Coronavirus pandemic and tourism: Dynamic stochastic general equilibrium modeling of infectious disease outbreak

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Introduction

In mid-December 2019, a novel and infectious coronavirus (COVID-19) struck Wuhan, the most populous city in central China. Similar to the severe acute respiratory syndrome (SARS) that emerged in 2003, COVID-19 is an airborne illness that is highly transmittable between humans. Immediately after the Chinese government shared information about the virus publicly in late January 2020, stricter preventive measures, such as community quarantines and temporary business closures, swept across Chinese cities. The local outbreak quickly developed into an emerging public health crisis to the extent that WHO recently declared it as an unprecedented global pandemic. In March, Europe has become the epicenter of the pandemic, and many countries imposed restrictions on human mobility. As of March 23, 2020, infections were confirmed in 190 countries/territories/areas, totaling 332,930 cases, more than 14,510 deaths, and an exponentially growing number of suspected cases worldwide (World Health Organization, 2020).

Infectious disease outbreaks, including coronavirus, greatly jeopardize the tourism industry given its reliance on human mobility. The Chinese hotel market witnessed a 71% year-over-year decline of occupancy in 23-26 January (Baker, 2020). In this research note, we propose and calibrate a dynamic stochastic general equilibrium (DSGE) model to understand the effect of infectious disease outbreak on tourism. By applying this model to the case of coronavirus epidemic, this study represents a pioneering research efforts on evaluating the impact of coronavirus on tourism. Compared to time-series and econometric analyses, the DSGE model can depict nuanced interactions across market decision makers under the general equilibrium framework. In contrast to the computable general equilibrium model (Blake, Sinclair, & Sugiyarto, 2003), decision makers in DSGE models optimize within a stochastic environment. Since the length and severity of the outbreak is uncertain, we believe it is more suitable to use DSGE model to address the risk of health disaster in this scenario

Model Specification

We incorporate health status and health disaster indicators into a quarterly based DSGE model with a focus on the tourism sector (Zhang & Yang, 2019). Health status is introduced within the household utility function *à la* Hall and Jones (2007), and it indicates the health stock accumulation. Our model contains three groups of decision makers: households, producers, and the government. Households derive utility from consumption and health status (Hall & Jones, 2007); consumption is divided between tourism goods and generic goods. Households also combine health expenditure with leisure time to rebuild and accumulate health (Yagihashi & Du, 2015), which is subject to disastrous risk during societal epidemics (World Health Organization, 2017). Producers consist of tourism goods producers and generic goods producers, with the latter providing products for generic consumption and health spending. The government balances its budget and enacts policies. More specific equations used in the DSGE model are detailed in our online supplementary materials.

Households

We assume that households' utility increases monotonically with both consumption C and health status H. We further decompose consumption into regular/generic goods spending C_m and tourism spending C_r^*. Individually, households maximize their expected lifetime utility. The occurrence of a health catastrophe (i.e., a society-wide epidemic) is reflected in the personal health accumulation equation, which captures the deterioration rate of health status over time. The coronavirus outbreak may influence personal health status directly and indirectly; the direct impact in this case refers to the consequences of coronavirus infection, whereas the indirect impact refers to the effects of delayed medical treatment due to limited medical resources allocated to non-coronavirus patients.

Two states of nature exist in the proposed DSGE model: normal circumstances and a disease outbreak. In our model, x_t is an indicator capturing the occurrence of a disease outbreak (e.g., coronavirus outbreak). Specifically, $x_t = 1$ with probability ω_t, in which case society is confronted with an economy-wide pestilence causing a large share Δ of health deterioration; otherwise, $x_t = 0$ during normal societal periods. A loss of health would affect welfare directly, as health appears in the utility function, and indirectly by altering the consumption of tourism and generic goods (Barro, 2006). Tourism consumption is related to health risks because tourists must travel and interact with crowds. Therefore, the dynamics of tourism consumption should follow the dynamics of economy-wide health status to some extent. Conversely, an epidemic outbreak would force the government to restrict travel due to associated health risks, and the degree of such restriction would depend on overall health status. We capture the negative impact of an epidemic on tourism consumption by using x_t after the household intertemporal budget constraint.

Producers and government

On the supply side, two sectors exist in the model economy: the tourism goods sector and generic goods sector. We specify sectoral production functions based on sectoral productivity and effective labor, the latter of which depends on labor health status. The government balances its budget every period and implements policies if needed, as we examine later. Finally, we set the market clearing conditions for goods markets (tourism and generic) when demand is equal to supply.

Simulation Results

Calibration

We divide our model parameters into four blocks: health disaster risk, utility function, health investment, and production. The literature has presented mixed evidence regarding the size and frequency of general disasters (Barro, 2006; Gourio, 2012), although empirical estimates specific to the health sector are lacking. In our baseline calibration, we identify a monthly disaster probability of 1.6%, implying that disaster occurs every 5 years on average. The mean disaster size is set to 10%, and the persistence of disaster risk is set to 0.6, depicting a moderate scenario (Barro & Ursúa, 2008). Our model solution follows Isoré and Szczerbowicz (2017), and simulation procedure and baseline calibration values can be found in the supplementary materials.

Impulse responses after health disaster risk shock

Figure 1 shows how the risk of a coronavirus outbreak would affect the tourism sector, displaying the impulse response functions (IRFs) to a shock of ω_t in our baseline scenario (solid line in Figure 1). As health disaster risk increases, we see a gradual deterioration in health status. As health status influences labor productivity, declining health status leads to lower tourism and generic output. Apart from the supply side, tourism demand also declines given its relationship with health risk, whether spontaneously or due to government-instituted bans on human mobility. To rebuild health, households begin to increase their health spending and leisure time while reducing their working time in the tourism and other sectors. More resources spent in the health sector cause health status to improve over time and eventually revert to the pre-shock level. These trends represent a typical path during the outbreak of a social-wide pestilence (World Health Organization, 2018).

(Insert Figure 1 about here)

Figure 1 also indicates how the economy evolves under different conditions relative to the persistence of health disaster risk. This figure plots the IRFs to a shock in ω_t under three persistence scenarios: $\rho = 0.6$ (baseline), $\rho = 0.4$ (optimistic), and $\rho = 0.8$ (pessimistic). Higher persistence means that the increase in health disaster risk endures, as the time path of ω_t conveys. Figure 1 also reveals that a longer and greater risk of health disasters pushes the tourism sector and the overall economy into an abyss. The peak points of decline in tourism sector output and labor are thus much lower, and the downturn lasts much longer, as risk persistence increases. More resources are hence needed to pull the economy out of trouble due to prolonged risk of a health disaster.

Figure 2 displays how the size of a disaster matters when the risk persistence is flat. This figure presents the IRFs to a shock in ω_t with different disaster sizes: $\Delta = 10\%$ (baseline), $\Delta = 5\%$ (optimistic), and $\Delta = 15\%$ (pessimistic). A larger disaster size corresponds to a larger share of post-outbreak health deterioration potentially. As indicated in Figure 2, all variables, including tourism sector output and labor, decline more as the disaster size increases. The persistence of this effect also changes, as it peaks at impact or at later points after the outbreak. The time paths in Figures 1 and 2 closely resemble the comparison among COVID-19, SARS in 2003, and Middle East Respiratory Syndrome in 2014 (Peeri et al., 2020).

(Insert Figure 2 about here)

Because travel can increase infection risk and the government imposes travel bans, we assume that a connection exists between tourism consumption and health disaster risk. Figure 3 illustrates the IRFs of the tourism sector with and without this connection. As shown, the connection further reduces sector activity. Tourism prices continue to rise alongside further declines in supply as specified in the model. Because more resources are applied to restore health status, health demonstrates a swifter recovery overall. Government warnings stoke public fear, and travel bans further restrict outdoor activities, both of which exacerbate negative outcomes for the tourism sector (McLaughlin, 2020).

(Insert Figure 3 about here)

Welfare and policies

Household welfare is determined by expected lifetime consumption and health status. As the coronavirus outbreak hinders tourism consumption and health status, welfare also declines, as presented in Figure 4. One possible policy to facilitate post-crisis tourism recovery is to subsidize tourism consumption. Such policies, like providing tourism consumption vouchers for residents, have been proved to be useful after the global financial crisis in China (Yan & Zhang, 2012). From a general equilibrium perspective, tourism sector subsidies must be financed by resources redistributed from other sectors; therefore, higher tourism sector consumption would have a crowd-out effect. Our simulation result appears in Figure 5, in which we compare the baseline case to those involving a sectoral policy and comprehensive policy. A sectoral policy refers to one in which the tourism sector is subsidized two periods (quarters) after the outbreak, whereas a comprehensive policy includes simultaneous subsidies to the health sector as well. As indicated, the sectoral policy overcomes the tourism sector decline; however, such mitigation comes at the cost of a deeper recession in the generic sector. The rebuilding of health status is also weaker because resources are extracted from the health sector. Overall welfare declines accordingly. By contrast, the comprehensive policy improves tourism consumption and health rebuilding, albeit at the cost of regular consumption. Because health status plays a notable role in households' utility, general welfare improves.

(Insert Figure 4 about here)

(Insert Figure 5 about here)

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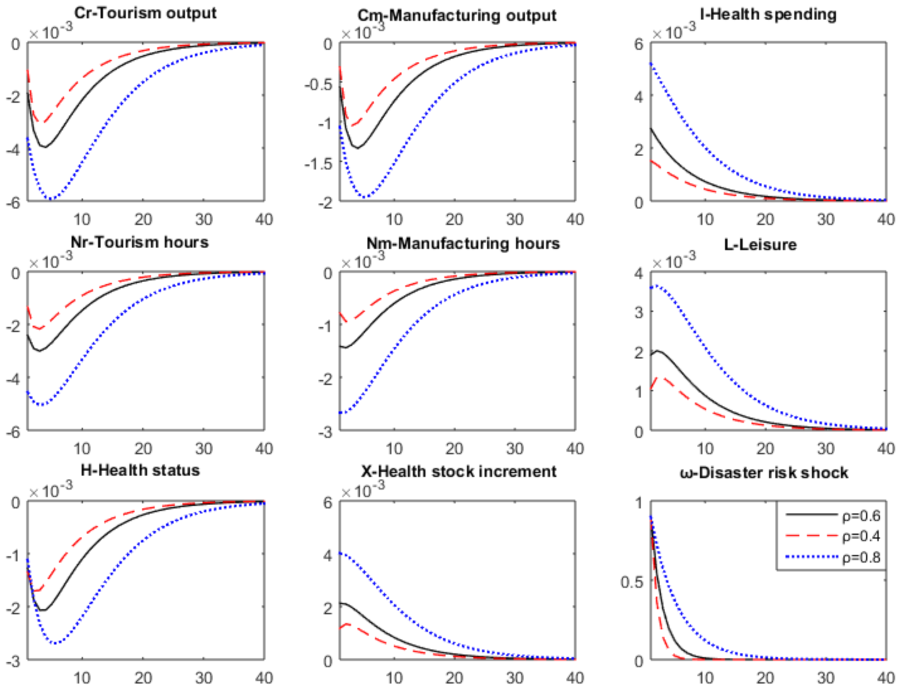

Figure 1 Effect of a 1% increase in health disaster risk at different levels of risk persistence (Note: ω-health disaster risk)

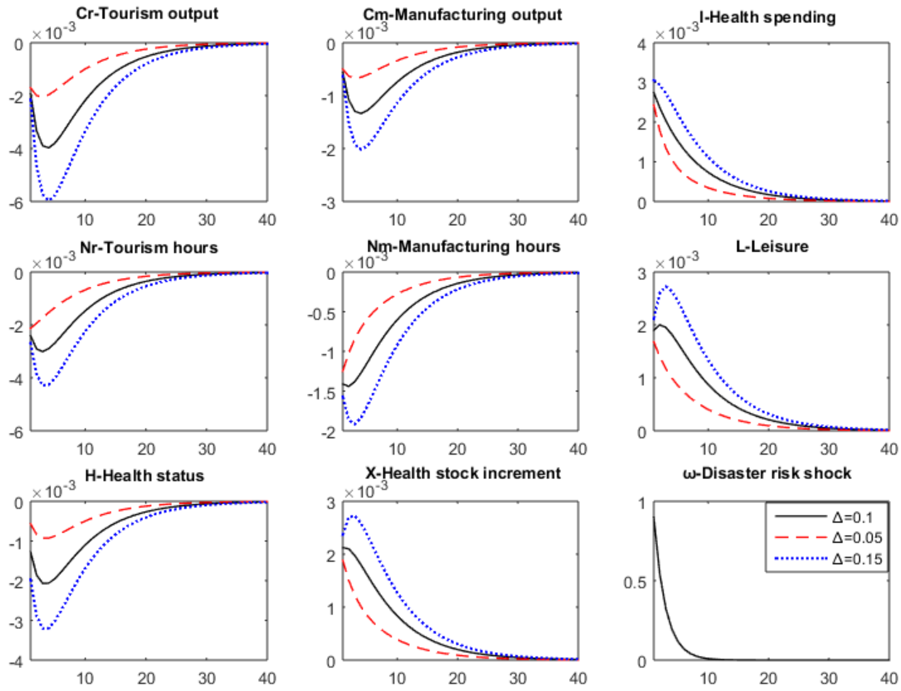

Figure 2 Effect of a 1% increase in health disaster risk at different disaster sizes

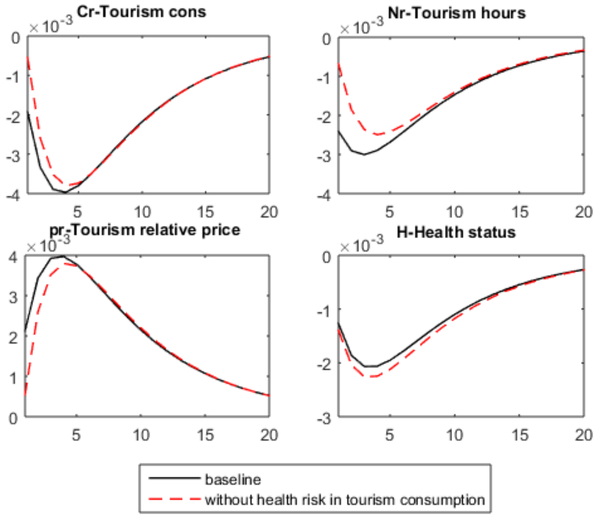

Figure 3 Effect of a 1% increase in health disaster risk on tourism sector (role of health risk in tourism consumption)

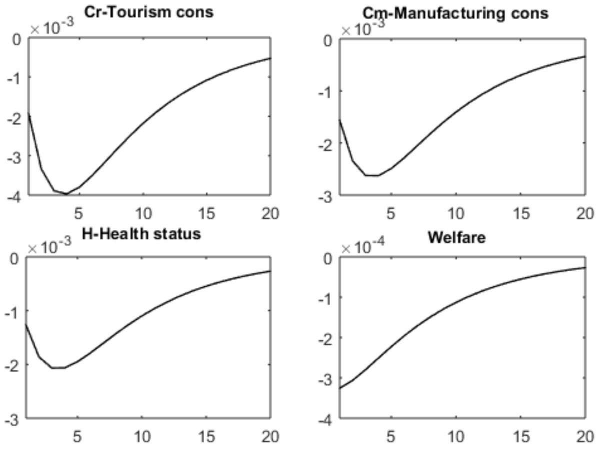

Figure 4 Effect of a 1% increase in health disaster risk on welfare and its elements

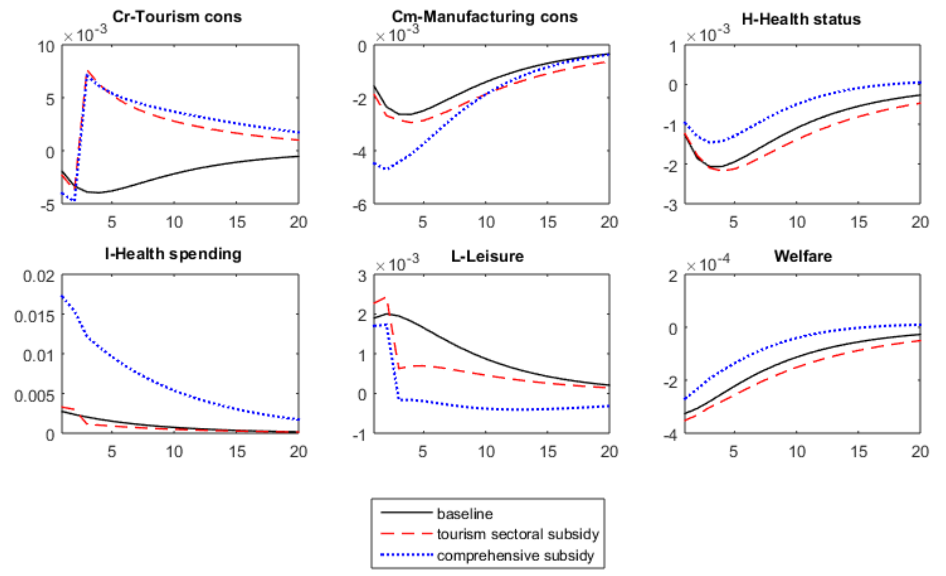

Figure 5 Effect of a 1% increase in health disaster risk under different tourism subsidy policies

Supplementary Materials

1. Model specification

Households

Households' utility increases monotonically with both consumption C and health status H. Consumption is decomposed into regular/generic goods spending C_m and tourism/recreational spending C_r^*, where C_r has an asterisk given its relationship with health disaster risk (to be defined later). Specifically, households maximize their expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \ln C_t + \eta \frac{H_t^{1-\gamma}}{1-\gamma} \right\} \tag{1}$$

$$C_t = {C_{r,t}^*}^{\varphi} C_{m,t}^{1-\varphi}$$

where β is the subjective discount factor; η is the weight of health status in the utility function; γ is the inverse of the intertemporal elasticities of substitution for health status; and φ is the share of tourism goods in the consumption bundle, whereas a unit elasticity of substitution exists between the two types of goods in the bundle.

The occurrence of a health disaster (i.e., a society-wide epidemic) is captured in the following health accumulation equation:

$$H_{t+1} = [X_t + (1-\delta)H_t] e^{x_t \ln(1-\Delta)} \tag{2}$$

where X_t is the health increment, and δ is the deterioration rate of health status. Households' health investment is determined by combining health spending and leisure hours in the following manner:

$$X_t = (I_t)^{\kappa}(1 - N_t)^{1-\kappa} \tag{3}$$

where I_t denotes health expenditure and $1 - N_t$ denotes leisure hours, defined as normalized total hours less hours spent working. κ and $1 - \kappa$ represent the elasticity of health investment relative to health spending and leisure, respectively. Two states of nature exist in the model, namely normal circumstances and times of health disaster. x_t is an indicator variable capturing the occurrence of a health disaster. Specifically, $x_t = 1$ with probability ω_t, in which case society is hit by an economy-wide pestilence causing a large share Δ of health to be eliminated; otherwise, $x_t = 0$ denotes a normal societal period. The loss of health would affect welfare directly, as health appears in the utility function, and indirectly by affecting the consumption of tourism and generic goods.

The relationship between health disaster risk and tourism consumption is captured by the following reduced-form equation:

$$C_{r,t}^{*} = C_{r,t}e^{x_t \ln H_t^{\chi}} \tag{1'}$$

where χ measures the elasticity of tourism consumption with respect to health status, and the property of x_t remains. Working hours consist of time devoted to producing regular goods $N_{m,t}$ and recreational goods $N_{r,t}$ as follows:

$$N_t = N_{r,t} + N_{m,t} \tag{4}$$

Finally, households face the following intertemporal budget constraint:

$$P_{r,t}C_{r,t} + P_{m,t}C_{m,t} + P_{m,t}I_t + B_{t+1} = W_tN_{r,t} + W_tN_{m,t} + R_{d,t}B_t - T_t \quad (5)$$

where B_t is a generalized one-period bond that provides a saving opportunity for households, and $R_{d,t}$ is the interest rate. W_t is the real wage; $P_{r,t}$ and $P_{m,t}$ are the relative prices of recreational goods and regular goods, respectively; and T_t is the net transfer from the government. A household will maximize lifetime utility (Eq. [1]) subject to health accumulation (Eq. [2]), health investment function (Eq. [3]), working time constraint (Eq. [4]), and intertemporal budget constraint (Eq. [5]).

Producers

On the supply side, two sectors are specified in the model economy: the tourism goods sector and generic goods sector. Sectoral production functions are given by

$$Y_{r,t} = A_{r,t}\left(N_{r,t}H_t\right)^{\alpha_r} \quad (6)$$

$$Y_{m,t} = A_{m,t}\left(N_{m,t}H_t\right)^{\alpha_m} \quad (7)$$

where Eqs. (6) and (7) represent recreational goods production and regular goods production, respectively. $Y_{r,t}$ and $Y_{m,t}$ are the two sectoral goods. α_r and α_m are the elasticity of effective labor in the two sectoral production functions, where effective labor is denoted as the working time indexed by health status. Here, we implicitly assume that the physical capital is fixed and normalized to one. $A_{r,t}$ and $A_{m,t}$ denote sectoral productivity shocks. The two sectoral producers will minimize production costs subject to Eqs. (6) and (7).

Government and market clearing

The government balances its budget every period and institutes policies if needed, as we will examine later. The government budget is given by

$$G_t + R_{d,t}B_t = B_{t+1} + T_t \tag{8}$$

The market clearing conditions for the goods markets (i.e., recreational and regular) are given by

$$Y_{r,t} = C_{r,t} \tag{9}$$

$$Y_{m,t} = C_{m,t} + I_t + G_t \tag{10}$$

2. Derivation of equilibrium conditions

Households

$$\max E_t \sum_{j=0}^{\infty} \beta^j \left[\ln(C_{t+j}) + \eta \frac{(H_{t+j})^{1-\gamma}}{1-\gamma} \right]$$

$$\begin{aligned} C_t &= {C_{r,t}^*}^{\varphi} C_{m,t}^{1-\varphi} \\ &= \left(C_{r,t} e^{x_t \ln H_t^{\chi}}\right)^{\varphi} C_{m,t}^{1-\varphi} \\ &= \left[\omega_t C_{r,t} H_t^{\chi} + (1-\omega_t) C_{r,t}\right]^{\varphi} C_{m,t}^{1-\varphi} \end{aligned}$$

s.t.

$$H_{t+1} = [X_t + (1-\delta)H_t] e^{x_t \ln(1-\Delta)} \tag{11}$$

$$= [X_t + (1-\delta)H_t](1-\omega_t \Delta)$$

$$X_t = (I_t)^{\kappa}(1-N_t)^{1-\kappa} \tag{12}$$

$$P_{r,t}C_{r,t} + P_{m,t}C_{m,t} + P_{m,t}I_t + B_{t+1} = W_t N_{r,t} + W_t N_{m,t} + R_{B,t}B_t + T_t \tag{13}$$

First-order conditions (F.O.C):

$C_{r,t}$: $$\varphi {C_{r,t}^*}^{-1}\left[\omega_t H_t^{\chi} + (1-\omega_t)\right] = \Lambda_t p_{r,t} \tag{14}$$

$C_{m,t}$: $$(1-\varphi)C_{m,t}^{-1} = \Lambda_t p_{m,t} \tag{15}$$

I_t: $$\Theta_t \kappa \frac{X_t}{I_t}(1-\omega_t \Delta) = \Lambda_t p_{m,t} \tag{16}$$

N_t: $$\Theta_t (1-\kappa) \frac{X_t}{1-N_t}(1-\omega_t \Delta) = \Lambda_t w_t \tag{17}$$

B_t: $$\Lambda_t = \beta \Lambda_{t+1} R_{B,t+1} \tag{18}$$

H_t: $$\Theta_t = \beta \varphi \chi \frac{C_{r,t+1}}{C^*_{r,t+1}} H_t^{\chi-1} \omega_{t+1} + \beta \eta H_t^{-\gamma} + \beta \Theta_{t+1} (1-\delta)(1-\omega_{t+1}\Delta) \tag{19}$$

Producers

$$\min_{N_{k,t}} w_t N_{k,t}\,, \quad k = r, m$$

s.t.

$$Y_{k,t} = A_{k,t} \left(N_{k,t} H_t \right)^{\alpha_k}$$

F.O.C

$$w_t = \alpha_k p_{k,t} A_{k,t} \left(N_{k,t} \right)^{\alpha_k - 1} (H_t)^{\alpha_k} \tag{20}$$

Government

$$G_t + R_{d,t} B_t = B_{t+1} + T_t \tag{21}$$

Market clearing

$$Y_{r,t} = C_{r,t} \tag{22}$$

$$Y_{m,t} = C_{m,t} + I_t + G_t \tag{23}$$

Steady state

$$R_B = \frac{1}{\beta} \tag{24}$$

$$\frac{X}{H} = \frac{1}{1-\omega\Delta} - (1-\delta) \tag{25}$$

$$\frac{\Theta}{\Lambda} = \frac{1}{1-\omega\Delta} \tag{26}$$

$$\frac{C}{H} = \left[\frac{1}{1-\omega\Delta} - \beta(1-\delta) \right] \Big/ (\beta\varphi\chi\omega + \beta\eta) \tag{27}$$

$$\frac{w}{X} = \frac{1-\kappa}{1-N} \tag{28}$$

$$\frac{P_m Y_m}{X} = \frac{N_m}{1-N} \frac{1-\kappa}{\alpha_m} \tag{29}$$

$$\frac{P_r Y_r}{X} = \frac{N_r}{1-N}\frac{1-\kappa}{\alpha_r} \tag{30}$$

Solution for simulation

We solve the model by using high-order perturbation methods for the system of equilibrium conditions. The solution forms a state-space representation as follows

$$\boldsymbol{y_t} = \mathbf{g}(\boldsymbol{x_t}, \sigma) \tag{31}$$

$$\boldsymbol{x_{t+1}} = \mathbf{h}(\boldsymbol{x_t}, \sigma) + \sigma\theta\epsilon_{t+1} \tag{32}$$

where $\boldsymbol{y_t}$ is a vector of control variables, $\boldsymbol{x_t}$ a vector of state variables, and ϵ_t a vector of i.i.d innovations. σ is an auxiliary perturbation parameter, and θ determines the variance-covariance matrix of innovations. Functions $\mathbf{g}$ and $\mathbf{h}$ are constructed by approximated Taylor series expansion with unique order. We then simulate the system according to the state-space representation. Since we are interested in the effect of the risk of health disaster, we thus simulate the impulse response functions of the system conditional on the particular shock.

3. Calibration

Table S Baseline calibration

Parameter	Description	Value
Disaster risk		
$\boldsymbol{\omega}$	Mean probability of disaster	0.016
$\boldsymbol{\Delta}$	Size of disaster	0.1
$\boldsymbol{\rho}$	Persistence of disaster risk	0.6
Utility function		
$\boldsymbol{\beta}$	Discount factor	0.99
$\boldsymbol{\varphi}$	Share of recreational goods in consumption	0.1
$\boldsymbol{\eta}$	Weight of health	0.8
$\boldsymbol{\gamma}$	Risk aversion coefficient	3
Investment		
$\boldsymbol{\delta}$	Health deterioration rate	0.08
$\boldsymbol{\kappa}$	Elasticity of health spending	0.27
Production		
$\boldsymbol{\alpha_r}$	Labor share in recreational goods production	0.8
$\boldsymbol{\alpha_m}$	Labor share in regular goods production	0.4