different ways to measure the comovement between two time series, which are analyzed in detail by (Vallejos, 2008). In this study, the copula-based comovement measure will be used to study the degree and dependency structure of time series, which can be asymmetric. In this context, the comovement between X_t and Y_t is defined through Kendall's tau coefficient (Li, 2014) as follows:

$$
\tau_{XY} = 4 \int_0^1 \int_0^1 C(u,v)\partial C(u,v) - 1,
$$

where the function $C: [0,1] \times [0,1] \to [0,1]$ is a copula of dimension 2. If $\tau_{XY} > 0$, then the movement from (X_t, Y_t) to (X_{t+1}, Y_{t+1}) is a concordant comovement; otherwise, it is said to be discordant. Among the copulas used in this study, the bivariate normal copula and the t copula are defined as

$$
\begin{aligned}
C(u,v;\rho) &= \Phi_\rho\left(\Phi^{-1}(u), \Phi^{-1}(v)\right), \\
C(u,v;\rho,\nu) &= t_{\rho,\nu}\left(t_\nu^{-1}(u), t_\nu^{-1}(v)\right),
\end{aligned}
$$

where $\rho \in [-1, 1]$ is the correlation coefficient, $\Phi(\cdot)$ is the cumulative distribution function of the bivariate normal distribution, ν is the degrees of freedom parameter, t_ν^{-1} is the inverse of the bivariate t c.d.f. and ρ is as previously defined. The following ranges were considered to classify the value of Kendall's tau coefficient τ_{xy} ((Akoglu, 2018), (Miot, 2018)):

$\tau_{xy} \in [0, 0.30]$ Comovement Negligible
$\tau_{xy} \in [0.31, 0.50]$ Comovement Weak
$\tau_{xy} \in [0.51, 0.70]$ Comovement Moderate
$\tau_{xy} \geq 0.71$ Comovement Strong.

3. Descriptive analysis of the results

In Fig. 4, it can generally be seen that all the regions of Chile during the first days of March 2020 showed an increase in COVID-19 infections, as identified from the maroon curve with an instantaneous reproduction number $R0 > 1$, where there was no infection control. In the following days, sanitary measures were implemented in the country, mainly Phase 1 and Phase 2 quarantines. The effect of these measures in controlling the infection and reducing the number of infections is observed in the green curve with $R0 \leq 1$. From Fig. 4, it can also be noted that in the first 7 regions and in the Metropolitan region, there was a peak of $R0 > 1$; then, there was a sustained decrease, and $R0 \leq 1$, which is associated with the effective implementation of quarantines.

From the specific analysis of Table 1, which is based on the effectiveness of quarantines in Phase 1 implemented in each of the regions of Chile, it was revealed that these quarantines were effective in certain regions of the country. In particular, the quarantines in periods (b) and (c) were effective in region 2, where a decrease in cases in absolute terms of 10% and 6.6%, respectively, were observed. This conclusion is supported by Fig. 5, which shows the impact of Phase 1 lockdowns in region 2 in all intervention periods. Due to space constraints, only this figure is presented; however, all figures that reflect the causal impact and source codes are available from the authors upon request.

In region 3, the implementation of quarantine in period (a) provided a significant reduction (10%) of COVID-19 cases. The same results occur in regions 4, 5 and 6, where the implementation of quarantine led to a reduction in the number of infections by 18%, 17% and 28%, respectively. Finally, in regions 7, 11 and 15, the quarantine caused a reduction in the number of infections by 9.1%, 9.8% and 13%, respectively, in periods (a), and (b). In all these regions, the behavior of the curve $X_{r,t}^{(1)}$ was sinusoidal, with a Kendall's tau coefficient between $0.31 < \tau_{xy} \leq 0.55$, indicating weak to moderate comovement (see Table 3).

In the other regions, there was no significant evidence of the quarantine being effective, which corroborates the absolute causal effect manifested by the difference between the predictions in the subsequent period without considering intervention (prediction column) and the value of the response considering intervention (actual column), resulting in a positive and
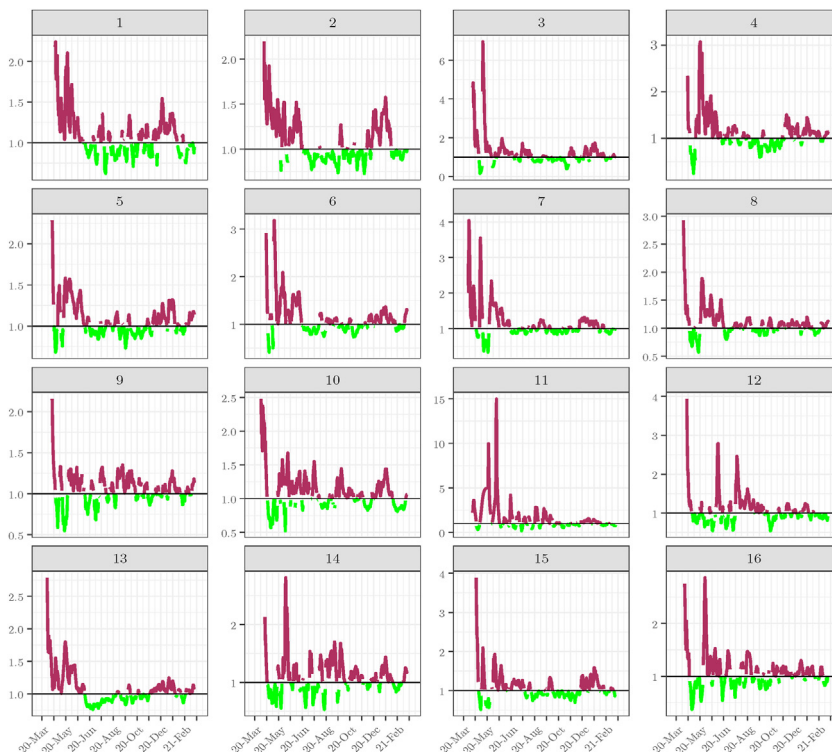

Fig. 4. Instantaneous reproduction number $R0$. $R0 \leq 1$ is represented by a green curve, and the maroon curve represents $R0 > 1$ by each region.

Table 1

Effect of Phase 1 in different regions of Chile (on March 3, 2020 to March 15, 2021).

Region	Intervention	Actual	Posterior inference-average		Posterior probabilities	Probabilities of causal impact
			Prediction (s.d.)	Absolute effect (s.d.)		
1	a	0.12	0.03 (0.010)	0.089 (0.07, 0.11)	0.001	99.9%
	b	0.30	0.25 (0.062)	0.052 (−0.08, 0.17)	0.183	82.0%
2	a	0.21	0.03 (0.008)	0.190 (0.17, 0.20)	0.001	99.9%
	b	0.12	0.22 (0.059)	−0.100 (−0.22, 0.01)	0.036	96.4%
	c	0.36	0.42 (0.120)	−0.066 (−0.28, 0.17)	0.292	71.0%
3	a	0.08	0.18 (0.040)	−0.100 (−0.18, −0.03)	0.006	99.5%
	b	0.24	0.21 (0.059)	0.025 (−0.09, 0.15)	0.333	67.0%
4	a	0.27	0.45 (0.100)	−0.180 (−0.39, 0.00)	0.029	97.1%
5	a	0.27	0.44 (0.150)	−0.170 (−0.48, 0.09)	0.125	87.0%
6	a	0.18	0.46 (0.180)	−0.280(-0.67, 0.07)	0.063	94.0%
7	a	0.17	0.26 (0.066)	−0.091 (−0.22, 0.04)	0.087	91.0%
	b	0.22	0.15 (0.069)	0.063 (−0.09, 0.20)	0.161	84.0%
8	a	0.11	0.01 (0.002)	0.110 (0.10, 0.11)	0.001	99.9%
	b	0.29	0.18 (0.043)	0.100 (0.01, 0.18)	0.015	98.6%
9	a	0.08	0.01 (0.004)	0.069 (0.06, 0.08)	0.001	99.9%
10	a	0.04	0.01 (0.001)	0.037 (0.03, 0.04)	0.001	99.9%
	b	0.41	0.11 (0.034)	0.290 (0.22, 0.36)	0.001	99.9%
11	a	0.14	0.14 (0.037)	0.005 (−0.07, 0.08)	0.442	56.0%
	b	0.15	0.25 (0.054)	−0.098 (−0.20, 0.00)	0.031	96.9%
12	a	0.05	0.001(0.000)	0.047 (0.046, 0.047)	0.001	99.9%
	b	0.24	0.11 (0.031)	0.130 (0.05, 0.18)	0.004	99.6%
13	a	0.11	0.01 (0.002)	0.100 (0.09, 0.10)	0.001	99.9%
14	a	0.30	0.15 (0.023)	0.150 (0.11, 0.20)	0.001	99.9%
15	a	0.24	0.02 (0.006)	0.220 (0.21, 0.24)	0.001	99.9%
	b	0.28	0.40 (0.088)	−0.130 (−0.30, 0.04)	0.074	93.0%
	c	0.48	0.55 (0.120)	−0.071 (−0.29, 0.18)	0.284	72.0%
16	a	0.16	0.04 (0.009)	0.120 (0.10, 0.14)	0.001	99.9%
	b	0.32	0.19 (0.026)	0.130 (0.08, 0.18)	0.001	99.9%
	c	0.64	0.51 (0.064)	0.130 (0.01, 0.26)	0.019	98.1%
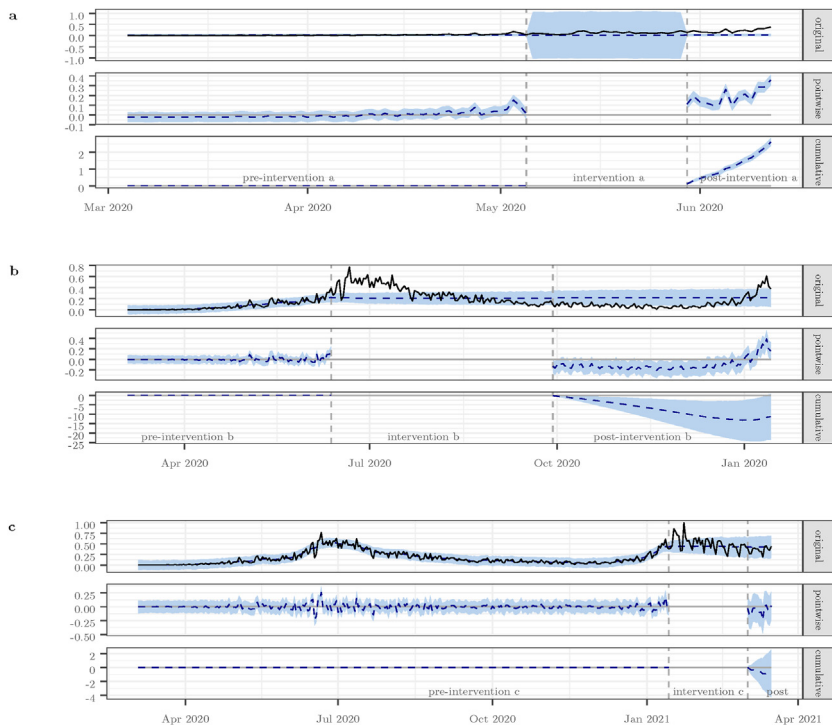
Fig. 5. Causal effect of the Phase 1 quarantine in Antofagasta (region 2). Each block in the figure shows the time series of the proportion of infections by COVID-19, the punctual incremental impact (daily), and the cumulative impact. (a) The quarantine intervention period from May 06, 2020, to May 30, 2020. (b) The quarantine intervention period from June 13, 2020, to September 01, 2020. (c) The quarantine intervention period from January 14, 2021, to March 03, 2021.

statistically significant result. Regions 1, 3 and 11 in the periods highlighted in Table 1 were special cases. For these cases, although quarantines did not produce an expected negative effect, an absolute causal effect of less than 5%, with low causal impact probabilities of 82%, 67% and 56%, respectively, were observed. These observations may indicate that the effect may be false and would not generally be considered statistically significant. However, when looking at the graphs of these regions, decreases or at stable numbers of COVID-19 infections were observed after the implementation of the Phase 1 quarantines. In these cases, the comovement analysis concluded a weak agreement ($0.41 < \tau_{xy} \leq 0.46$) with curve $Y_{r,t}$.

Finally, it is relevant to mention that in the south-central regions of the country (regions 8, 9, 10, 12, 14 and 16), the quarantines were not effective or at least they did not manage to keep the number of infections constant in the study period.

Regarding the effectiveness of the quarantines in Phase 2, it can be inferred from Table 2 that a statistically significant negative effect was observed in regions 3, 4, and 5 during intervention periods (a), (a) and (b), respectively. Similar to the case in Phase 1, a statistically nonsignificant effect was observed in regions 2 and 6 for the quarantine periods; however, the absolute effect was negative, which implies that the number of infections after intervention remained constant or decreased slightly. Concerning comovement, weak concordant movement was only observed in regions 2 and 5; in the rest of the regions, no concordance was observed.

Metropolitan region 13 is a special case. According to our criteria, it was concluded that the effect of the implementation of Phases 1–2 in period (a) was not effective. In Phase 1, there was an average increase off 11% in terms of postintervention cases, while in the absence of intervention, an average increase of 1% ($D = 10\% > 0$) was expected. In Phase 2, an average value of 5% was observed; in contrast, in the absence of intervention, we expected an average response of 17%, which implies a nonsignificant negative effect of 11%. However, from Figs. 2–3 it can be seen that the behavior of the curve corresponding to Phase 1 coincides with the intensity of the contagions ($\tau_{xy} = 0.40$), where a strong reduction in cases was achieved in the middle of the period, without reaching the prequarantine indicators. In contrast, the Phase 2 curve does not show any potential effect on the decrease in the number of infected cases ($\tau_{xy} = 0.28$); therefore, the prolongation of Phase 2 carries a cost of well-being and mental health that can affect the population.

4. Discussion

In Chile, the first reported case of COVID-19 occurred during March 2020; then, the number of cases at the national level began to increase, and the government declared a constitutional state of exception due to a health emergency. At the end of the same month, the closure of all borders, a night curfew, sanitary cordons and quarantine were decreed in metropolitan region 13, and measures were also extended to other regions over time (Gobierno de Chile, 2020), as shown in Fig. 2. At this time, the closure of educational, commercial and tourism centers and activities that led to the crowding of people occurred, and teleworking and physical distancing were preferred according to the recommendations of the WHO (W. H. Organization, 2017). During the first 3 months of the pandemic, the number of cases increased in all regions of the country. Fig. 2 shows that the Ministry of Health implemented quarantine as active cases expanded in the territory. Evidence has shown that in other parts of the world during the same period, contagion was stopped through actions such as travel bans ((Ryan et al., Wiysonge)). For example, Australia decreased COVID-19 imports by 79% and delayed the outbreak until May 2020 by closing borders ((Adekunle et al., 2020)). In Chile, the borders were closed during the same month; however, the entry of people from abroad had already occurred with reduced epidemiological control measures and outbreak blocking for more than 30 days ((Gobierno de Chile, 2020)).

Table 2
Effect of Phase 2 in different regions of Chile (on March 3, 2020 to March 15, 2021).

Region	Intervention	Actual	Posterior inference-average		Posterior probabilities	Probabilities of causal Impact
			Prediction (s.d.)	Absolute effect (s.d.)		
1	a	0.25	0.14 (0.023)	0.11 (0.07, 0.16)	0.001	99.9%
2	a	0.11	0.36 (0.880)	−0.24 (−2.10, 1.50)	0.400	60.0%
3	a	0.05	0.22 (0.025)	−0.17 (−0.22, −0.13)	0.001	99.9%
4	a	0.07	0.38 (0.027)	−0.31 (−0.36, −0.26)	0.001	99.9%
	b	0.39	0.10 (0.081)	0.29 (0.16, 0.48)	0.014	98.7%
5	a	0.30	0.32 (0.150)	−0.02 (−0.30, 0.29)	0.421	58.0%
	b	0.15	0.27 (0.099)	−0.12 (−0.32, 0.08)	0.098	90.0%
6	a	0.19	0.33 (0.260)	−0.14 (−0.66, 0.35)	0.295	70.0%
7	a	0.19	0.20 (0.170)	−0.01 (−0.33, 0.32)	0.478	52.0%
8	a	0.21	0.18 (0.024)	0.03 (−0.02, 0.07)	0.104	90.0%
9	−	−	−	−	−	−
10	−	−	−	−	−	−
11	a	0.21	0.13 (0.042)	0.08 (0.01, 0.17)	0.024	97.6%
12	a	0.38	0.04 (0.005)	0.34 (0.33, 0.35)	0.001	99.9%
13	a	0.05	0.17 (0.270)	−0.11 (−0.63, 0.40)	0.331	67.0%
14	−	−	−	−	−	−
15	a	0.50	0.28 (0.073)	0.22 (0.08, 0.35)	0.002	99.8%
16	a	0.38	0.20 (0.031)	0.18 (0.12, 0.24)	0.001	99.9%

Table 3
Kendall correlation coefficient with normal and t copula models for percentage of confirmed COVID-19 cases and Phases 1–2 (on March 3, 2020 to March 15, 2021).

Region	Copula	Phase 1			Phase 2
		τ_{XY}	AIC	τ_{XY}	AIC
1	Normal	0.41	−126.28	−0.06	0.76
	t	0.40	−120.61	−0.06	3.55
2	Normal	0.41	−132.3	0.44	−95.49
	t	0.41	−125.78	0.44	−90.10
3	Normal	0.41	−114.21	0.21	−14.61
	t	0.40	−108.38	0.21	−11.89
4	Normal	0.28	−37.2	0.29	−33.41
	t	0.28	−32.66	0.29	−31.12
5	Normal	0.32	−67.05	0.48	−132.12
	t	0.32	−61.47	0.48	−130.44
6	Normal	0.46	−175.32	0.29	−38.76
	t	0.46	−170.74	0.29	−36.19
7	Normal	0.55	−274.63	0.38	−77.16
	t	0.55	−271.74	0.38	−73.82
8	Normal	0.47	−190.53	0.32	−50.14
	t	0.46	−183.54	0.32	−46.51
9	Normal	0.49	−219.15	0.37	−67.73
	t	0.49	−213.46	0.38	−66.63
10	Normal	0.43	−158.49	0.42	−92.86
	t	0.43	−160.17	0.42	−89.23
11	Normal	0.46	−132.58	0.23	−13.16
	t	0.46	−130.51	0.22	−10.03
12	Normal	0.42	−130.24	−0.13	−4.11
	t	0.41	−125.63	−0.13	−1.71
13	Normal	0.40	−127.79	0.28	−39.01
	t	0.40	−121.04	0.27	−35.84
14	Normal	0.56	−276.79	0.31	−46.83
	t	0.56	−273.34	0.34	−51.71
15	Normal	0.32	−52.94	0.31	−24.74
	t	0.32	−51.05	0.30	−22.06
16	Normal	0.29	−47.96	0.37	−59.62
	t	0.28	−44.79	0.37	−57.48

Quarantines continued to be implemented, and due to the epidemiological statistical analysis carried out on a daily basis, the Ministry of Health decided to apply sanitary restrictions to new communes in different regions of the country. Although the data in Fig. 2 reveal that there was an increase in the number of COVID-19 infections, as reflected in the number of instantaneous reproductions greater than 1, during the first 3 months of the pandemic at a general level in Chile, paradoxically different behavior was observed between regions that applied the measures of the step-by-step plan, highlighting the regions of the north of the country. For example, as shown in Fig. 2, Phase 1 quarantines were more effective in Arica (region 15), Antofagasta (region 2), Atacana (region 3), Coquimbo (region 4), Valparaíso (region 5) and O'Higgins (region 6) in comparison to the other regions of the country. Additionally, regions such as Atacana (region 3), Coquimbo (region 4), Valparaíso (region 5) and Metropolitana (region 13) had moderate effectiveness in controlling the COVID-19 pandemic.

Another aspect that we must highlight from this study is that the quarantines implemented in central-southern and extreme southern Chile (regions 8, 9, 10, 11, 12, 14 and 16) were not effective. Figs. 2–3 show that the number of infections increased throughout the study period despite the implementation of both Phase 1 and Phase 2 quarantines. This fact should be considered for future quarantine interventions in the southern zone of Chile. A possible cause of noneffectiveness is the great difference in the growth of the domestic product (GDP) per capita (GDP/population) between the extreme regions of the country and the metropolitan region (Mieres, 2020), which is associated with compliance with confinement measures and preventive health care available to the inhabitants of these regions.

However, periods with long quarantines are observed, and a unifying criterion is not observed to apply the confinement interventions of the population in all the regions. In particular, in the metropolitan region, prolonged quarantines were implemented over time. The intervention analysis indicated that Phase 2 did not have an effective causal effect in reducing the number of infections. This is a worrisome tendency since, in practice, it means that prolonged quarantine harms the mental health of the population.

Other countries used similar strategies, such as border closures, quarantines, and reduced mobility. The authors pointed out that the success of the quarantine was produced by factors such as the reduction of the interconnection between the territories of a country or between countries, a decrease in imported active cases, and the implementation and enforcement of local measures to contain community transmission and outbreak locks (Burns et al., Pfadenhauer et al.). In addition, the places where the quarantines were carried out early and in a timely manner experienced lower economic and health costs, and

additionally, the implementation of prevention and epidemiological control measures ensured the effectiveness of the quarantine ((Nussbaumer-Streit et al., Zachariah et al.)).

4.1. Conclusion

In the regions located in the north and in the center of Chile, the application of quarantines in Phase 1 was effective as a strategy to avoid the increase in COVID-19 infections, as described in the intervention analysis. In addition, a progressive increase in infections, hospitalizations and deaths was observed during the first quarter of 2021.

Regarding Phase 2, it can be noted that quarantines did not significantly reduce infections in most regions; effectiveness was only observed in five regions of north and central of Chile, in particular, regions 2, 3, 4, 5 and 6 in which a reduction in cases was observed after intervention through this quarantine. Additionally, it should be mentioned that simultaneously with its implementation, a second peak of infections was observed due to the greater mobility of people between regions, relaxation of sanitary restrictions for the holidays and then the arrival of autumn (Gobierno de Chile, 2020). It would be relevant in subsequent studies to identify the sociocultural variables that favored the increase in infections during the first quarter of 2021 and to analyze the behavior of the effective number of reproductions with the start of the vaccination plan against COVID-19. Another aspect of interest to consider would be to analyze the differences in decision-making to apply the step-by-step plan in each of the regions because in some of them, the decisions to change from Phase 1 to Phase 2 in certain regions coincided with the increase and decrease of infections. However, in other regions, decision-making did not coincide with infection rates; for example, in regions 7, 8, 9, 10, 14 and 16, a significant increase in infections was observed, independent of the phases implemented to reduce infections. In this context, it would also be pertinent to evaluate whether the guidelines issued by the Ministry of Health at the central level (metropolitan region 13) were consistent with those applied at the regional and community levels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adekunle, A., Meehan, M., Rojas-Alvarez, D., Trauer, J., & McBryde, E. (2020). Delaying the covid-19 epidemic in Australia: Evaluating the effectiveness of international travel bans. *Australian & New Zealand Journal of Public Health, 44*(4), 257—259.

Akoglu, H. (2018). User's guide to correlation coefficients. *Turkish journal of emergency medicine, 18*(3), 91—93.

S. M. Bergstresser, Why a coronavirus quarantine in the us is a bad idea, Last accessed on.

Baur, Dirk G. (2003). What is Co-movement? *EUR Working Paper, 20759.* https://doi.org/10.2139/ssrn.570585. In press.

Brodersen, K. H., Gallusser, F., Koehler, J., Remy, N., & Scott, S. L. (2015). *Inferring causal impact using bayesian structural time-series models* (pp. 247—274). The Annals of Applied Statistics.

Brodersen, K. H., Hauser, A., & Hauser, M. A. (2017). *Package 'causalimpact'.*

J. Burns, A. Movsisyan, J. M. Stratil, M. Coenen, K. M. Emmert-Fees, K. Geffert, S. Hoffmann, O. Horstick, M. Laxy, L. M. Pfadenhauer, et al., Travel-related control measures to contain the covid-19 pandemic: A rapid review, Cochrane Database of Systematic Reviews (9).

J. Courtney, Covid-19: Tracking the pandemic with a simple curve approximation tool (scat), medRxiv.

Feroze, N. (2020). Forecasting the patterns of covid-19 and causal impacts of lockdown in top five affected countries using bayesian structural time series models, Chaos. *Solitons & Fractals, 140,* Article 110196.

Feroze, N. (2021). Assessing the future progression of covid-19 in Iran and its neighbors using bayesian models. *Infectious Disease Modelling, 6,* 343—350.

Z. Gao, J. Zhu, J. Yang, Q. Liu, Z. Liu, D. Li, Q. Wang, Estimating the efficacy of traffic blockage and quarantine for the epidemic caused by 2019-ncov (covid-19), https://www. medrxiv. org/content/10.1101/2020.02. 14.20022913 v3.

Gobierno de Chile, Plan de acción coronavirus. paso a paso. https://www.gob.cl/coronavirus/pasoapaso/, (2020)—. (Accessed 7 August 2022).

J. Jia, J. Ding, S. Liu, G. Liao, J. Li, B. Duan, G. Wang, R. Zhang, Modeling the control of covid-19: Impact of policy interventions and meteorological factors, arXiv preprint arXiv:2003.02985.

Kaffure, L. H. (2010). El concepto de pandemia: Debate e implicaciones a propósito de la pandemia de influenza de 2009. *Revista Gerencia y Políticas de Salud, 9*(19), 4.

Li, F. (2014). Identifying asymmetric comovements of international stock market returns. *Journal of Financial Econometrics, 12*(3), 507—543.

R. Li, W. Lu, X. Yang, P. Feng, O. Muqimova, X. Chen, G. Wei, Prediction of the epidemic of covid-19 based on quarantined surveillance in China, medRxiv.

Mathys, G., Ea, B., et al. (1980). An appraisal of the effectiveness of quarantines. *Annual Review of Phytopathology, 18*(1), 85—101.

Mieres, M. (2020). Brevis, La dinámica de la desigualdad en Chile: Una mirada regional. *Revista de análisis económico, 35*(2), 91—133.

Ministerio de Salud de Chile, Plan paso a paso. https://www.minsal.cl/wp-content/uploads/2020/07/ConocePlanPasoaPaso.pdf, (2020)—. (Accessed 7 August 2022).

Miot, H. A. (2018). Correlation analysis in clinical and experimental studies. *Jornal Vascular Brasileiro.* SciELO Brasil.

Navas Thorakkattle, M., Farhin, S., et al. (2022). Forecasting the trends of covid-19 and causal impact of vaccines using bayesian time series and arima. *Annals of Data Science,* 1—23.

B. Nussbaumer-Streit, V. Mayr, A. I. Dobrescu, A. Chapman, E. Persad, I. Klerings, G. Wagner, U. Siebert, D. Ledinger, C. Zachariah, et al., Quarantine alone or in combination with other public health measures to control covid-19: A rapid review, Cochrane Database of Systematic Reviews (9).

Observatorio de Medicina UC. (2020). ¿epidemia, pandemia o endemia?. https://observatorio.medicina.uc.cl/epidemia-pandemia-o-endemia/. (Accessed 7 August 2022).

Organization, W. H. (2020). *Considerations for quarantine of contacts of covid-19 cases: Interim guidance, 19.* Technical documents. august 2020.

T. Qiu, H. Xiao, Revealing the influence of national public health policies for the outbreak of the sars-cov-2 epidemic in wuhan, China through status dynamic modeling, MedRxiv.

R. C. Team, et al., R: A language and environment for statistical computing.

J. Ryan, A. V. Mazingisa, C. S. Wiysonge, Cochrane corner: Effectiveness of quarantine in reducing the spread of covid-19, The Pan African Medical Journal 35 (Suppl 2).

Taghrir, M. H., Akbarialiabad, H., & Marzaleh, M. A. (2020). Efficacy of mass quarantine as leverage of health system governance during covid-19 outbreak: A mini policy review. *Archives of Iranian Medicine, 23*(4), 265.

Vallejos, R. (2008). Assessing the association between two spatial or temporal sequences. *Journal of Applied Statistics, 35*(12), 1323–1343.

W. H. Organization. (1999). *Plan de preparación para la pandemia de influenza : El rol de la oganización mundial de la salud y guías para la planificación nacional y regional, ginebra, suiza, abril 1999*.

W. H. Organization. (2011). Aplicación del reglamento sanitario internacional. 64 asamblea mundial de la salud. 5 de mayo de 2011. https://apps.who.int/gb/ebwha/pdf_files/WHA64/A64_10-sp.pdf. (Accessed 7 August 2022).

W. H. Organization. (2017). Pandemic influenza risk management: A who guide to inform and harmonize national and international pandemic preparedness and response. https://apps.who.int/iris/handle/10665/259893. (Accessed 7 August 2022).

World Health Organisation. (2020a). Press conferences on covid-19. https://www.who.int/emergencies/diseases/novel-coronavirus-2019. (Accessed 3 January 2020).

World Health Organization. (2020b). Who characterizes covid-19 as a pandemic. https://www3.paho.org/hq/index.php?option=com_content&view=article&id=15756:who-characterizes-covid-19-as-a-pandemic&Itemid=1926&lang=en. (Accessed 7 August 2022).

World Health Organization. (2020c). Who releases guidelines to help countries maintain essential health services during the covid-19 pandemic. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/maintaining-essential-health-services-and-systems. (Accessed 7 August 2022).

Xie, L. (2022). The analysis and forecasting covid-19 cases in the United States using bayesian structural time series models. *Biostatistics & Epidemiology, 6*(1), 1–15.

Yang, Z., Zeng, Z., Wang, K., Wong, S.-S., Liang, W., Zanin, M., Liu, P., Cao, X., Gao, Z., Mai, Z., et al. (2020). Modified seir and ai prediction of the epidemics trend of covid-19 in China under public health interventions. *Journal of Thoracic Disease, 12*(3), 165.