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# Recursive Zero-COVID model and quantitation of control efforts of the Omicron epidemic in Jilin province

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ABSTRACT

Since the beginning of March 2022, the epidemic due to the Omicron variant has developed rapidly in Jilin Province. To figure out the key controlling factors and validate the model to show the success of the Zero-COVID policy in the province, we constructed a Recursive Zero-COVID Model quantifying the strength of the control measures, and defined the control reproduction number as an index for describing the intensity of interventions. Parameter estimation and sensitivity analysis were employed to estimate and validate the impact of changes in the strength of different measures on the intensity of public health preventions qualitatively and quantitatively. The recursive Zero-COVID model predicted that the dates of elimination of cases at the community level of Changchun and Jilin Cities to be on April 8 and April 17, respectively, which are consistent with the real situation. Our results showed that the strict implementation of control measures and adherence of the public are crucial for controlling the epidemic. It is also essential to strengthen the control intensity even at the final stage to avoid the rebound of the epidemic. In addition, the control reproduction number we defined in the paper is a novel index to measure the intensity of the prevention and control measures of public health.

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## 1. Introduction

Affected by the fourth wave of SARS-CoV-2 Omicron variant in the world, the enhancing frequency of local epidemics in China is caused by the imported cases, resulting in a large number of domestic epidemics (Central People's Government of the People's Republic of China, 2022a). Since March 2022, the epidemic has developed rapidly in Jilin Province. This outbreak is

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characterized by multiple sporadic, clustered infected, and widespread. The number of infected humans exceeded 10,000 cases two weeks later, and more than 50,000 cases in early April (People's Government of Jilin Province, 2022a, 2022b, Health Commission of Jilin Province,2022), of which about 98% of the infections being tested positive were found in Jilin City and Changchun City (People's Government of Jilin Province, 2022b). In addition, it has been investigated that the epidemic started to spread in the community in late February (Central People's Government of the People's Republic of China, 2022, People's Daily Online, 2022). The short generation interval, fast transmission speed, and shorter incubation of the Omicron virus lead to the increase in the difference between the efficiency of PCR testing and the speed of virus transmission. This further results in a rapid increase in the number of infectious people (People's Government of Jilin Province, 2022b).

To curb the development of the epidemic, the officials in Jilin Province were serious concern with the strategy of Dynamic Zero-COVID, and followed the three keys of controlling the source of infection, cutting off the route of transmission, and protecting susceptible groups. With the efforts, Jilin City and Changchun City achieved Zero-COVID Status at the community level on April 8 and April 13, 2022, respectively (Health Commission of Jilin Province, 2022, Central People's Government of the People's Republic of China, 2022), which is a success in controlling the spread of the disease. Subsequently, the prevention and control of the epidemic in Jilin Province have always been aimed at eliminating cases at the community level (People's Government of Jilin Province, 2022c-3), and all departments adhere to the implementation of hierarchical control. As of May 12, there were no new local confirmed cases and local asymptomatic infections in all states in the province (Health Commission of Jilin Province, 2022)(see Fig. 1). During the battle against the epidemic in Jilin Province, although a dynamic zero-COVID situation was achieved, there were still some problems in the process, such as the lack of close connection of the detection process, the inability to fully cover the testing population, the irregularity of the testing process and so on. How to quantify the implementation intensity of interventions, clarify the weak links in prevention and control, and evaluate the effectiveness of control measures are important issues that need to be solved urgently.

Classical dynamic models are one of the important models to describe the transmission mechanism of infectious diseases. For example, the model proposed by Kermack and McKendrick (Kermack et al., 1991a,b,c) was widely used in the prevention and control of infectious diseases, and the model results provided a certain scientific basis for control strategies. The model studies for COVID-19 were mainly based on the transmission mechanism of the epidemic (Rong et al., 2020a, 2020b, Li et al., 2020; Zhou et al., 2022). Moreover, the transmission ability of diseases, estimations of potential cases, and the evaluation of the reproduction number were the early focuses of modeling studies (Shen et al., 2020; Imai et al., 2020, Song et al., 2020; Chen et al., 2020). The beneficial implementation of non-pharmaceutical interventions (NPIs) to mitigate the spread of COVID-19 has also been widely studied (Yuan et al., 2020, 2022).

Although this kind of model has been well applied in predicting the disease, assessing the efficiency of prevention and control measures, etc., they cannot directly character the number of infections at the community level. However, to know changes of the number of infections at the community level is the key for controlling COVID-19. Moreover, a reasonable indicator facilitates quantifying and evaluating the effectiveness of prevention and control measures. In June 2021, the World Health Organization proposed such indicators and recommended thresholds for measuring transmission intensity and health system response capacity (World Health Organization, 2021), while a more effective indicator to characterize and quantify the intensity of prevention and control measures is urgent. Consequently, it is necessary to develop a comprehensive indicator that can be used to quantify the intensity of prevention and control in the public health sector.

In this study, based on the recursion idea, comprehensively consider various prevention and control measures, and construct a recursive Zero-COVID model to describe the changes in the number of infections at the community level. In this model, we ignore the traditional SEIR comprtments and instead focus on undiscovered, newly reported, and the change in the number of infected persons in the isolated zone during the epidemic. The model can be used to assess the effectiveness of current prevention and control measures, based on the changes in public health prevention and control measures in Changchun City and Jilin City. The implementation intensity of the measures is defined as an indicator that can comprehensively characterize the intensity of prevention and control measures.

## 2. Materials and methods

### 2.1. The development of the epidemic

With the rapid escalation of COVID-19 cases due to the Omicron variant in Jilin Province, the authorities responded quickly and issued prevention and control measures to curb the spread of COVID-19. For example, to effectively control the sources of the infection, PCR testing for the whole population, checking and management in the whole region, isolation and control of epidemic-related personnel, and medical (Fangcang) treatment are implemented; measures such as suspending personnel gathering, strengthening community control, environmental disinfection and sterilization, tracing and isolation can effectively cut off routes of transmission; the closure and control of public places, the closed management of communities, residents' self-government at home and self-testing and self-inspection can protect the susceptible. In addition, the local governments and healthcare departments have adopted stricter and more efficient prevention and control measures than before, improved the efficiency and quality of PCR testing continuously, then mobilized medical resources and strengthened the intensity of management (Central People's Government of the People's Republic of China, 2022a, Health Commission of Jilin Province, 2022).

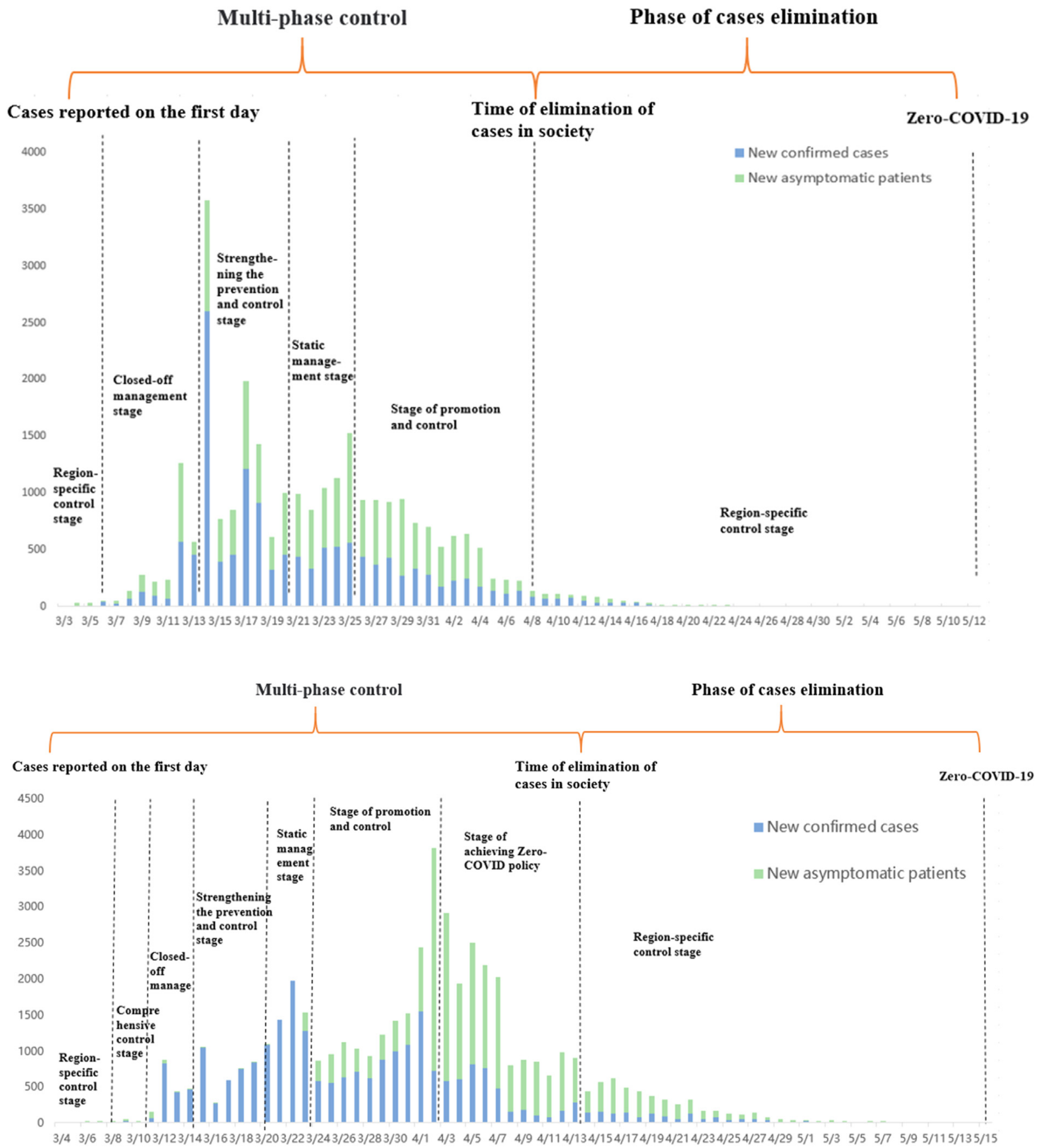


**Fig. 1.** The daily number of new infections and the change of prevention and control measures in Jilin City (above) and Changchun City (below). The implementation of control measures in each control stage is listed in Table 1.

According to the development of the epidemic, we take the reporting time of the first case of COVID-19 as the "starting point" of the epidemic. The total number of infections on the *i-th* day is denoted as $N_i$, the number of newly reported infections is $M_i$, and the total number of undiscovered infections at this time is $A_i$. If the number of newly reported infections continues to be zero, the epidemic will end; otherwise, a new round of whole-population inspection, traceability, and isolation in epidemic regions will be carried out to identify the isolation groups such as close contacts and sub-close contacts. Meanwhile, PCR testing will be performed on the whole population. After screening in the population, the number of infected people in the control group is set as $Q_i$, and the number of undiscovered infections at the community level at this time is $L_i$. If the number of infections at the community level is zero, the goal of eliminating cases at the community level will be alleviated; otherwise, the same intervention process will continue until the number of infections at the community level is zero. Further, the controlled population will be focused until the number of newly reported infections is zero (see Fig. 2 for details).

### 2.2. The control reproduction number $R_c$

The basic reproduction number $R_0$ defined as $R_0 = \beta_0\, k/\gamma$ is available to characterize the transmission ability of infectious diseases in the absence of control measures (Heesterbeek, 2002). Here $\beta_0$ is the probability of the susceptible being infected in each effective contact with the infected, $k$ is the number of effective contacts between the susceptible and the infectious, and $1/\gamma$ is the average timespan of the infection. In addition, the control reproduction number $R_c$ can be used to reflect the intensity of prevention and control for a disease, when there are control measures to intervene. $R_c$ measures the average number of new infections produced by one infection. The quantitative assessment of this indicator facilitates the assessment of the effectiveness of current prevention and control measures.

As we all know, controlling the sources of infection, cutting off the routes of transmission, and protecting the susceptible population are the three basic steps to curb the spread of infectious diseases. The essence of these controls is to reduce the effective contacts between the infectious and the susceptible (simplified as the effective contacts), and to reduce the transmission duration. Since the implementation of control measures in a single basic step can reduce the effective contacts, we then set $k_1$, $k_2$ and $k_3$ are the number of effective contacts during PCR testing (for controlling the source of infection), tracking and isolation (for cutting off the route of transmission), and home isolation (for protecting susceptible people), and there is $k_n < k, n = 1, 2, 3$. The control measures for controlling the sources of infection and cutting off the routes of transmission can effectively reduce the transmission duration, and the control measures for protecting susceptible people do not change the transmission duration. Then, we define $1/\gamma_1$, $1/\gamma_2$ and $1/\gamma_3$ as the transmission durations during PCR testing, tracking and isolation, and home isolation, respectively, and $1/\gamma_1 < 1/\gamma$, $1/\gamma_2 < 1/\gamma$, $1/\gamma_3 = 1/\gamma$. $\sigma_e$ represents the average duration of infectivity during the incubation period. $\sigma_1$ is the time interval from testing sampling to the inspection result in a round of whole-population PCR testing. $\sigma_2$ is the time interval from the discovery of the infection to the transfer to the Fangcang shelter hospital. $\sigma_3$ is the traceability tracking duration. Whence,

$$\frac{1}{\gamma_1} = \sigma_e + \sigma_1 + \sigma_2, \frac{1}{\gamma_2} = \sigma_e + \sigma_3, \frac{1}{\gamma_3} = \frac{1}{\gamma}.$$

Due to the limited resources for prevention and control, the proportion of resource input in the measures involved in the three control steps is not the same. The weights of resource input to controlling the source of infection, cutting off the

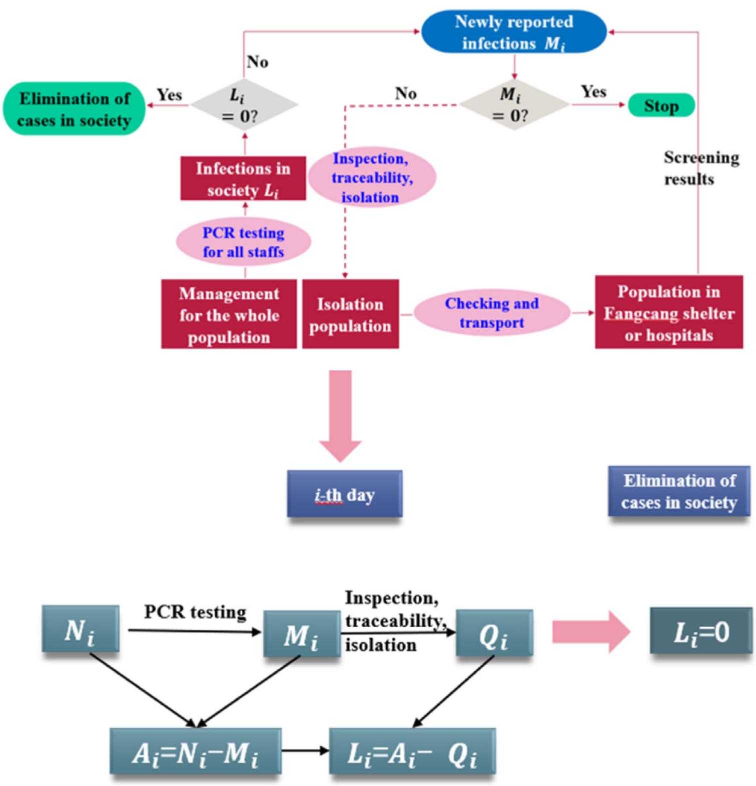


**Fig. 2.** Development of the epidemic (above) and diagram of the COVID transmission (below).

transmission route, and protecting the susceptible are defined as $l_1, l_2$ and $l_3$, and satisfy $l_1 + l_2 + l_3 = 1$. In summary, the control reproduction number (novel index) is given by

$$R_c = \beta_0\left(l_1\frac{k_1}{\gamma_1} + l_2\frac{k_2}{\gamma_2} + l_3\frac{k_3}{\gamma_3}\right). \tag{1}$$

Note that if no control measures are implemented, then the parameters satisfy $k_1 = k_2 = k_3 = k, \gamma_1 = \gamma_2 = \gamma_3 = \gamma$, and $l_1 + l_2 + l_3 = 1$, hence the expressions of $R_c$ and $R_0$ are the same. The authorities usually adjust the control intensity with the development of the Omicron epidemic (assuming that there are $m$ control stages with different control intensities), and the parameter values of each stage are different, so the control reproduction number of the $j$-th stage is

$$R_{cj} = \beta_0\left(l_1\frac{k_{1j}}{\gamma_{1j}} + l_2\frac{k_{2j}}{\gamma_{2j}} + l_3\frac{k_{3j}}{\gamma_{3j}}\right), j = 1, 2, 3\ldots, m. \tag{2}$$

### 2.3. Recursive model under Zero-COVID policy

Let $\tau$ be the time interval between the first entering infection and the confirmed and reported cases, during which the virus spread freely. According to the definition of the basic reproduction number, define $\mathrm{T} = 1/\gamma$ as the average infectious period of the virus, and the number of new infections infected by an infectious person per unit time is $(\mathrm{R}_0/\ \mathrm{T})$. Therefore, before control, the total number of cumulative infections by an infection is $(1 + (\mathrm{R}_0/T))^{\tau-1}$, $\tau \geq 1$.

The implementation of Zero-COVID control measures will shorten the transmission duration of the infections or reduce population contacts. Hence, we assume that the indicators of the control ability of the public health interventions are different within different time $i$ ($\geq$1 and are integers), which is denoted as $R_{ci}$. Note that the indicator on the first day is the same as the reproduction number, i.e., $R_{c1} = R_0$. The screening coefficient of is affected by both the total time of detection, isolation, and transit, $1/\gamma_{1i}$, and the total time of traceability, $1/\gamma_{2i}$, then the screening coefficient can be expressed as $\lambda_i \max\{\gamma_{1i}, \gamma_{2i}\}$, where $\lambda_i$ is the screening rate of the *i-th* day. Starting from the first day of newly reported infections (confirmed + asymptomatic infections), the development of the epidemic can be deduced as follows.

**First day:** The total number of whole infections is $N_1 = (1 + R_{c1}/T)^{\tau-1}$, and the number of newly reported infections is $M_1 = \lambda_1 \max\{\gamma_{11}, \gamma_{21}\}N_1$, the number of undiscovered infections is $A_1 = N_1 - M_1$, the number of quarantined infections who infected by reported infections is $Q_1 = f_1 M_1 R_{c1}/T$, where $f_1$ is the proportion of infected people among all infections in the quarantined population (the efficiency of inspection-traceability-isolation), and the number of undiscovered infections at the community level is $L_1 = A_1 - Q_1$.

**Second day:** The total number of whole infections is $N_2 = \mathrm{A}_1 + (\mathrm{A}_1 - Q_1)R_{c2}/T$, and the number of newly reported infections is $M_2 = \lambda_2 \max\{\gamma_{12}, \gamma_{22}\}N_2$, the number of undiscovered infections is $A_2 = N_2 - M_2$, the number of quarantined infections who infected by reported infections is $Q_2 = f_2 M_2 R_{c2}/T$, and the number of undiscovered infections at the community level is $L_2 = A_2 - Q_2$.

**(*i*-1)-*th* day:** The total number of whole infections is $N_{i-1} = A_{i-2} + (A_{i-2} - Q_{i-2})R_{ci-1}/T$, and the number of newly reported infections is $M_{i-1} = \lambda_{i-1} \max\{\gamma_{1(i-1)}, \gamma_{2(i-1)}\}N_{i-1}$, the number of undiscovered infections is $A_{i-1} = N_{i-1} - M_{i-1}$, the number of quarantined infections who infected by reported infections is $Q_{i-1} = f_{i-1} M_{i-2} R_{ci-1}/T$, and the number of undiscovered infections at the community level is $L_{i-1} = A_{i-1} - Q_{i-1}$.

Following the recursive iteration law of daily development for COVID-19, for the $i$-th day ($i$>1), the Recursive Zero-COVID model is

$$\begin{cases} N_i = A_{i-1}\left(1 + \frac{1}{\mathrm{T}}R_{ci}\right) - Q_{i-1} * \frac{1}{T}R_{ci}, \\ M_i = \lambda_i \max\{\gamma_{1i}, \gamma_{2i}\}N_i, \\ A_i = N_i - M_i, \\ Q_i = f_i M_i \frac{1}{T} R_{ci}, \qquad\qquad i = 2, 3, 4\ldots \\ L_i = A_i - Q_i, \\ \textit{with initial condition as}: \\ N_1 = (1 + R_{c1}/T)^{\tau-1},\ M_1 = \lambda_1 \max\{\gamma_{11}, \gamma_{21}\}N_1, \\ Q_1 = \frac{f_1 M_1 R_{c1}}{T}, Q_1 = \frac{f_1 M_1 R_{c1}}{T}, L_1 = A_1 - Q_1\ . \end{cases} \tag{3}$$

here, descriptions of model parameters are summarized in Tables 3–5 in the Appendix.

### 2.4. Numerical fitting and parameter estimation

To evaluate the effectiveness of the Recursive Zero-COVID model in characterizing the change of undiscovered infections at the community level, we employed the least square method for numerical fitting and parameter estimation. The numerical simulations are based on the epidemic development of Changchun and Jilin Cities and the division of multi-stage control intervals and are based on the data before the date of elimination of cases at the community level of the two cities. Following the division of multi-stage control intervals in Jilin and Changchun Cities (Tables 1 and 2), it is assumed that the parameters in the model are unchanged in the same stage, but are different in different stages. For simplicity, we define the region-specific control stage in Jilin City (the region-specific control stage in Changchun City) as the second stage, the comprehensive control stage in Jilin City (the comprehensive control stage in Changchun City) as the third stage and the stage of promotion and control in Jilin City (the stage of achieving Zero-COVID policy in Changchun City) as the last stage. The fitting results are shown in Fig. 3, and the parameter values are listed in Tables 3 and 4 Fig. 4 depicts the curve of the number of remaining infections at the community level shown in the two cities.

### 2.5. Sensitive analysis

Given the uncertainty of the parameters related to the control measures, we employed the Latin Hypercube Sampling/Partial Rank Correlation Coefficient (LHS/PRCC) (Kirschner, 2008) sensitivity analysis method to identify which parameters are more significant at the time of elimination of cases at the community level. The parameters involved here were the screening efficiency (λ), the efficiency of inspection-traceability-isolation ($f$), implementation efficiency of control measures ($\gamma_1, \gamma_2, \gamma_3$), and the number of effective contacts ($k_1, k_2, k_3$). Based on the control stages, the number of effective contacts and implementation efficiency of control measures are defined as $k_{1j}, k_{2j}, k_{3j}$ $\gamma_{1j}, \gamma_{2j}, \gamma_{3j}, f_j$ and $\lambda_j$ (where $j$ is a positive integer, for Jilin City: $2 \le j \le 6$, for Changchun City: $2 \le j \le 8$). The parameters studied and the sampling ranges are provided in Tables 3–5 and the radar charts of sensitivity analysis are shown in Fig. 5.

### 2.6. Quantitative analysis of the index of prevention and control intensity

Aiming to explore the effectiveness of the defined index of prevention and control intensity, we calculated the index of prevention and control intensity $R_{cj}$ of each city at different stages j according to the parameter values (see Tables 2 and 3 for details). In particular, let $R_{c1} = R_0 = 10$ (Burki, 2002), and the results are listed in Fig. 8.

## 3. Results

### 3.1. Estimation for the date of elimination of cases at the community level and parameters

The data-fitting results show that the model solution has a similar trend with the changing of infections (see Fig. 3). Based on the estimated values of parameters, the dates of elimination of cases at the community level of Jilin and Changchun Cities predicted by the model are April 8 and April 17, respectively (Fig. 4), which are in good agreement with the real situation (April 8 and April 13). This shows that the Recursive Zero-COVID model can capture the dynamics of the number of remaining infections at the community level, and the prediction is reliable.

From Tables 3 and 4, it can be seen that among the total number of effective contacts during the whole-population PCR testing, tracing and transit, and home isolation, the number of effective contacts during whole-population PCR testing is the largest, and the effective contacts in Jilin City satisfy $k_{j1} \ge 8, j = 2, 3 \ldots 6$ (the effective contacts in Changchun City satisfies $k_{j1} \ge 18, j = 2, 3 \ldots 8$). We observed that the estimated values of effective contacts during the whole-population PCR testing were much higher than the expected value (0 times), which indicated that there were still irregularities in personnel organization and management during the process of the PCR testing.

Furthermore, the results of parameter estimation showed that the numbers of effective contacts during whole-population PCR testing, tracing and transit, and home isolation in Changchun City was higher than the corresponding values in Jilin City. In the third to sixth control stages, the values of the efficiency of inspection-traceability-isolation in Changchun City are lower than the parameter value in the second stage ($f_2 = 0.8, f_3 = 0.4, f_4 = f_5 = f_6 = 0.5, f_2 > f_j, j = 3, 4, 5, 6$). This indicates that in these four control stages, although the government requires more effort in interventions, the actual intensity (efficiency) of inspection-traceability-isolation decreases due to limited medical resources in the real scenarios, even lower than the control intensity in the first stage. The result ($f_2 > f_j, j = 3, 4, 5, 6$) reflects that in the early stage of the epidemic, the actual intervention intensity in Changchun City is lower than the expected intensity, which may be one of the reasons for the high number of infections in Changchun City in April 2022.

### 3.2. Impact factors on the time of elimination of cases at the community level

Our findings from Fig. 5(a) show that the parameters that affect most the date of elimination of cases at the community level in Jilin City are the implementation efficiency of control measures in the sixth control stage $\gamma_{26}$, the number of effective contacts in the regular prevention and control stage $k$, the number of effective contacts in the sixth control stage $k_{36}$, the

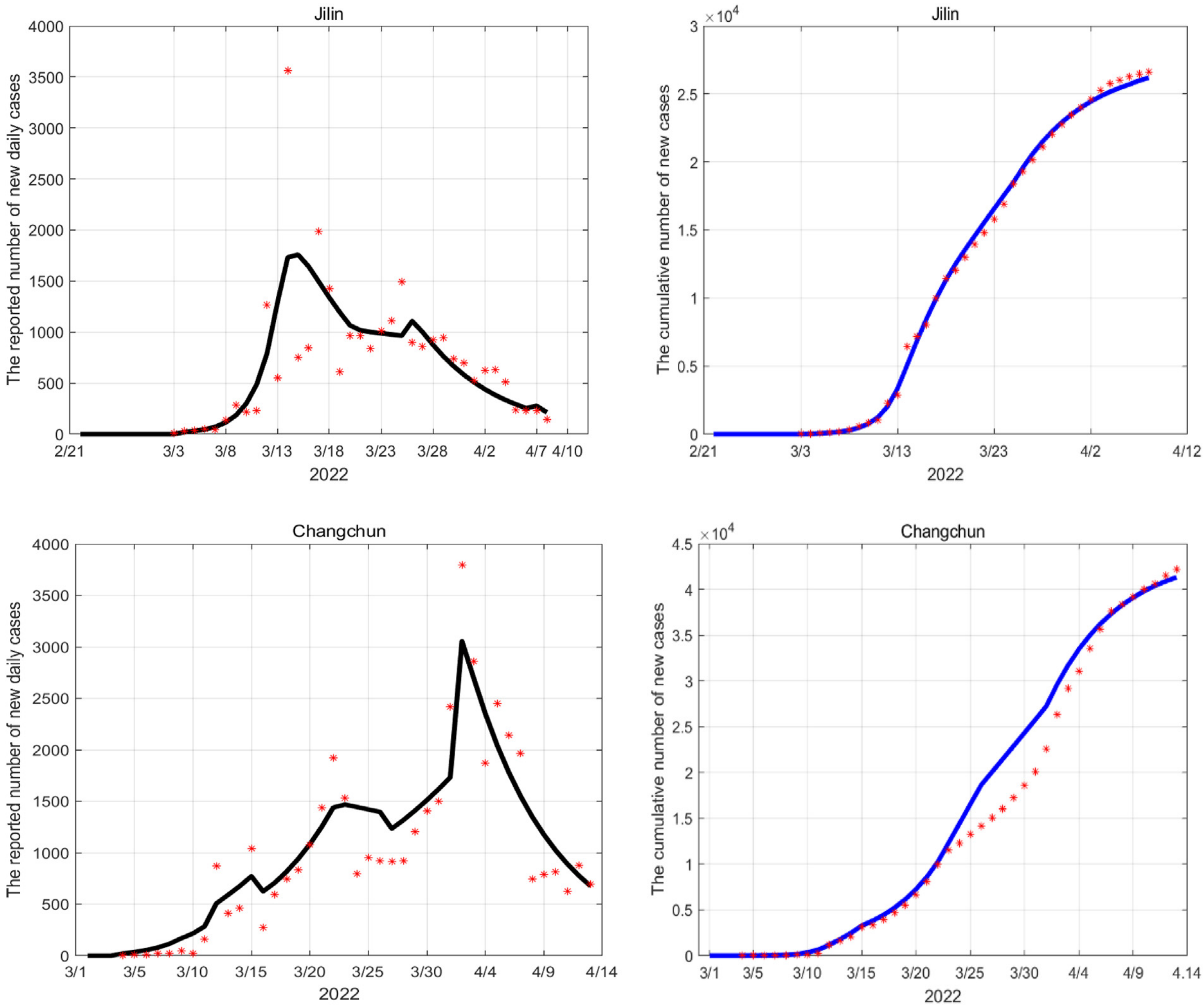


**Fig. 3.** The reported numbers of daily new cases and the cumulative cases in Jilin City (above) and Changhcun City (below). The red asterisks are the number of reported infections (diagnosed, asymptomatic infection and asymptomatic transferred to confirmed cases, data until April 8 and April 13). The solid line is the model fitting curve.

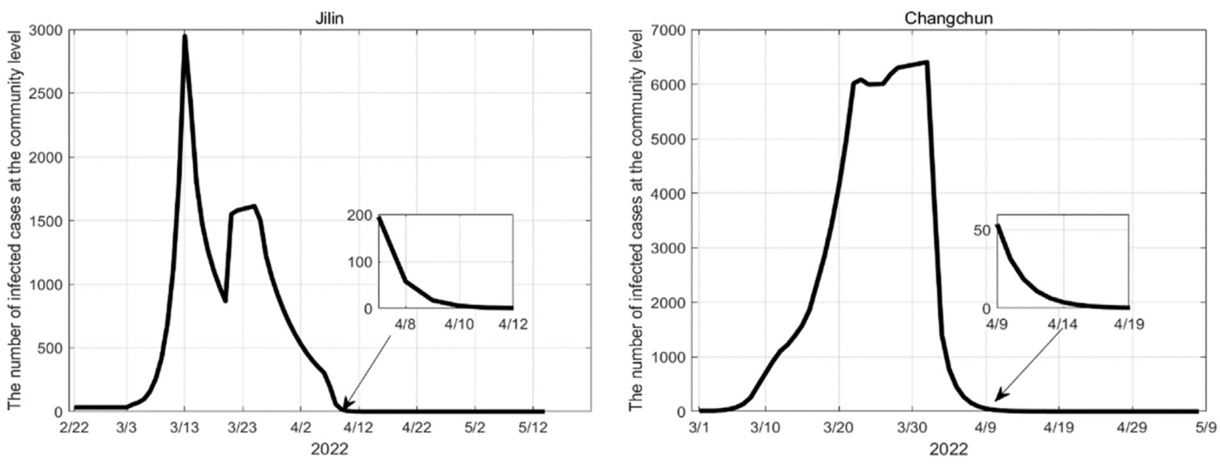


**Fig. 4.** The number of infected cases at the community level and predicted times of the elimination of cases at the community level in Jilin and Changchun Cities (April 8 and April 17).

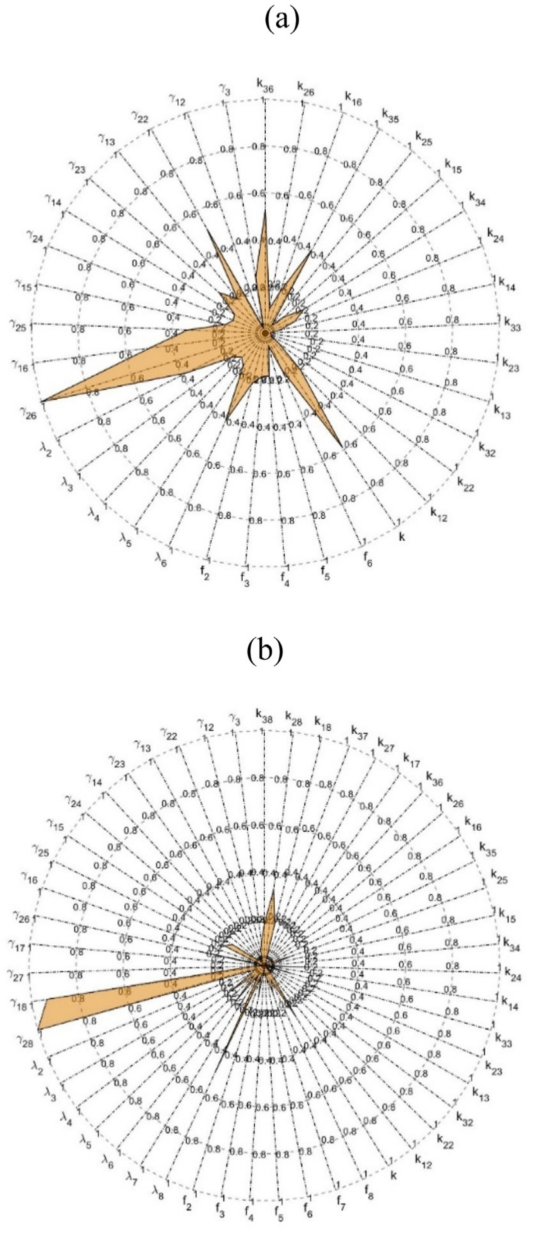


**Fig. 5.** Sensitivity analysis of the date of elimination of cases at the community level to parameters in (a) Jilin City and (b) Changchun City. The date of elimination of cases at the community level is more sensitive to the implementation efficiency of measures in the final stage, which means the control efforts in the sixth control stage in Jilin City (March 26-April 6) and the control efforts in the eighth control stage in Changchun City (April 3-April 13) have an important impact on this elimination time.

implementation efficiency of control measures in the second control stage $\gamma_{22}$, the number of effective contacts during home isolation in the fifth control stage $k_{35}$ and the screening efficiency in the sixth control stage $\lambda_6$. Moreover, the efficiencies of inspection-traceability-isolation $f_j$ weekly affect the time of elimination of cases at the community level. Similarly, the results of sensitivity analysis in Changchun City (Fig. 5(b)) show that the parameters with strong correlation are: the implementation efficiency of control measures in the final control stage $\gamma_{28}, \gamma_{18}$, the screening efficiency $\lambda_8$, and the number of effective contacts during the tracing and transit $k_{28}$. The results also suggest that the date of elimination of cases at the community level is more sensitive to the control parameters in the final stage, that is, the control efforts in the sixth control stage in Jilin City (March 26 - April 6) and the eighth control stage in Changchun City (April 3–13) have a significant impact on the arrival of the time of elimination of cases at the community level. This implies that in the final control stage when the number of new infections is low, it is still necessary to strengthen the implementation intensity of various control measures to achieve the goal of eliminating cases at the community level as soon as possible.

### 3.3. Effect factors on the number of undiscovered infections at the community level

To capture the key factors on the control effect, we analyzed the effect of the efficiency of inspection-traceability-isolation $f$ and screening efficiency $\lambda$, and transit duration $\sigma_2$ on the number of undiscovered infections at the community level (see Fig. 6). Fig. 6 (a) shows that if the efficiency of inspection-traceability-isolation and the transit duration in Jilin City remain unchanged after April 3, and the screening efficiency is reduced by 25%, the number of undiscovered infections at the community level will rebound, and the elimination of cases at the community level will not be achieved before the end of April. If the efficiency of inspection-traceability-isolation remains unchanged, and the transit duration increases by 12 h, the number of undiscovered infections at the community level will also rebound on a certain scale, and it is still impossible to eliminate cases at the community level before the end of April. If the efficiency of inspection-traceability-isolation is reduced by 25% and the intensity of other control measures remains unchanged, the rebound degree of the number of undiscovered infections at the community level will be reduced compared with the first two cases, and it is expected to reach the goal of elimination of cases at the community level by the end of April (see the dotted line in Fig. 6 (a)).

The analysis results show that (Fig. 6 (b)) if the prevention and control efforts in Changchun are lower than those in the final control stage (such as reducing the efficiency of inspection-traceability-isolation, extending the transit duration, etc.), the date of elimination of cases at the community level will be delayed. The lower the prevention and control efforts, the more undiscovered infections at the community level, and the longer the delay time. In particular, if the screening efficiency is reduced by 25%, the number of undiscovered infections at the community level will rebound significantly, and as of May 9, there are still 1000 undiscovered infections at the community level (see Fig. 6 (b)). This implies that when the epidemic tends to the end and the number of undiscovered infections at the community level is small, there is still great uncertainty about the final trend of the epidemic. At this time, there is still a great risk of a rebound in the epidemic, and vigilance cannot be relaxed to weaken the control intensity.

Fig. 7 depicts the impact of the start time of the final control stage on changes in the number of remaining infections in Jilin and Changchun Cities. The results show that (Fig. 7 (a)) if the start time of the final control stage is advanced, the date of elimination of cases at the community level in Jilin City will also be significantly advanced. For example, if the start time is 3 days (March 23), 5 days (March 21), or 7 days (February 28) earlier, the date of elimination of cases at the community level will be 3, 5, and 10 days earlier, respectively. We obtained from the model analysis of Changchun city that with the advance of the start time of the final control stage, the date of elimination of cases at the community level in Chagnchun city will be correspondingly advanced, and the peak value of the number of undiscovered infections at the community level will also decrease.

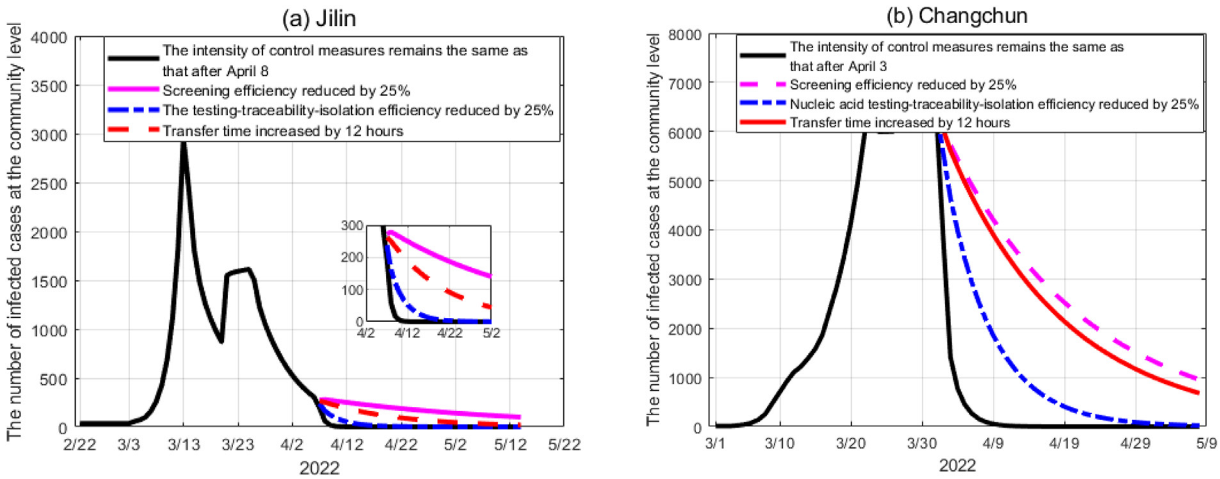


**Fig. 6.** The impact of control measures on the number of undiscovered infections at the community level in Jilin and Changchun Cities. Reducing the prevention and control efforts (such as: reducing the efficiency of inspection-traceability-isolation, prolonging the transfer duration, etc.) will result in a delay of the time of elimination of cases at the community level. The lower the prevention and control efforts, the more remaining infections at the community level and the longer the delay.

### 3.4. Quantitative analysis of the index of prevention and control intensity

It can be seen from Fig. 8 (a) that the index of prevention and control intensity in Jilin City $R_{c2}$ decreases significantly, while $R_{c3}$ increases to the maximum value, and with the strengthening of control intensity, $R_{cj}$ decreases gradually. The decline of the index of prevention and control intensity in the second, fourth to sixth stages indicates that existing control measures are very effective in controlling the epidemic. The reason for the surge in $R_{c3}$ may be that the number of infections increased rapidly and the medical resources were limited at this stage, which led to the reduction of actual efficiency of traceability and transition, find more details in Table 2.

The conclusion reminds authorities to accelerate the disposal of local clusters of outbreaks, and coordinate the key links such as PCR testing, tracing, isolation and transit, and community control, while unswervingly adhering to the general policy of elimination of cases at the community level. Comparing the data of daily new infections in Jilin City in Figs. 8 (a) and Fig. 3, it can be seen that the value of $R_{c4}$ decreased significantly, and the daily number of newly reported infections began to decrease gradually. This indicates that this index can be used as an applicable index to judge the implementation intensity of control measures.

With the increase of the intensity of control measures, the index of prevention and control intensity in Changchun City decreased subsequently until it reached 1.55 in the final stage (see Fig. 8 (b)). The value is similar to Cai's estimation of the control reproduction number for the Omicron outbreak in China (i.e., $R_t \leq 2$) (Cai et al., 2022). Comparing the data of daily newly infected persons in Changchun in Figs. 8 (b) and Fig. 3, when the value of $R_{c5}$ is significantly lower than that of $R_{c4}$, the number of newly reported cases in Changchun City also showed a downward trend (Fig. 3). As the number of the index of prevention and control intensity showed a downward trend, the number of new infections in Changchun rebounded again (from March 30 to April 2). Subsequently, in the final control stage, $R_{c8}$ dropped to the lowest value of 1.55, and the daily number of newly reported infections in Changchun gradually decreased to 564 cases. Implying that the index of prevention and control intensity $R_{cj}$ can effectively describe the control effect of intervention measures and the risk of epidemic spread.

As shown in Fig. 8, the index of prevention and control intensity is not necessarily less than 1 when the cases at the community level are eliminated, that is, the epidemic is still not under complete control at this moment. It is significant to explore the relationship between the key control parameters when reaching the elimination of cases at the community level, from the Recursive Zero-COVID model (3), $L_i = A_i - q_i = 0$ means that the number of infections at the community level has been eliminated, then the critical value of the index of prevention and control intensity is

$$R^*_{ci} = \frac{T}{f_i}\left(\frac{1}{\lambda_i \max\{\gamma_1, \gamma_2\}} - 1\right). \tag{4}$$

We observed from Fig. 9 that the index of prevention and control intensity decreases with the increase of screening efficiency, the improvement of the efficiency of inspection-traceability-isolation, and the shortening of transit duration when the cases at the community level are eliminated. The area above the critical surface is $R_{ci} > 1$, and the area below the critical surface is the area $R_{ci} < 1$. In order to achieve the goal of the elimination of cases at the community level as soon as possible, the control efforts should be maintained or increased so that the parameter values remain below the critical surface.

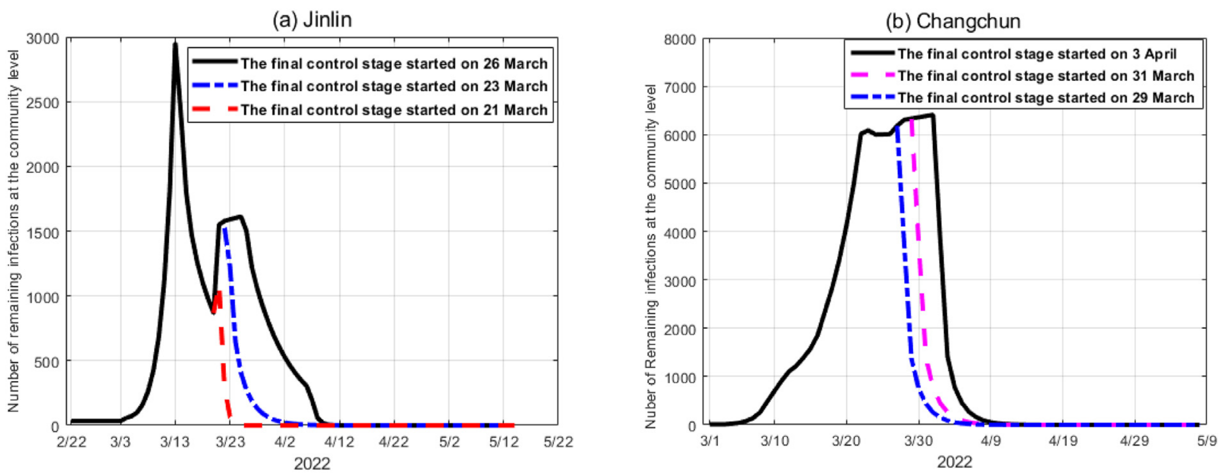


**Fig. 7.** The impact of the start time of the Dynamic Zero-COVID process on the number of infections at the community level in Jilin and Changchun Cities. If the start time of the Dynamic Zero-COVID process is ahead of schedule, the date of elimination of cases at the community level of the two cities will also be greatly advanced.

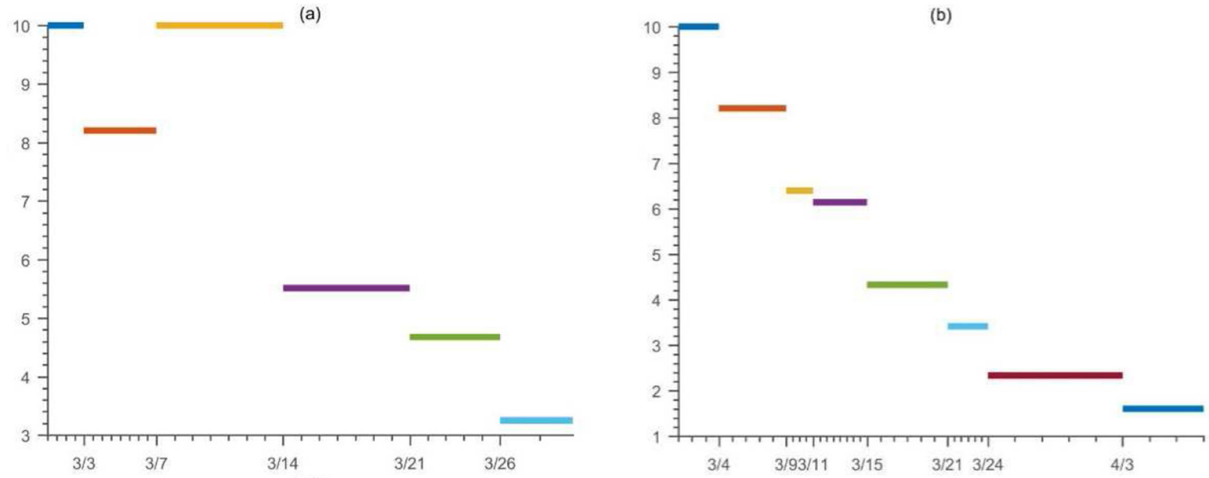


**Fig. 8.** The values of $R_{cj}$ with the change of control stages, (a) Jilin City and (b) Changchun City. $R_{cj}$ gradually decreases with the strengthening of prevention and control efforts.

## 4. Discussion

The Omicron epidemic situation makes the prevention and control severe due to its faster spread compared to the Delta virus. To characterize the changes in undiscovered cases at the community level and accurately predict the time of elimination of cases at the community level, we innovatively constructed a recursive Zero-COVID model based on the process of prevention and control and proposed an indicator $R_c$ to describe the intensity of prevention and control at each stage of the epidemic development. A general method for quantifying the intensity of prevention and control measures is developed and applied to the epidemic assessment in Jilin and Changchun Cities.

The results suggest that the recursive Zero-COVID model can effectively predict the date of elimination of cases at the community level in the epidemic area and is consistent with the actual situation (Fig. 4). Then it is reasonable to describe the changes in the number of undiscovered infections at the community level by this model. Further, the effectiveness of the measures in each control stage can be quantitatively evaluated according to the estimated values of key parameters. The results point out that a large number of effective contacts per unit of time during the PCR testing in the two cities was one of the possible reasons for the continued development of this epidemic. The number of effective contacts of all infections is higher than the corresponding value in Jilin City, which is an important factor that the epidemic situation in Changchun City is more severe than that in Jilin City. For the epidemic situation in Changchun City, the efficiency of inspection-traceability-isolation in the third to sixth stages of prevention and control is lower than that of the second one. The efficiency of inspection-traceability-isolation in the management and control stage is also an important reason why the epidemic is at a

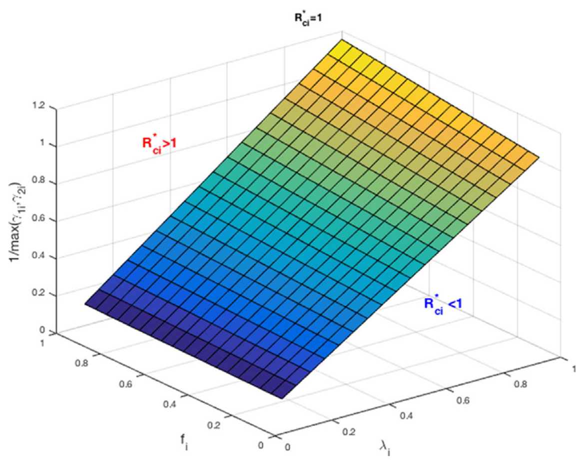


**Fig. 9.** Schematic diagram of the relationship between parameters at the moment of elimination of cases at the community level. Critical surface measures $R_{ci} = 1$.

high level and the disease spreads in some places. The results of the study remind the departments in other regions to standardize management and enhance the public's self-protection awareness when organizing PCR testing for epidemic prevention and control.

The sensitivity analyses indicated that the implementation efficiency of control measures had a significant impact on the time of elimination of cases at the community level. At the same time, the assessment of the intensity of prevention and control measures also showed that more timely and targeted control measures, rapid detection, and transit efficiency are essential. The start time of the Dynamic Zero-COVID process is also an important factor affecting the elimination of cases at the community level. The earlier the start time, the earlier the date of elimination of cases at the community level will arrive, and the lower the peak value of the unfounded infections at the community level. In particular, in the final control stage, although the number of daily infections is low and most of them are in quarantine, the epidemic still has a greater risk of rebound. At this time, the departments must maintain control intensity and coordinate the key links such as PCR testing, tracing, isolation, and transit, aiming to achieve the goal of eliminating cases at the community level as soon as possible.

In the quantitative analysis of the index of prevention and control intensity $R_c$, the trend of $R_c$ in the prevention and control in the two cities was obtained. This indicator can effectively describe the control effect of intervention measures and the transmission risk of this epidemic. The threshold of the index of prevention and control intensity $R_c$ when eliminating the cases at the community level (see Equation (4) and Fig. 9) is also given, which provides a theoretical basis for the prevention and control of a subsequent epidemic.

We now summarize some suggestions for the prevention and control of a new COVID-19 outbreak.

- Adhere to the Dynamic Zero-COVID policy, improve the speed of surveillance, and coordinate key links such as PCR testing, tracing, isolation and transportation, and community prevention and control, to control the sources of infection and cut off the channels of transmission.
- Emphasis is needed on both prevention and treatment, to strengthen the response framework of public health, unify the emergency supply system to improve the admission and cure rates, and reduce the infection rate.
- Build stringent lines of defense across society, guide the public to increase their awareness of responsibility and self-protection, improve the people's conscious fulfillment of anti-epidemic responsibilities and compliance with current strategies, and implement daily protection measures for individuals and families.

## 5. Conclusion

In this study, a recursive Zero-COVID model describing the transmission of omicron epidemics in the two major epidemic cities in Jilin Province is proposed, which provides a new idea for predicting the clearing time at the community level. Based on the reported data of infected people in Jilin and Changchun Cities, our recursive Zero-COVID model predicted that the “elimination of cases at the community level” of the two cities to be on April 8 and April 17, respectively. The model can effectively predict the date of elimination of cases at the community level in orther epidemic areas, such as the COVID-19 outbreak in Shanghai in March 2022. We can also evaluate the effectiveness of using control measures. Our findings also indicate that the intensity of the measures in the final stage has a greater impact on the date of “elimination of cases at the community level”, meanwhile, the stronger the implementation of prevention and control measures, the “elimination of cases at the community level” can be reached if the measures start earlier. In addition, the novel index we defined is reasonable to measure the intensity of the prevention and control measures of public health. At the same time, the application of the model will provide a reference for future responses to public health emergencies.

## 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.

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## Appendix

**Table 1**
Scenarios of control periods in Jilin City

| Period | Stage | Prevention and control measures |
| --- | --- | --- |
| Before March 3 | Regular prevention and control stage | No special control efforts for emergency |
| March 3 - March 6 | Region-specific control stage | After the confirmed cases were found in Jilin City on March 3, epidemiological investigations were started, risk areas were closed and controlled, and infections were isolated and transferred (People's Government of Jilin City, 2022a) |
| March 7 - March 13 | Closed-off management stage | Began to implement closed management, suspend production, suspend classes and other measures in Jilin City, and continued to carry out PCR testing (Health Commission of Jilin City, 2022b) |
| March 14- March 20 | Strengthening the prevention and control stage | Increase the deployment of medical teams, medical resources and technical forces; accurately and properly arrange epidemiological investigations, PCR testing and transit of quarantined personnel, and focus on strengthening social static control (People's Government of Jilin City, 2022c) |
| March 21- March 25 | Static management stage | Static management of the whole domain and personnel in the closed area are prohibited from leaving the house (Health Commission of Jilin City, 2022a) |
| March 26- April 8 | Stage of promotion and control | Further strengthen community-level management and control during the epidemic, such as household sampling, centralized isolation, emergency management and control, and on-site control. To insist on staying home and not gathering (Announcement of Jilin Municipal Public, 2022) |

**Table 2**
Table 1: Scenarios of control periods in Changchun City

| Period | Stage | Prevention and control measures |
| --- | --- | --- |
| Before March 4 | Regular prevention and control stage | No special control efforts for emergency |
| March 4 - March 8 | Region-specific control stage | Launch an emergency response mechanism and quickly investigate Changchun City (Changchun eHealth, 2022) |
| March 9 - March 10 | Comprehensive control stage | Complete the first round of the whole-population PCR testing in Changchun City (Changchun eHealth, 2022) |
| March 11 - March 14 | Closed-off management stage | Begin to implement closed management, suspend production, suspend classes and other measures, and continue to carry out nucleic acid testing. Stop all non-essential personnel movement (every household goes out once every two days) (People's Government of Changchun, 2022) |
| March 15- March 19 | Strengthening the prevention and control stage | Lunch the multiple rounds of PCR testing, and successively build and put into use multiple Fangcang shelter hospitals (Guangming Daily, 2022) |
| March 20- March 23 | Static management stage | Implement traffic control, the whole-population PCR testing and stops all non-essential movement of people in Changchun City (Changchun Epidemic Prevention, 2022, Notice of the Traffic Police, 2022) |
| March 24- April 2 | Stage of promotion and control | Maintain traffic control and stop all non-essential movements (Announcement of Changchun Public, 2022) |
| April 3 – April 13 | Stage of achieving Zero-COVID policy | Fully implement the Dynamic Zero-COVID dynamic zero-COVID-19 policy as soon as possible ("clearing" general attack, 2022) |

**Table 3**
Estimation of important parameters (Jilin City)

| | The number of effective contacts per unit time during the whole-population PCR testing $\boldsymbol{k_1}$ (times/day) | The number of effective contacts per unit time during the tracing, investigation, and transit $\boldsymbol{k_2}$ (times/day) | The number of effective contacts per unit time during the home quarantine $\boldsymbol{k_3}$ (times/day) | The Screening efficiency $\lambda$ (–) | The efficiency of inspection-traceability-isolation $\boldsymbol{f}$ (–) | The number of effective contacts per unit time $\boldsymbol{k}$ (times/day) |
| --- | --- | --- | --- | --- | --- | --- |
| Regular prevention and control stage | – | | | | | 10 |
| Region-specific control stage | 10 | 10 | 10 | 1 | 0.7 | – |

(continued on next page)

**Table 3** (*continued* )

| | The number of effective contacts per unit time during the whole-population PCR testing $\boldsymbol{k_1}$ (times/day) | The number of effective contacts per unit time during the tracing, investigation, and transit $\boldsymbol{k_2}$ (times/day) | The number of effective contacts per unit time during the home quarantine $\boldsymbol{k_3}$ (times/day) | The Screening efficiency λ (−) | The efficiency of inspection-traceability-isolation $\boldsymbol{f}$ (−) | The number of effective contacts per unit time $\boldsymbol{k}$ (times/day) |
|---|---|---|---|---|---|---|
| Closed-off management stage | 22 | 13 | 7 | 0.96 | 1 | |
| Strengthening the prevention and control stage | 10 | 10 | 5 | 0.81 | 1 | |
| Static management stage | 13 | 6 | 5 | 0.75 | 0.88 | |
| Stage of promotion and control | 8 | 5 | 4 | 0.85 | 0.89 | |

**Table 4**
Estimation of important parameters (Changchun City)

| | The number of effective contacts per unit time during the whole-population PCR testing $\boldsymbol{k_1}$ (times/day) | The number of effective contacts per unit time during the tracing, investigation and transit $\boldsymbol{k_2}$ (times/day) | The number of effective contacts per unit time during the home quarantine $\boldsymbol{k_3}$ (times/day) | The Screening efficiency λ (−) | The efficiency of inspection-traceability-isolation $\boldsymbol{f}$ (−) | The number of effective contacts per unit time $\boldsymbol{k}$ (times/day) |
|---|---|---|---|---|---|---|
| Regular prevention and control stage | – | | | | | 40 |
| Region-specific control stage | 40 | 40 | 40 | 0.42 | 0.8 | – |
| Comprehensive control stage | 40 | 28 | 30 | 0.5 | 0.4 | |
| Closed-off management stage | 30 | 28 | 40 | 1 | 0.5 | |
| Strengthening the prevention and control stage | 30 | 20 | 29 | 0.66 | 0.5 | |
| Static management stage | 28 | 20 | 20 | 0.8 | 0.5 | |
| Stage of promotion and control | 20 | 25 | 10 | 0.5 | 0.8 | |
| Stage of achieving Zero-COVID | 18 | 14 | 8 | 1 | 0.78 | |

**Table 5**
Parameters with the fixed values used in the modeling of COVID-19 transmission

| Parameter | Biological significance | Unit | Value | | Source |
|---|---|---|---|---|---|
| $\beta_0$ | Virus transmission coefficient | – | $4.4453 \times 10^{-2}$ | | Estimation |
| $1/\gamma$ | The transmission cycle of the Omicron Variant | day | 6.5 | | Assumption |
| $\tau$ | The response times of Jilin City (Changchun City) towards COVID-19 | day | 10 (3) | | Estimation |
| $l_1$ | The intensity of intervention-implementation in controlling the source of infection | – | 1/3 | | Assumption |
| $l_2$ | The intensity of intervention-implementation in cutting off transmission routes | – | 1/3 | | Assumption |
| $l_3$ | The intensity of intervention-implementation in protecting susceptible populations | – | 1/3 | | Assumption |
| $\sigma_e$ | The average duration that an infection is infectious during its incubation period | day | (1–1.5) | | Assumption |
| $\sigma_1$ | The average time required from sampling to the appearance of test results during a PCR testing of all staff | day | Jilin | Changchun | People's Government of Jilin Province, 2022a |
| | | | 3 | 4 | |
| | | | 3 | 3 | |
| | | | 1.5 | 2 | |
| | | | 0.6 | 1 | |
| | | | 0.5 | 1 | |
| | | | – | 0.8 | |
| | | | – | 0.5 | |
| $\sigma_2$ | The average time from detection of positive infection to admission to the Fangcang shelter hospital | day | Jilin | Changchun | People's Government of Jilin Province, 2022a |
| | | | 1 | 2.5 | |
| | | | 1 | 1.5 | |
| | | | 0.8 | 1 | |
| | | | 0.9 | 1 | |
| | | | 0.5 | 0.9 | |
| | | | – | 0.5 | |
| | | | – | 0.4 | |
| $\sigma_3$ | Survey and tracing duration | day | Jilin | Changchun | People's Government of Jilin Province, 2022a |
| | | | 1.5 | 2.5 | |
| | | | 1.5 | 2.5 | |
| | | | 1 | 1.5 | |
| | | | 0.9 | 1.5 | |
| | | | 0.4 | 1 | |
| | | | – | 0.7 | |
| | | | – | 0.5 | |

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