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The impact of lockdowns on macroeconomic performance: An application of epidemiology dynamics

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Abstract

This paper introduces susceptible-exposed-infectious-recovered epidemiology dynamics with vaccines into a Ramsey-Cass-Koopmans model, which investigates the impact of lockdowns and parameters related to infectious disease on macroeconomic performance. We find that changes in parameters related to infectious diseases other than lockdown restrictions, as long as they are adverse to people's health, will reduce the number of laborers who can work and have a negative impact on output, consumption, and welfare. Although lockdown restrictions can reduce public infections, they reduce economic activities. If the government does not have any economic revitalization policies, it will take a long time to recover from the impact of lockdown restrictions that reduce output and household welfare.

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1 Introduction

The purpose of this paper is to construct a Ramsey–Cass–Koopmans (RCK) model including the susceptible–exposed–infectious–recovered ($SEIR$) epidemiology dynamics with vaccines, and investigate the impact of infectious diseases and related government policies on macroeconomic performance, with special consideration of lockdown restrictions and vaccines. The innovation of this paper is that we combine the infectious disease model (i.e., $SEIR$) with the macroeconomic model and can discuss the impact of relevant government policies.[1] The contributions of the paper are as follows. First, we prove theoretically the existence and uniqueness of a steady state that can be used in analyses of macroeconomic performance as well as people's health. Second, we can analyze the long-run impact of parameters related to infectious disease and policies including vaccines and lockdowns. Moreover, through transitional dynamics analysis, we can investigate the impact of lockdowns and how long it will take for the economy to recover.

As well as domestic production capacity, many other factors potentially have an impact on a country's macroeconomic performance, including health-care quality, environmental sanitation, and people's health. Even in highly developed countries with high-quality public health systems, however, diseases may still threaten people's lives. Especially following globalization, the increased global movement of people and goods has increased the spread of infectious diseases, including COVID-19, which has recently affected human health and economies worldwide.

In response to the recent COVID-19 epidemic, governments around the world have begun to implement policies such as lockdowns or social distancing to mitigate the spread of disease. Therefore, many studies have discussed related policies. For example, Caulkins, Grass, Feichtinger, Hartl, Kort, Prskawetz, Seidl, and Wrzaczek (2021) used an optimal control model to discuss the optimal lockdown intensity for COVID-19. In addition, Alvarez, Argente, and Lippi (2020) used the susceptible–infected–recovered (SIR) framework to numerically analyze the impact of lockdowns. Note that Farboodi, Jarosch, and Shimer (2021) developed a quantitative framework and discussed the impact of social distancing.

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[1] As far as we know, there is currently no literature that combines the $SEIR$ model with a macroeconomic growth model, as most economists use the SIR model. However, many economists use $SEIR$ models to simulate the path of infectious diseases, and even governments of various countries use $SEIR$ models when predicting COVID-19. Therefore, this paper believes that using the $SEIR$ model combined with a macroeconomic growth model will be more consistent with the actual situation. This is also the innovation of this paper.

Moreover, Acemoglu, Chernozhukov, Werning, and Whinston (2021) developed a multigroup SIR model to discuss optimal lockdowns, and show that a strict and long lockdown for the elderly both reduces infections and enables less strict lockdowns for lower-risk groups. In their paper, they mentioned many studies that have used optimal control analysis of optimal policy related to lockdowns within the SIR framework. Differing from those papers that mainly use epidemiology dynamics model without combining macroeconomic growth models to analyze the impact of infectious diseases and lockdowns on people's health, we combine an epidemiology dynamics model with a macroeconomic growth model, and simultaneously analyze the impact of infectious diseases on human health and macroeconomic performance.[2]

In addition, André, Arbex, and Corrêa (2023) constructed a Network–SIR–Macro model, and showed that recession is more severe and occurs sooner in economies where individuals interact with more contacts while working or consuming. Differing from their work that focused on the negative effects of social networks, our paper mainly focuses on the impact of lockdowns during the epidemic and its long-term negative impact on the economy after the epidemic. Furthermore, Mendoza, Rojas, Tesar, and Zhang (2023) built a macroeconomic model with a saturated health system, and showed that strict lockdowns and large transfers yield sizable welfare gains and prevent a sharp rise in inequality. Differing from their work on the benefit of lockdowns during the epidemic, we consider how long the economy will take to recover following the negative effect of lockdowns on GDP.

Due to the characteristics of infectious diseases, people may not become ill when infected; that is, there is an incubation period, during which people still engage in production activities. To show this characteristic, in this paper, we introduce the $SEIR$ epidemiology dynamics with vaccines into a Ramsey growth model. We use the characteristics of lockdowns that reduce public contact and economic productivity to model lockdown restrictions. As infectious diseases usually only have a period of impact and will not be permanent, this paper will not only conduct a long-term comparative static analysis of parameters related to infectious diseases, but also analyze the transitional dynamics path of lockdown restrictions.

The structure of the paper is as follows. Section 2 constructs a benchmark growth model including epidemiology dynamics and proves the exis-

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[2] Note that Eichenbaum, Rebelo, and Trabandt (2021) and Eichenbaum, Rebelo, and Trabandt (2022) also developed the SIR-based macroeconomic model. However, they only set up a household sector but not a production sector (firms).

tence of the long-run equilibrium. This section also provides some comparative static analysis. Section 3 analyzes numerically the impact of lockdowns and parameters related to infectious disease. Section 4 provides brief concluding remarks.

2 The model

This section forms the basic analytical framework, which extends the RCK model to include $SEIR$ epidemiology dynamics with vaccines. We populate the economy in this model with a continuum of representative households of mass one, and a continuum of representative firms also of mass one.

2.1 The $SEIR$ epidemiology model with vaccines

Here, we briefly introduce the $SEIR$ epidemiology model with vaccines. The epidemiology dynamic model divides the population into several categories according to the epidemiological situation. In this paper, people face four epidemiological situations. The first is healthy and susceptible to the disease, referred to as S, while the second is where individuals have been infected but have not yet become ill (i.e., there is a significant latency period, referred to as E). The third is infected and capable of transmitting the disease, referred to as I, while the fourth is removed from the susceptible-infectious interaction by recovery through immunity, vaccination, or death, referred to as R. If the total population is N, then $S+E+I+R=N$.

People are born healthy with birth rate b and death rate d. If people have a v chance of vaccination and are thus removed from the susceptible-infectious interaction, the remainder remain susceptible to the disease. That is, if someone gets vaccinated, they will change from S category to R category. Susceptible people have a probability I/N of encountering infected people with contact rate β. Note that β is the average number of contacts per person per unit of time, and I/N the proportion of people in the economy who are sick and contagious. Regarding COVID-19, various countries may implement measures such as lockdown restrictions or stay-at-home orders (henceforth we refer to both as lockdown restrictions) to reduce the possibility of public contact. Assume that the ratio of lockdowns is $1-\theta \in [0,1)$, i.e., economies with $\theta \in (0,1]$ ratios still maintain normal operations. That is, the number of new infected cases per unit of time is $\beta\theta(I/N)S$, and they will change from S category to E category.

Assuming that the latency period is a random variable with exponential distribution with parameter a (i.e., the average latency period is $1/a$), the total number of individuals moving out of the exposed (latent) class E at each time is aE (from E category to I category). Infected people have a chance γ of recovering, i.e., the average infectious period is $1/\gamma$. Thus, the total number of individuals recovering from the disease at each time is γI (from I category to R category). We take COVID-19 as an example in which there are still very few people who have been vaccinated or have been infected, recovered, and then infected again. We set σ as the relapse rate of the disease (from R category back to I category). Therefore, according to Aron and Schwartz (1984) and Hethcote (2008), the $SEIR$ epidemiology model with vaccines yields the following system of differential equations:

$$\begin{aligned}
&\dot{S} = bN - vS - \beta\theta(I/N)S - dS,\\
&\dot{E} = \beta\theta(I/N)S - aE - dE,\\
&\dot{I} = aE - \gamma I - dI + \sigma R,\\
&\dot{R} = vS + \gamma I - dR - \sigma R,\\
&N = S + E + I + R,\\
&S, E, I, R \geq 0; S(0), E(0), I(0), R(0) \geq 0 \ \text{ given.}
\end{aligned}$$

Defining $s \equiv S/N$, $e \equiv E/N$, $r \equiv R/N$, and $s + r$ as the fraction of healthy people, we derive the following dynamic equation:

$$\dot{s} = b(1-s) - vs - \beta\theta(I/N)s, \tag{1}$$

$$\dot{e} = \beta\theta(I/N)s - (a+b)e, \tag{2}$$

$$\dot{r} = vs + \gamma(1 - s - e - r) - (\sigma + b)r. \tag{3}$$

Note that $I/N = 1 - s - e - r$ in equilibrium. However, we take it as given by households that people cannot control what epidemiological conditions they encounter.[3]

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[3] Note that, except for vaccines and lockdowns, the government also has many policies to mitigate the spread of disease. For example, the government can influence people's health through R&D or purchase of medicines to treat disease, which can increase the value of the recovery rate, γ. Moreover, the government can set regulations, such as social distancing policies or buying masks and forcing people to wear masks to reduce the chance of them being infected by contact with infected people, which can reduce the contact rate, β. In addition, the government can develop or buy vaccines and force or encourage people to be vaccinated, which can increase the chance of vaccination, v. In our long-run comparative static results, we show that the proportion of unhealthy people decreases, whereas labor, output, and thus consumption and capital accumulation increase as γ increases, v increases, or β falls.

2.2 Households

A member of the representative household is endowed with one unit of time. Sick people cannot engage in production. People in the incubation period continue to work because they are not sick yet and do not know they are sick. Thus, the proportion of people who work is $s + e + r$.

We denote k as capital per capita, and use w and r^k to denote the wage and rental rates, respectively. At any point in time, the representative household's flow budget constraint is:

$$\dot{k} = w(s + e + r) + r^k k - c - (\delta + b - d)k, \tag{4}$$

where δ is the depreciation rate of capital. The budget constraint indicates that unspent income is used to accumulate capital.

The household's lifetime utility is represented as:

$$U = \int_{t=0}^{\infty} u(c) e^{-(\bar{\rho}-b+d)t} dt, \tag{5}$$

where $u(c) = \frac{c^{1-\varepsilon}-1}{1-\varepsilon}$, c is consumption, and $\bar{\rho} > 0$ is the time preference rate. To simplify the analysis, we define $\rho = \bar{\rho} - b + d$. In (5), we use a conventional constant relative risk aversion utility function with a constant intertemporal elasticity of substitution, $1/\varepsilon$, for consumption.

2.3 Firms

The representative firm produces a single final good Y by renting capital and employing labor under the following production technology: $Y = \theta A K^{1-\alpha}[(s + e + r)N]^{\alpha}$, where $A > 0$ is productivity and $1 - \alpha \in (0, 1)$ is the capital share. Note that when the lockdown restriction or stay-at-home order is enforced, some production will also be affected. Defining $k \equiv K/N$ as capital per capita and $y \equiv Y/N$ as GDP per capita, we can rewrite the production function as follows: $y = \theta A k^{1-\alpha}(s+e+r)^{\alpha}$. The firm's objective is to choose inputs to maximize the following profits:

$$\pi = y - w(s + e + r) - r^k k. \tag{6}$$

2.4 Equilibrium and steady state

An equilibrium consists of the time paths of the households' choices, the firms' choices, and prices, such that households optimize, firms optimize, and all markets clear. In equilibrium, $I/N = 1 - s - e - r$. In the long run,

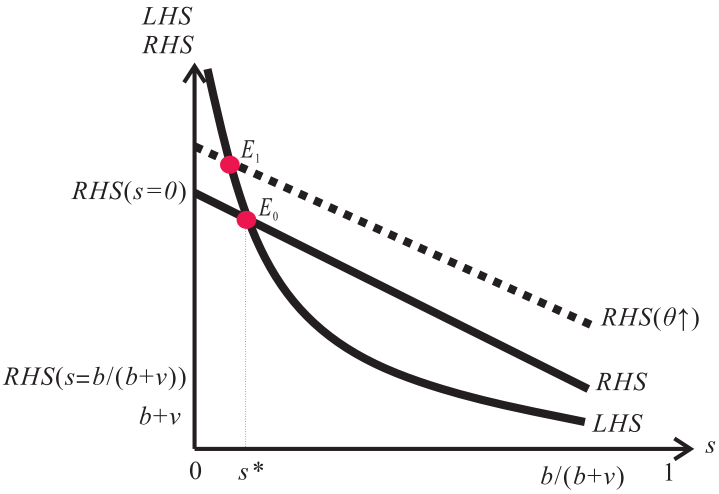

Figure 1: The existence of steady state and comparative static

by using $\dot{s} = \dot{e} = \dot{r} = \dot{k} = \dot{c} = 0$, we can derive the following relationships along the steady state:

$$\tfrac{b}{s} = b + v + \beta\theta\tfrac{a(b+\sigma)-[v(a-\sigma)+a(b+\sigma)]s}{(a+b)(b+\sigma+\gamma)}. \tag{7a}$$

$$e = \tfrac{b}{a+b} - \tfrac{v+b}{a+b}s, \tag{7b}$$

$$r = \tfrac{1}{b+\sigma+\gamma}[\tfrac{a\gamma}{a+b} + (v + \tfrac{\gamma(v-a)}{a+b})s], \tag{7c}$$

$$k = [\tfrac{1-\alpha}{\rho+\delta+b-d}\theta A]^{1/\alpha}(s + e + r), \tag{7d}$$

$$c = [\tfrac{\rho}{1-\alpha} + \tfrac{\alpha}{1-\alpha}(\delta + b - d)]k, \tag{7e}$$

The left-hand side (LHS) of (7a) is decreasing in s from infinity when $s = 0$ to the level $b+v$ when $s = b/(b+v)$. The right-hand side (RHS) of (7a) is also decreasing in s from the level $b+v+\beta\theta a(b+\sigma)/[(a+b)(b+\sigma+\gamma)]$ which is smaller than infinity when $s = 0$ to the level $b+v+\beta\theta\sigma v/[(v+b)(b+\sigma+\gamma)]$, which is larger than $b+v$ when $s = b/(b+v)$. See Figure 1 (solid line, point E_0). Thus, there exists a unique long-run value of s, where $0 < s < b/(b+v)$. Then, the unique long-run levels of e, r, k and c can be derived from (7b)-(7e) in sequence.

This paper focuses on the impact of lockdowns. Here, we discuss the effects of changing θ. When the value of θ is low, government lockdown restrictions have a greater negative impact on the normal operation of the economy. An increase in θ increases the level of the RHS of (7a) and does not change the level of the LHS of (7a) . Therefore, the long-run level of s must decrease (see point E_1 in Figure 1); therefore, the long-run level of e

must increase according to (7b). In addition, the long-run level of r must decrease under the condition that $v > a$ according to (7c). If people are infected, whether they have already developed symptoms or have not yet developed symptoms (during the incubation period), it means they are not in a healthy situation. Thus, the fraction of unhealthy people in this paper is $(E + I)/N = 1 - s - r$, which will increase as the level of θ increases. Intuitively, when the level of θ is larger (closer to one), the economy operates more normally. This also means that people have more frequent contacts and are more likely to be infected; thus, the fraction of unhealthy people increases.

Moreover, the impact of lockdown restrictions on macroeconomic performance, such as output production, is uncertain. Although these policies can make people less infected, economic operations will be negatively affected. To understand the above effects more clearly, we use numerical analysis.

3 Numerical analysis

In this section, we calibrate the model using United States (US) data.

3.1 Calibration

As the spread and incubation period of infectious diseases are usually measured in days, in this paper, we calibrate the model in the long run to reproduce the key features of the US economy at a daily frequency to quantify the results. The historical population dataset of the Organization for Economic Cooperation and Development (OECD) shows that the annual population growth rate in the US in 2020 was 0.3515%, and thus, the daily population growth rate is around 0.00096%. In addition, according to OECD dataset, the weekly mortality in the US in 2020 is 0.01958% and thus $d = 0.0028\%$. Hence, we estimate the birth rate as $b = 0.0038\%$.

Regarding the coefficients in the $SEIR$ epidemiology dynamics, following Atkeson (2020, p. 6–9), we set the recovery rate $\gamma = 1/18 = 0.0556$ reflecting an estimated duration of illness of 18 days, $\beta = \gamma * R_0 = (1/18) * 2.5 = 0.1389$ representing the value of R_0, which corresponds to the transmission of the disease with no mitigation efforts,[4] and $a = 1/5.2 = 0.1923$ reflected an estimated incubation period of the disease of 5.2 days. Regarding the vaccination rate, we take flu vaccination coverage as an example.

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[4] Atkeson (2020) considered R_0 ranged from 1.6 to 3.0. We choose the value of $R_0 = 2.5$ according to Atkeson (2020, p. 8), which is also the estimated value of R_0 in China, where Covid-19 first appeared.

According to the US CDC, the flu vaccination coverage among children six months through to 17 years of age in the US during 2016–2017 was 59% and among adults over 18 years was 43.3%. That is, we set $v = 0.5$. Suppose the government did not enforce lockdown at the beginning, and thus $\theta = 1$. Assume that the rate for breakthrough infections is $\sigma = 0.0001$. Using the above parameter values and (7a), we can calibrate the proportion of the S category as $s = 0.0075\%$. Then, the proportions of the E and R categories can be calibrated sequentially as $e = 0.0000097473\%$ and $r = 0.9981$ by using (7b) and (7c), respectively, Thus, the proportion of unhealthy people (E and I categories) is $1 - s - r = 0.0018$.

In addition, we set the capital share in the production function at 0.36 according to Kydland and Prescott (1982); therefore, $1-\alpha = 0.36$. Kydland and Prescott (1991) used 4% as the annual rate of time preference; thus, we set $\bar{\rho} = 0.0110\%$. According to Lucas (1990), we set $\varepsilon = 2$. Assume that the depreciation rate of capital is $\delta = 0.05/365 = 0.0137\%$. We normalize $A = 1$, and thus we can calibrate $k = 87805$, $y = 60.1406$, $c = 47.2669$, and household welfare is $U = -211.6533$.

3.2 The long-run comparative static

We now explore the impact of lockdown restrictions and the spread of infectious disease on people's health and related macroeconomic variables. The results of the implementation of the lockdown, i.e., changing θ, are shown in Figure 2. Note that an increase in the rate of lockdowns represents a decrease in θ. An increase in θ implies that people are more likely to be infected, so the number of unhealthy people increases, and thus healthy laborers decreases. However, fewer lockdowns mean the firm's production levels are closer to normal, and thus, output increases as θ increases, as do consumption and accumulation of capital. Note that as the utility function is only a function of consumption, higher consumption represents an increase in household welfare. That is, there is a trade-off for the government. If the government is to keep people healthy, it must sacrifice production. This is why even if there is an infectious disease, such as COVID-19, the government cannot keep the city closed because it will have a great negative impact on the economy.

For the impact of the spread of infectious disease, to save space, we list all comparative static results in Table 1. Regarding the impact of an increase in the recovery rate, i.e., a higher γ, because people are more likely to recover even if infected, the proportion of unhealthy people decreases as γ increases, whereas labor, output, and thus consumption and capital accumulation increase as γ increases. The impact of an increase in the contact

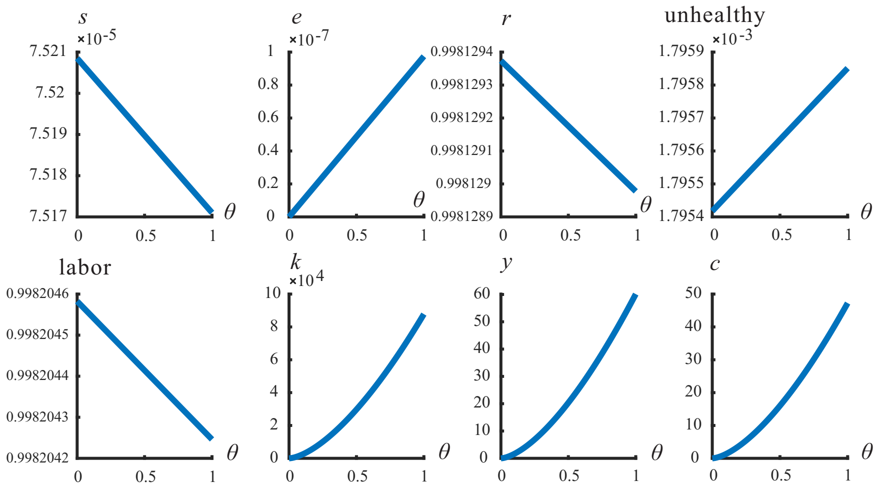

Figure 2: The long-run impact of lockdowns

rate (β) or in breakthrough infections (σ), is like the effect of decreasing γ, as is the intuition. Moreover, with more people vaccinated, i.e., a higher v and the more people are in the R category, like an increase in γ, healthy people increase and thus labor, output, consumption, and capital accumulation increase as v increases. Furthermore, a shorter incubation period (i.e., an increase in a or a decrease in $1/a$) means more infected people have symptoms, so there is less labor available to work, and thus output, consumption, and capital accumulation all decrease as a increases.

3.3 Transitional dynamics

We now examine the impact of changing the parameter related to infectious disease along the transitional dynamics path. Because changes in other parameters related to infectious diseases except for lockdowns have a consistent impact on workable labor and output, and lockdown restrictions have trade-offs on people's health and output, we focus on the impact of lockdown restrictions in this section. Note that for changes in parameters related to infectious diseases other than lockdown restrictions, as long as they are adverse to people's health, it will reduce the number of laborers who can work and have a negative impact on output, consumption, and welfare. As lockdown restrictions are usually calculated in days and are not permanent policies, we take Louisiana in the US as an example. The government in Louisiana issued a stay-at-home order on March 22, 2020, and extended that order until May 15, 2020, (i.e., 54 days in total). If the implementation of the stay-at-home order reduces normal economic activities by

Table 1: Comparative static analysis in the long run

	s	e	r	unhealthy	labor	k	y	c
θ	$-$	$+$	$-$	$+$	$-$	$+$	$+$	$+$
γ	$+$	$-$	$+$	$-$	$+$	$+$	$+$	$+$
β	$-$	$+$	$-$	$+$	$-$	$-$	$-$	$-$
a	$-$	$-$	$+$	$-$	$-$	$-$	$-$	$-$
σ	$-$	$+$	$-$	$+$	$-$	$-$	$-$	$-$
v	$-$	$-$	$+$	$-$	$+$	$+$	$+$	$+$

Note: $+$ and $-$ indicate that the effects of changing the parameters on the related variables are monotonically increasing and decreasing, respectively.

10%, we set $\theta = 0.9$ during the stay-at-home order period. The results of the transitional dynamics paths are shown in Figure 3. To clearly understand the impact of the moment when the stay-at-home order is implemented, we only show the changes for the first 200 periods in the graphs.

The time path of changing θ is consistent with the theoretical analysis and long-term comparative static results. However, it will take more than 1,000 days for output, capital accumulation, and consumption to return to the situation without lockdown restrictions. Stay-at-home orders (i.e., lockdown restrictions) can indeed reduce public infections (i.e., the number of unhealthy people decreases) and increase the number of people who can work. However, this policy will reduce economic activity. Overall, lockdown restrictions are not conducive to production. The results in Figure 3 also means that if the government does not have any economic revitalization policies, the impact of lockdown restrictions on the reduction of output and the loss of household welfare will take a long time to recover.

4 Concluding remarks

This paper analyzes *SEIR* epidemiology dynamics with vaccines in the RCK model and discusses the impact of lockdowns and parameters related to infectious disease on people's health, output, and household welfare. We show that changes in parameters related to infectious diseases other than lockdown restrictions, as long as they are adverse to people's health, will reduce the number of laborers who can work and have a negative impact

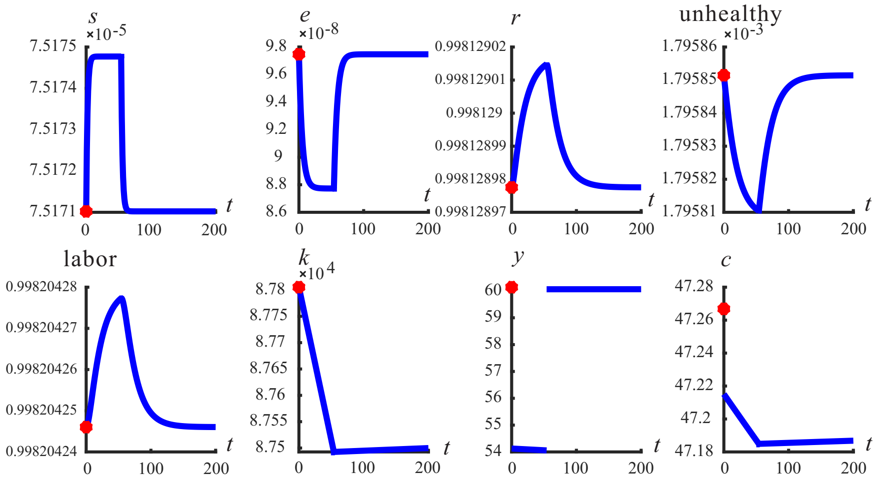

Figure 3: The transitional dynamics of short-term lockdowns

Note: In period 0–54, $\theta = 0.9$, after that $\theta = 1$.

on output, consumption, and welfare. Although lockdown restrictions can reduce public infections, they reduce economic activity. Our numerical analysis shows that without economic stimulus policies, the economic damage caused by lockdown restrictions will take a long time from which to recover.[5]

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[5] Regarding economic stimulus policies, the government can implement loose monetary policies, such as quantitative easing; or loose fiscal policies, such as increasing government spending, tax cuts, or transfers. As this paper focuses on the impact of lockdowns, we leave the relevant economic stimulus policies to future research.

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