Bank & Finance
Consulting Group

A Benchmark Macroeconomic Model on Excess Deaths, Economic Production's Losses and Economic Policies During the COVID-19 Pandemic

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Summary

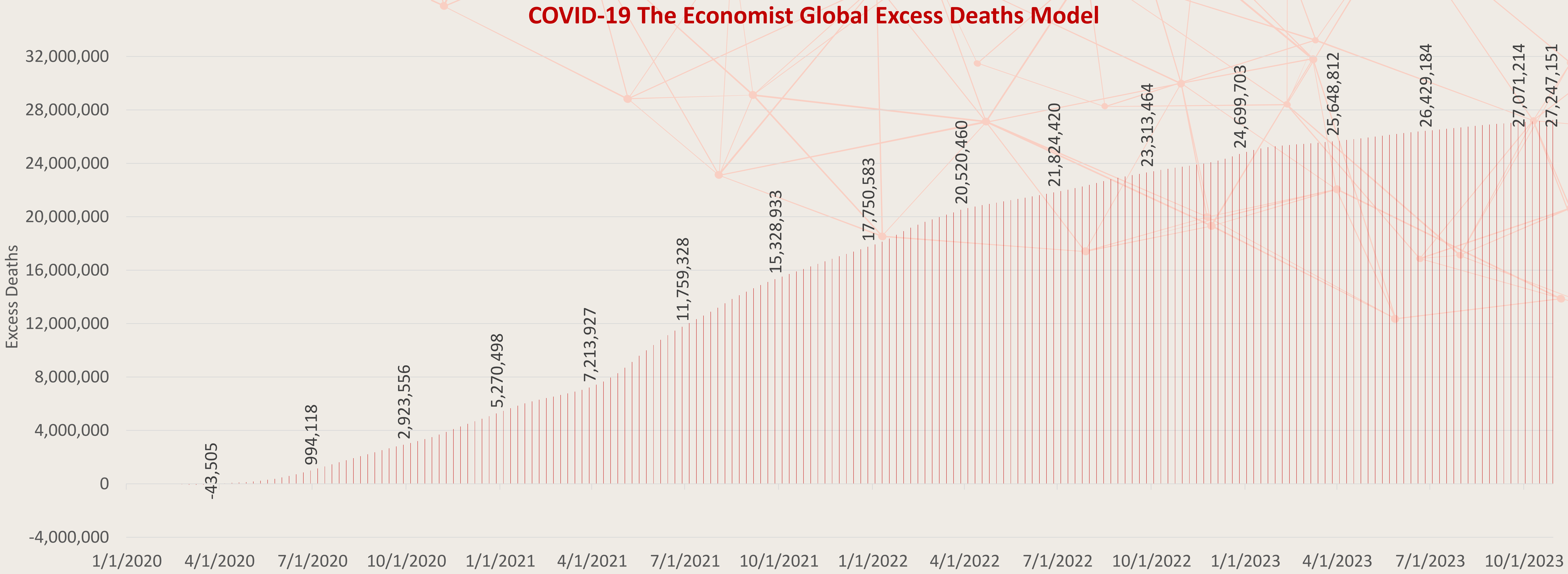
- The COVID-19 Pandemic had an enormous toll on lives, with excess mortality surpassing 27 million people.
- It also caused a large loss in economic production, with an expected global GDP loss accumulated from 2020 to 2023 of $26,732 billion (equivalent to 20.47% of the $130,580 billion world GDP in 2019). At the country level, average GDP loss, relative to potential, in the 2020 to 2023 period, is expected to account for 31% of each country's GDP in 2019.
- 13,530 million COVID-19 vaccines have been administered worldwide, with 70.6% of the world population receiving at least one dose.
- From January 2020 to June 2021, the accumulated fiscal measures to combat the COVID-19 Pandemic accounted for US$10,417 billion (9.7% of World's GDP), with $1,458 billion (1.4%) in additional health expenditure, $8,882 billion (8.2%) in non-health expenditure.
- In addition, from January 2020 to June 2021, worldwide liquidity support accounted for $6,132 billion (6.2%), with $388 billion (0.4%) in equity injections, loans, asset purchases or debt assumptions, $4,054 billion (4.1%) in credit guarantees, and $1,690 billion (1.6%) in quasi-fiscal operations.
- From 2019 to 2021, real interest rates decreased, on average, 4.32% with 115 out of 141 countries, with available information, experiencing a reduction in real interest rates.
- Thinking about how the COVID-19 virus, excess mortality, production losses and policies are jointly determined is a challenging endeavor.
- In this presentation we provide a benchmark macroeconomic model to think about the joint determination of these variables in a Dynamic Stochastic General Equilibrium Model.

Summary (cont.)

- Some key characteristics of the model are:
  - The economy generates goods and services combining technology, capital, and workers.
  - Workers have an endogenous excess mortality rate which is a positive function of preconditions and COVID-19, and a negative function of policies intended to reduce excess mortality.
  - COVID-19 increases with its spread, which in turn is a positive function of the exposure of workers due to production needs and a negative function of policies intended to reduce contagion, and it decreases with the recovery rate.
  - In this benchmark version we assume that policy positively responds to COVID-19 and its cost reduces the consumption and investment possibilities.
  - This model can be extended to accommodate different type of policies affecting different dimensions of the optimality rules, for example financial and monetary policies lowering the real cost of investment.
- We present the model with its solution in terms of policy and transition functions and impulse response functions.
  - We show that the model's endogenous variables, as output, excess mortality, and COVID-19 are a function of state variables and shocks.
  - The impulse response function to a policy shock lowers COVID-19 and excess mortality. This increases available workers and incentivizes investment, yielding higher production.
  - The impulse response function to the recovery rate reduces COVID-19 and therefore excess mortality and the required policies. This allows an increase in workers and incentivizes investment that increases output.
  - The impulse response function to preconditions increases excess mortality and lowers labor input and investment, which reduces production.
- This model serves as an initial framework to study how policies implemented in different countries during the COVID-19 pandemic could have contributed to reducing their excess mortalities and GDP losses.

Excess Deaths During the COVID-19 Pandemic

According to John Hopkins University Coronavirus Resource Center, until 10 March 2023 there were 676,609,955 recorded infectious COVID-19 cases and 6,881,955 deaths have been officially recorded due to COVID-19. According to The Economist there have been 27,247,151 excess deaths from 1 January 2020 to 29 October 2023.

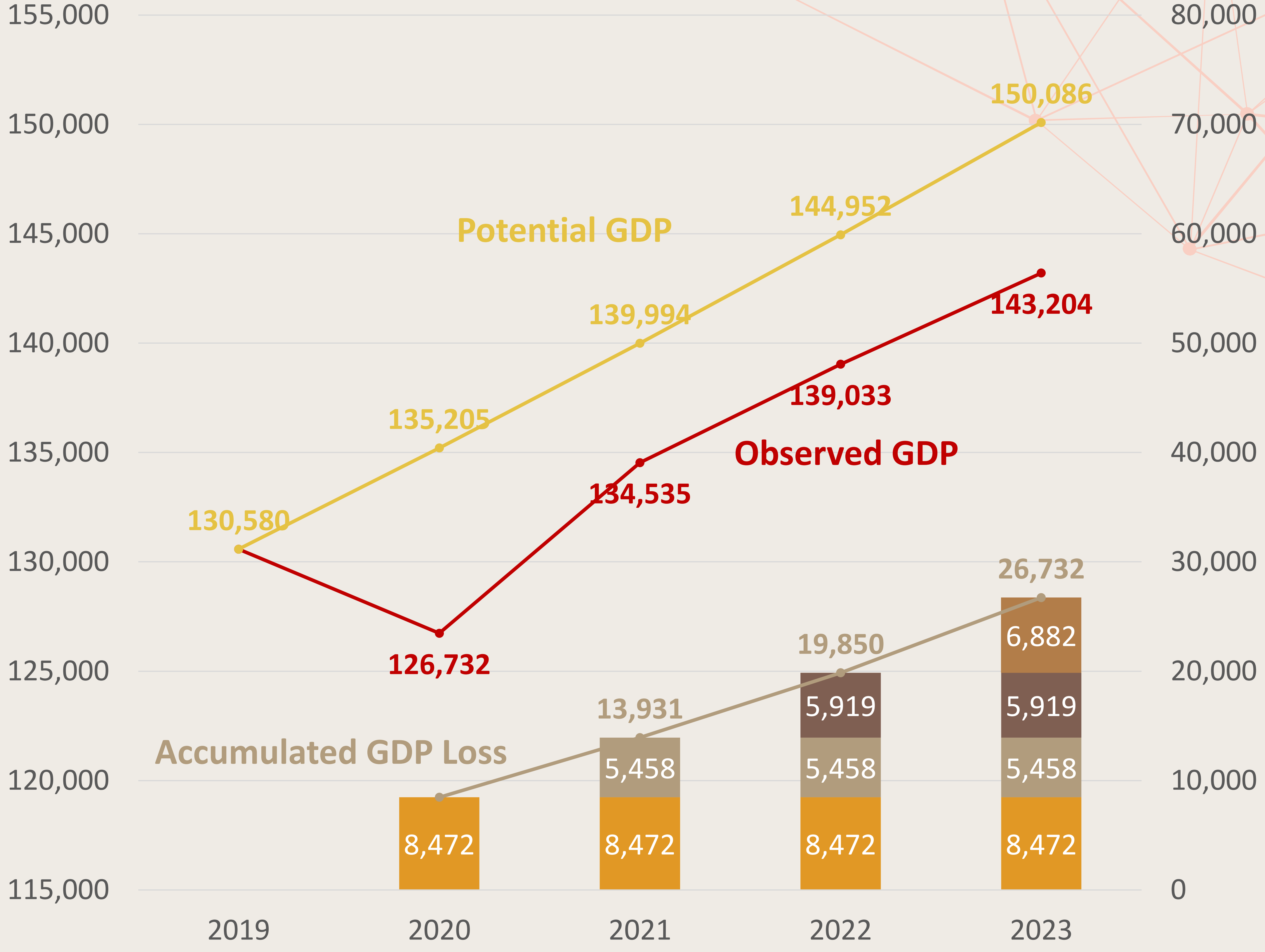


Source: Cumulative Estimated Daily Excess Deaths per 100,000 People in the Population from 1 January 2020 to 29 October 2023 from The Economist.
https://github.com/TheEconomist/covid-19-the-economist-global-excess-deaths-model/blob/main/output-data/export_world_cumulative.csv

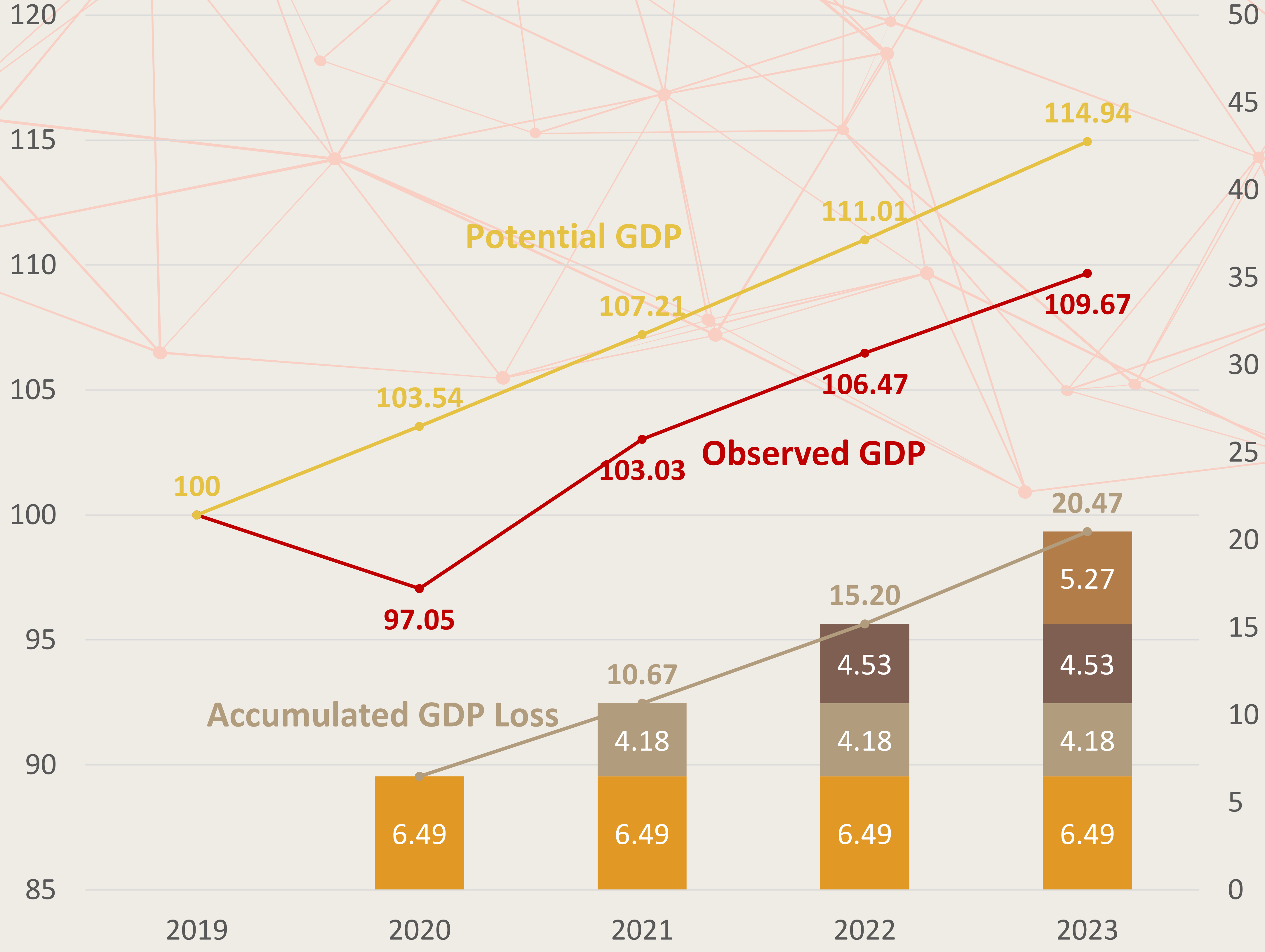
World GDP Loss Relative to Potential During the COVID-19 Pandemic

The expected global GDP loss accumulated from 2020 to 2023 is $26,732 billion (equivalent to 20.47% of the $130,580 billion world GDP in 2019). The realized losses are $8,472 billion (6.49%) in 2020, $5,458 billion (4.18%) in 2021, and $5,919 billion (4.53%) in 2022. The expected GDP loss for 2023 is $6,882 billion (5.27%).

World's GDP Loss Relative to Potential; Observed from 2020 to 2022 and Expected for 2023, PPP (constant 2017 international $ billions)



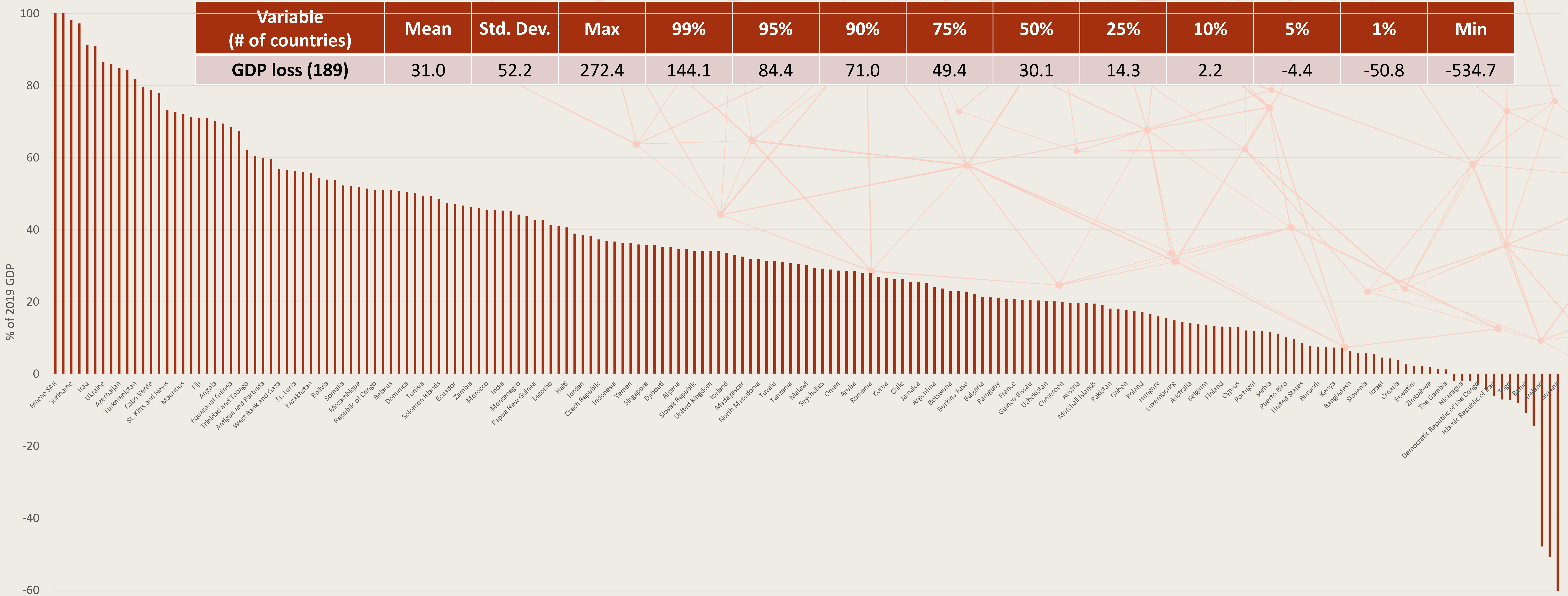
World's GDP Loss Relative to Potential; Observed from 2020 to 2022 and Expected for 2023, (expressed in % of 2019 GDP)



Source: Own calculations. Data for years 2019, 2020, 2021 and 2022 is from the World Bank Indicators, while data for 2023 is from the International Monetary Fund World Economic Outlook (WEO) October 2023. Output loss compares the potential output assuming that during 2020, 2021 and 2022, the world economy had grown at the 2000 to 2019 average growth rate of 3.54%, relative to the observed levels of -2.95% in 2020, 6.16% in 2021 and 3.34% in 2022. For 2023 we use the WEO Growth Projections for the Global Economy of 3%.

Output Loss Relative to Potential from 2020 to 2023 (in % of 2019 GDP)

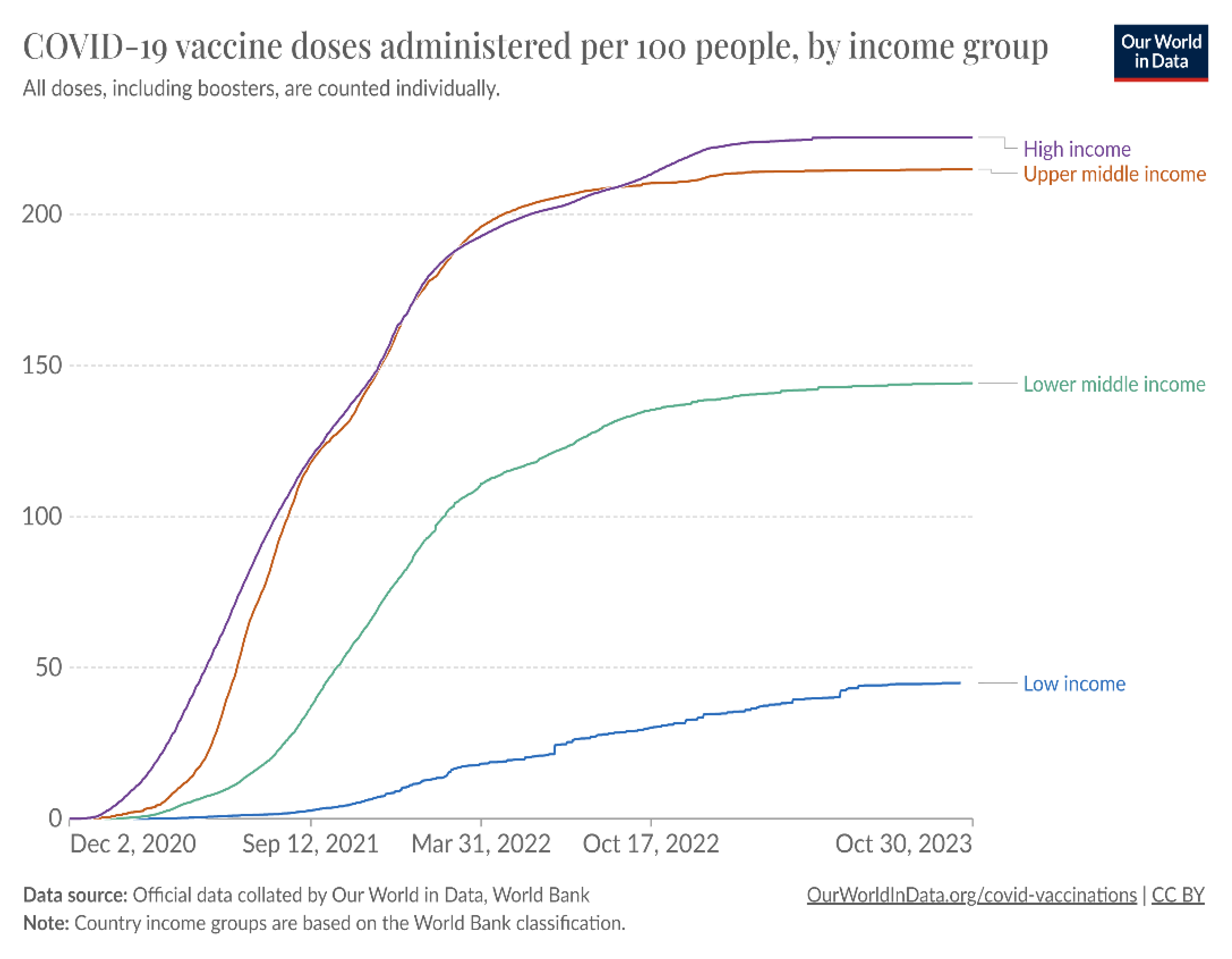
Variable (# of countries)	Mean	Std. Dev.	Max	99%	95%	90%	75%	50%	25%	10%	5%	1%	Min
GDP loss (189)	31.0	52.2	272.4	144.1	84.4	71.0	49.4	30.1	14.3	2.2	-4.4	-50.8	-534.7

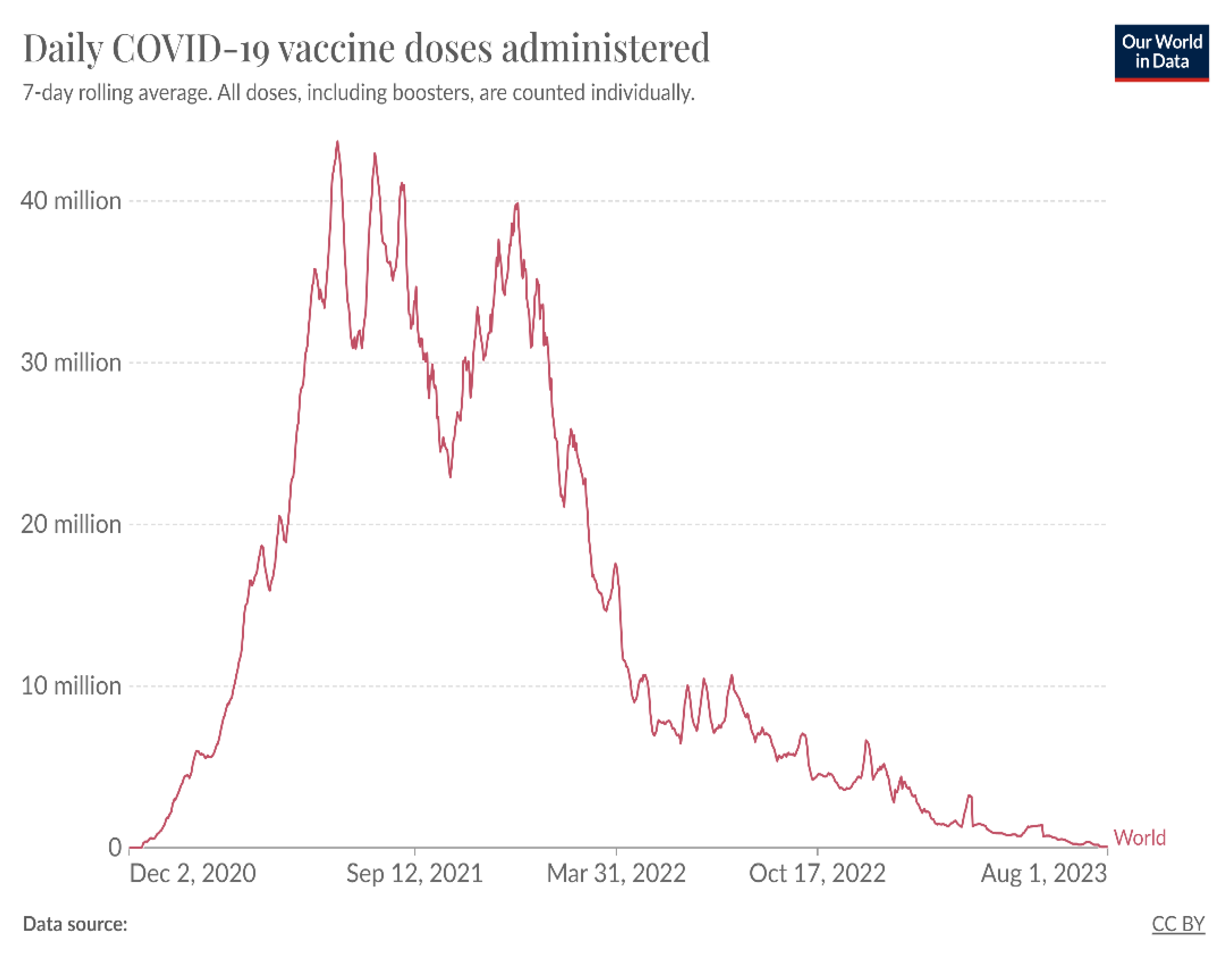


Source: Own calculations. Data for years 2019, 2020, 2021 and 2022 is from the World Bank Indicators, while data for 2023 is from the International Monetary Fund World Economic Outlook (WEO) October 2023. Output loss is computed as the difference between potential output and observed (or expected for 2023) output. Potential output is computed using the assumption that from 2020 to 2023, each country grows at its 2000 to 2019 average rate.

COVID-19 Vaccines

Governments around the world implemented numerous health policies to try to reduce the impact of this pandemic: COVID-19 vaccines started being administered in December 2021, one year after the emergence of the virus. Up to 29 October 2023, 13,530 million vaccines have been administered worldwide, with 70.6% of the world population receiving at least one dose.





Source: https://ourworldindata.org/covid-vaccinations

Fiscal and Financial Policies

From January 2020 to June 2021, the accumulated fiscal measures to combat the COVID-19 Pandemic accounted for US$10,417 billion (9.7% of World's GDP), with $1,458 billion (1.4%) in additional health expenditure, $8,882 billion (8.2%) in non-health expenditure. In addition, during the same period, worldwide liquidity support accounted for $6,132 billion (6.2%), with $388 billion (0.4%) in equity injections, loans, asset purchases or debt assumptions, $4,054 billion (4.1%) in credit guarantees, and $1,690 billion (1.6%) in quasi-fiscal operations.

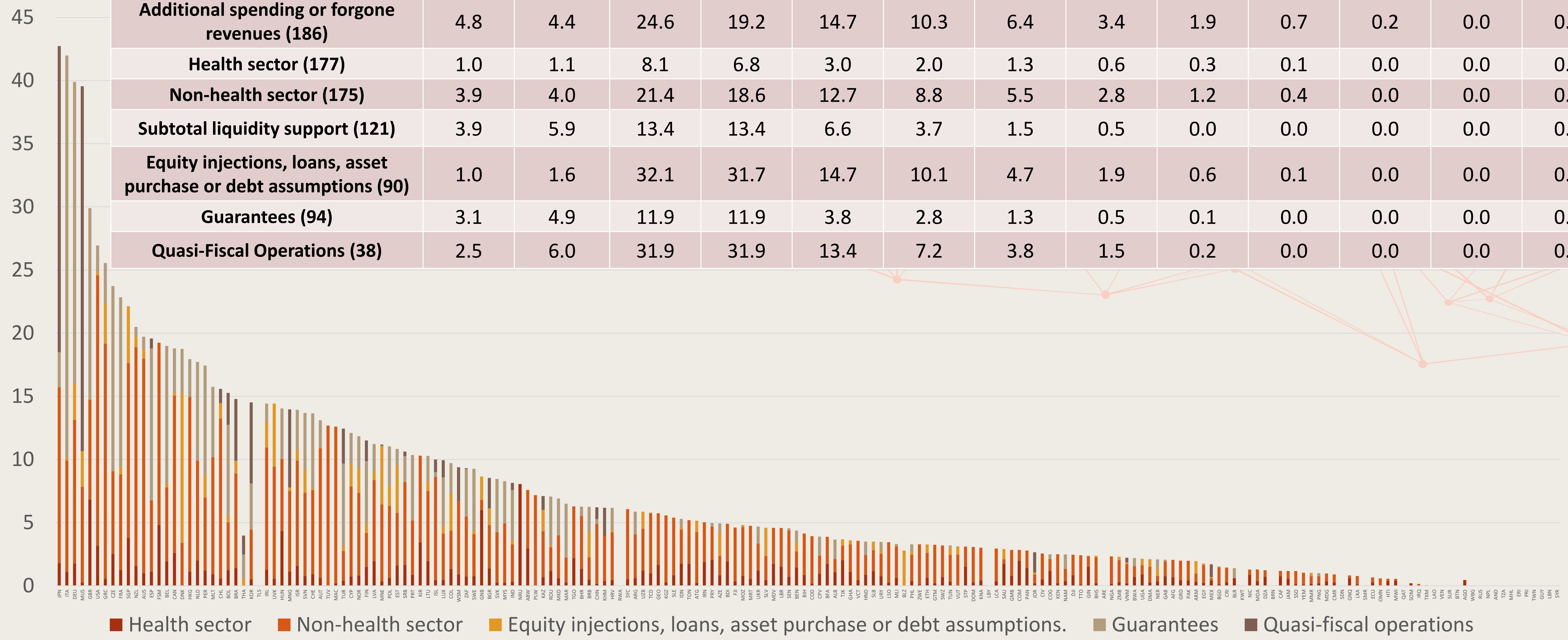
Discretionary fiscal and financial response to the COVID-19 Pandemic

	Above the line measures				Liquidity support			
	Additional spending or foregone revenues			Accelerated spending / deferred revenue			Contingent liabilities	
	Subtotal	Health sector	Non-health sector		Subtotal	Below the line measures: equity injections, loans, asset purchase or debt assumptions.	Guarantees	Quasi-fiscal operations
USD Billion	**10,417**	1,458	8,882	772	**6,132**	388	4,054	1,690
Percent of GDP	**9.7**	1.4	8.2	0.9	**6.2**	0.4	4.1	1.6

Source: IMF Fiscal Monitor: Database of Country Fiscal Measures in Response to the COVID-19 Pandemic.

Fiscal and Financial Impulse from January 2020 to June 2021 (in % of 2019 GDP)

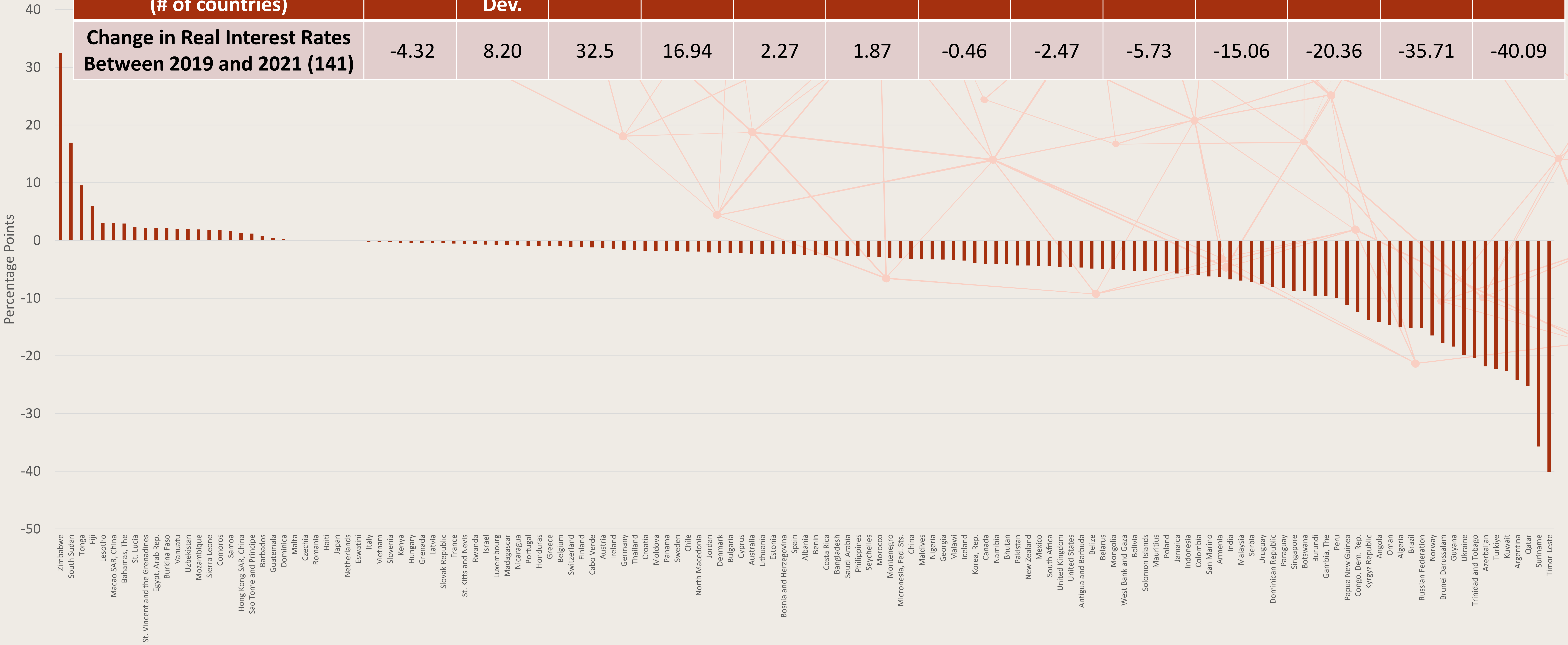
Variable (# of countries)	Mean	Std. Dev.	Max	99%	95%	90%	75%	50%	25%	10%	5%	1%	Min
Additional spending or forgone revenues (186)	4.8	4.4	24.6	19.2	14.7	10.3	6.4	3.4	1.9	0.7	0.2	0.0	0.0
Health sector (177)	1.0	1.1	8.1	6.8	3.0	2.0	1.3	0.6	0.3	0.1	0.0	0.0	0.0
Non-health sector (175)	3.9	4.0	21.4	18.6	12.7	8.8	5.5	2.8	1.2	0.4	0.0	0.0	0.0
Subtotal liquidity support (121)	3.9	5.9	13.4	13.4	6.6	3.7	1.5	0.5	0.0	0.0	0.0	0.0	0.0
Equity injections, loans, asset purchase or debt assumptions (90)	1.0	1.6	32.1	31.7	14.7	10.1	4.7	1.9	0.6	0.1	0.0	0.0	0.0
Guarantees (94)	3.1	4.9	11.9	11.9	3.8	2.8	1.3	0.5	0.1	0.0	0.0	0.0	0.0
Quasi-Fiscal Operations (38)	2.5	6.0	31.9	31.9	13.4	7.2	3.8	1.5	0.2	0.0	0.0	0.0	0.0



Source: Discretionary fiscal and financial response is from IMF Fiscal Monitor: Database of Country Fiscal Measures in Response to the COVID-19 Pandemic. Original data, reported in % of 2020 GDP is converted to % of 2019 GDP using observed 2020 growth rates.

Monetary Policy: Change in Real Interest Rates Between 2019 and 2021

Variable (# of countries)	Mean	Std. Dev.	Max	99%	95%	90%	75%	50%	25%	10%	5%	1%	Min
Change in Real Interest Rates Between 2019 and 2021 (141)	-4.32	8.20	32.5	16.94	2.27	1.87	-0.46	-2.47	-5.73	-15.06	-20.36	-35.71	-40.09



A Benchmark Macroeconomic Model under COVID-19

An economy generates goods and services, y_t, combining (exogenous) technology, a_t, with capital, k_t, and workers, n_t, using the production function:

$$y_t = a_t k_t^{\alpha} n_t^{1-\alpha} \qquad (1)$$

where undepreciated capital, $(1-\delta)k_t$, is augmented with investment, i_t, through:

$$k_{t+1} = (1-\delta)k_t + i_t \qquad (2)$$

Population, which for simplicity is assumed equivalent to workers, has a stable component of mortality and births proportional to the population captured by, μ, and in the context of COVID-19, an endogenous excess mortality component, em_t, to evolve according to:

$$n_{t+1} = (1-\mu)n_t - em_t \qquad (3)$$

where excess mortality is a positive function of (exogenous) preconditions, $precond_t$, times the spread of COVID-19 virus, $covid_t$ and a negative function of how the pandemic is handled, pol_t. For simplicity we assume that these three factors affect excess mortality in the following form:

$$em_t = precond_t * covid_t - pol_t \qquad (4)$$

We assume that COVID-19 evolves based on the spread, spr_t, and (exogenous) recovery, rec_t, rates according to:

$$covid_{t+1} = (1 + spr_t - rec_t)covid_t \qquad (5)$$

A Benchmark Macroeconomic Model under COVID-19 (cont.)

We assume that spread is proportional to the production needs and that it is reduced by effective policies according to:

$$spr_t = \varphi y_t - pol_t \tag{6}$$

Consumption, c_t, is given by non-invested production and is subject to net taxes, $t_t = pol_t$, required to pay for the policy measures according to:

$$c_t = y_t - i_t - pol_t \tag{7}$$

Within the context of the COVID-19 pandemic, we assume that policy, pol_t, responds to COVID, $covid_t$, and has an exogenous policy component, ε_t^{pol}, according to:

$$pol_t = (covid_t)^{\theta_{pol}} e^{\varepsilon_t^{pol}} \tag{8}$$

To analyze the impact of COVID-19 in consumption, $c_t \geq 0$, and excess mortality, $em_t \gtreqless 0$, paths of endogenous variables, are chosen to:

$$\max_{\{c_t, em_{t+1}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t [u(c_t) - v(em_t)] \tag{9}$$

subject to equations (1) to (8). In addition, k_0 and n_0 are given and $\lim_{t\to\infty} \frac{k_t}{(1+r_t)^t} \to 0$.

Optimization Problem

The Lagrange function associated with this problem can be expressed as:

$$\max_{\left\{\begin{matrix} c_t, i_t, y_t, em_t, \\ k_{t+1}, n_{t+1}, covid_{t+1}, \\ spr_t, pol_t \end{matrix}\right\}_{t=0}^{\infty}} \mathcal{L} = \sum_{t=0}^{\infty} \beta^t \left\langle \begin{matrix} [u(c_t) - v(em_t)] \\ +\lambda_{1,t}[a_t k_t^{\alpha} n_t^{1-\alpha} - y_t] \\ +\lambda_{2,t}[(1-\delta)k_t + i_t - k_{t+1}] \\ +\lambda_{3,t}[(1-\mu)n_t - em_t - n_{t+1}] \\ +\lambda_{4,t}[precond_t * covid_t - pol_t - em_t] \\ +\lambda_{5,t}[(1 + spr_t - rec_t)covid_t - covid_{t+1}] \\ +\lambda_{6,t}[\varphi y_t - pol_t - spr_t] \\ +\lambda_{7,t}[y_t - i_t - pol_t - c_t] \\ +\lambda_{8,t}\left[(covid_t)^{\theta_{pol}} e^{\varepsilon_t^{pol}} - pol_t\right] \end{matrix} \right\rangle \quad (10)$$

First Order Necessary Conditions for Optimality

$$\frac{\partial \mathcal{L}}{\partial c_t} = \frac{\partial u(c_t)}{\partial c_t} - \lambda_{7,t} = 0 \tag{11}$$

$$\frac{\partial \mathcal{L}}{\partial i_t} = \lambda_{2,t} - \lambda_{7,t} = 0 \tag{12}$$

$$\frac{\partial \mathcal{L}}{\partial y_t} = -\lambda_{1,t} + \lambda_{6,t}\varphi + \lambda_{7,t} = 0 \tag{13}$$

$$\frac{\partial \mathcal{L}}{\partial em_t} = -\frac{\partial v(em_t)}{\partial em_t} - \lambda_{3,t} - \lambda_{4,t} = 0 \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial k_{t+1}} = -\lambda_{2,t} + \lambda_{1,t+1}\beta[\alpha a_{t+1} k_{t+1}^{\alpha-1} n_{t+1}^{1-\alpha}] + \lambda_{2,t+1}\beta(1-\delta) = 0 \tag{15}$$

$$\frac{\partial \mathcal{L}}{\partial n_{t+1}} = -\lambda_{3,t} + \lambda_{1,t+1}\beta[(1-\alpha) a_{t+1} k_{t+1}^{\alpha} n_{t+1}^{-\alpha}] + \lambda_{3,t+1}\beta(1-\mu) = 0 \tag{16}$$

$$\frac{\partial \mathcal{L}}{\partial covid_{t+1}} = -\lambda_{5,t} + \lambda_{4,t+1}\beta precond_{t+1} + \lambda_{5,t+1}\beta(1 + spr_{t+1} - rec_{t+1}) + \lambda_{8,t+1}\beta\theta_{pol}(covid_{t+1})^{\theta_{pol}-1} e^{\varepsilon_t^{pol}} = 0 \tag{17}$$

$$\frac{\partial \mathcal{L}}{\partial spr_t} = \lambda_{5,t} covid_t - \lambda_{6,t} = 0 \tag{18}$$

$$\frac{\partial \mathcal{L}}{\partial pol_t} = -\lambda_{4,t} - \lambda_{6,t} - \lambda_{7,t} - \lambda_{8,t} = 0 \tag{19}$$

Interpretation of the Optimality Conditions

- The solution also includes the Lagrange first-order conditions with respect to the multipliers $\lambda_{i,t}$, $i = 1, 2, \cdots, 8$ from which the model's set-up given by equations (1) to (8) are recovered.
- In addition, we assume that technology, preconditions, recovery, and policy innovations are subject to exogenous first-order autoregressive process.
- Equation (11), the optimality condition for consumption, $\frac{\partial \mathcal{L}}{\partial c_t}$, states that the multiplier on the economy's resource constraint, $\lambda_{7,t}$, is equalized to the marginal utility of consumption, $\lambda_{7,t} = \frac{\partial u(c_t)}{\partial c_t}$.
- Equation (12), the optimality condition for investment, $\frac{\partial \mathcal{L}}{\partial i_t}$, tells us that the marginal benefit of increasing investment, captured by the multiplier on the capital accumulation equation, $\lambda_{2,t}$, is equalized to the marginal cost of decreasing consumption, $\lambda_{2,t} = \lambda_{7,t}$.
- Equation (13), the optimality condition for output, $\frac{\partial \mathcal{L}}{\partial y_t}$, states that an increase in output, which is captured by the multiplier on the production function, $\lambda_{1,t}$, relaxes the multiplier on the resource constraint, $\lambda_{7,t}$. A particular feature of our set-up is the assumption that COVID-19 spread is proportional to the production volume, therefore we get an extra term related to how COVID-19 is disseminated, $\lambda_{1,t} = \lambda_{6,t}\varphi + \lambda_{7,t}$.
- Equation (14), the optimality condition for excess mortality, $\frac{\partial \mathcal{L}}{\partial em_t}$, states that the multiplier on the evolution of population, $\lambda_{3,t}$, plus the multiplier on excess mortality, $\lambda_{4,t}$, is equalized to the marginal disutility caused by excess mortality $\lambda_{3,t} + \lambda_{4,t} = -\frac{\partial v(em_t)}{\partial em_t}$.

Interpretation of the Optimality Conditions (cont.)

- Equation (15), the optimality condition for next period capital, $\frac{\partial \mathcal{L}}{\partial k_{t+1}}$, states that the marginal cost of increasing next period capital, in terms of forgone marginal utility of consumption, here captured by the multiplier, $\lambda_{2,t}$, is equalized to the marginal benefit given by the marginal productivity of capital plus the undepreciated remaining capital stock, $\lambda_{2,t} = \lambda_{1,t+1}\beta[\alpha a_{t+1}k_{t+1}^{\alpha-1}n_{t+1}^{1-\alpha}] + \lambda_{2,t+1}\beta(1-\delta)$.
- Equation (16), the optimality condition for next period population, $\frac{\partial \mathcal{L}}{\partial n_{t+1}}$, states that the marginal cost of increasing next period's population, in terms of the part related to the marginal disutility of excess mortality, is equalized to the marginal benefit given by the marginal of labor plus next period's population net of the standard demographic's birth and death dynamics: $\lambda_{3,t} = \lambda_{1,t+1}\beta[(1-\alpha)a_{t+1}k_{t+1}^{\alpha}n_{t+1}^{-\alpha}] + \lambda_{3,t+1}\beta(1-\mu)$.
- Equation (17), the optimality condition for next period COVID-19, $\frac{\partial \mathcal{L}}{\partial covid_{t+1}}$, states that the marginal cost of increasing next period's COVID, is given by the increase in excess mortality scaled by preconditions, the net increase augmented by spread and reduced by recoveries and the marginal response of policy, $\lambda_{5,t} = \lambda_{4,t+1}\beta precond_{t+1} + \lambda_{5,t+1}\beta(1 + spr_{t+1} - rec_{t+1}) + \lambda_{8,t+1}\beta\varepsilon_{pol}(covid_{t+1})^{\varepsilon_{pol}-1}$.
- Equation (18), the optimality condition for the spread, $\frac{\partial \mathcal{L}}{\partial spr_t}$, states that the multiplier on the spread's determination, $\lambda_{6,t}$, equals the marginal effect on the COVID-19 evolution, $\lambda_{6,t} = \lambda_{5,t}covid_t$.
- Equation (19), the optimality condition for the policy, $\frac{\partial \mathcal{L}}{\partial pol_t}$, states the marginal cost in terms of forgone consumption due to the resources needed to implement the policy, captured by the multiplier $\lambda_{7,t}$, is equalized to the marginal benefit in terms of lower spread, lower COVID-19, and lower excess mortality, $\lambda_{7,t} = -\lambda_{4,t} - \lambda_{6,t} - \lambda_{8,t}$.

Model's Solution

- The model is integrated by equations (1) to (8), (11) to (19) and the exogenous processes for technology, preconditions, recovery, and policy innovations, which are assumed exogenous with a first-order autoregressive process.

- The solution to this discrete time dynamic optimization economic problem takes the form of a system of non-linear difference equations. Except in very restricted versions of the RBC model (see Campbell 1991), there are no closed-form solutions. We focus on approximation techniques of the log-linear model around the steady state where we denote with $\widetilde{var}_t = \frac{var_t - var_{ss}}{var_{ss}}$, that is the deviation of the variable from the steady-state.

- The solution of the problem is given by:

$$Y_t = RX_{t-1} + SZ_t$$

$$Y_t = \tilde{c}_t, \tilde{\imath}_t, \tilde{y}_t, \widetilde{em}_t, \tilde{k}_{t+1}, \tilde{n}_{t+1}, \widetilde{covid}_{t+1}, \widetilde{spr}_t, \widetilde{pol}_t, \tilde{a}_t, \widetilde{precond}_t, \widetilde{rec}_t, \tilde{\lambda}_{1,t}, \tilde{\lambda}_{2,t}, \tilde{\lambda}_{3,t}, \tilde{\lambda}_{4,t}, \tilde{\lambda}_{5,t}, \tilde{\lambda}_{6,t}, \tilde{\lambda}_{7,t}, \tilde{\lambda}_{8,t}$$

$$X_t = \tilde{k}_t, \tilde{n}_t, \widetilde{covid}_t, \tilde{a}_{t-1}, \widetilde{precond}_{t-1}, \widetilde{rec}_{t-1}$$

$$Z_t = \varepsilon_t^a, \varepsilon_t^{precond}, \varepsilon_t^{rec}, \varepsilon_t^{pol}$$

Policy and Transition Functions

- The policy and transition functions are expressed as:

$$y_t = 0.3333k_t + 0.6800n_t - 0.0022covid_t + 0.9501a_{t-1} - 0.0001rec_{t-1} - 0.0025precond_{t-1} + 0.0021pol_{t-1} + 1.0001\varepsilon_t^a - 0.0027\varepsilon_t^{precond} - 0.0001\varepsilon_t^{rec} + 0.0022\varepsilon_t^{pol}$$

$$em_t = -0.0022k_t - 0.0045n_t + 0.1667covid_t - 0.0063a_{t-1} + 0.0095rec_{t-1} + 0.1900precond_{t-1} - 0.1583pol_{t-1} - 0.0067\varepsilon_t^a + 0.2000\varepsilon_t^{precond} + 0.0100\varepsilon_t^{rec} - 0.1667\varepsilon_t^{pol}$$

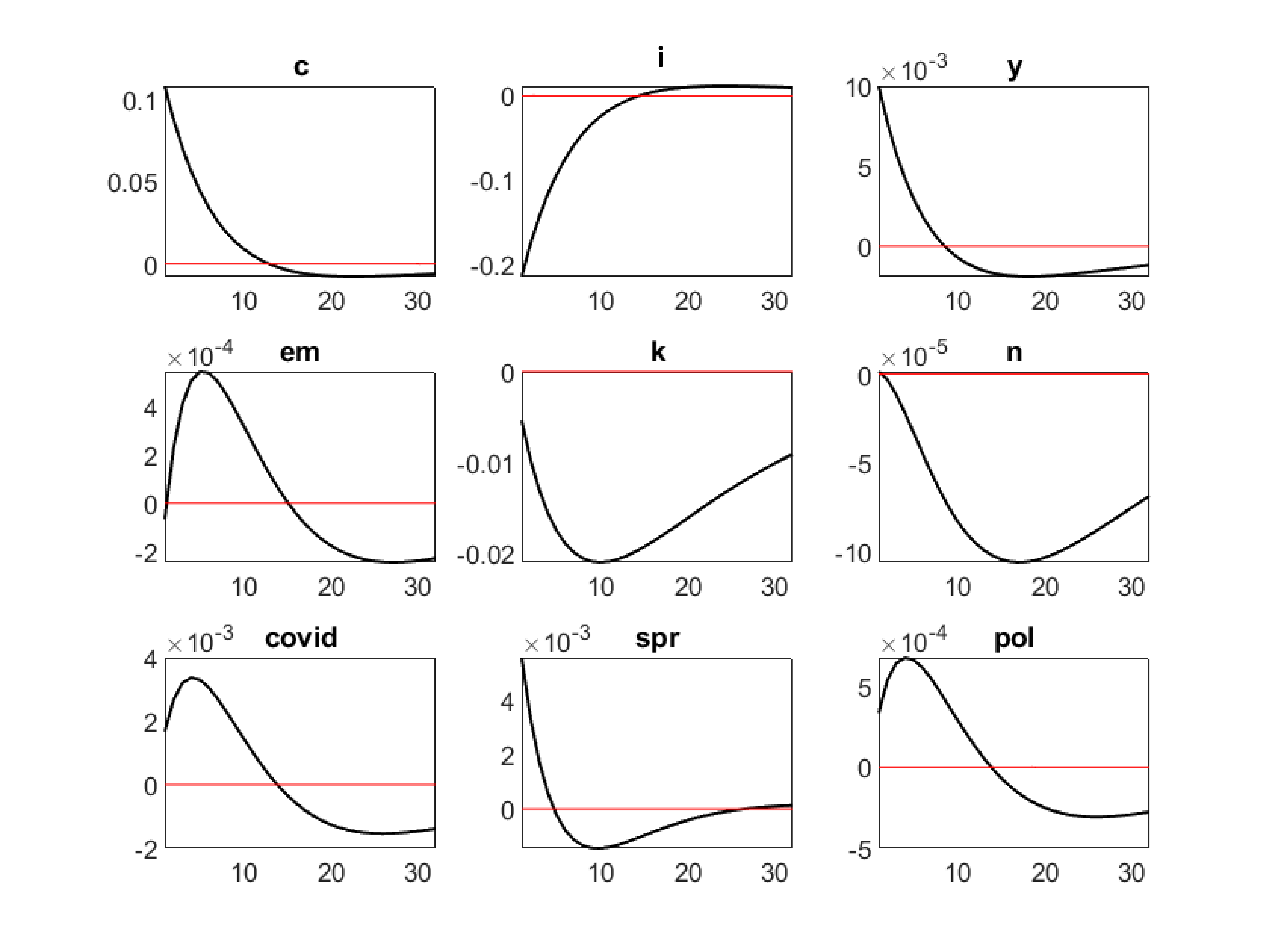
$$covid_t = 0.0556k_t + 0.1133n_t + 0.8330covid_t + 0.1583a_{t-1} - 0.2375rec_{t-1} - 0.0004precond_{t-1} - 0.7913pol_{t-1} + 0.1667\varepsilon_t^a - 0.0004\varepsilon_t^{precond} - 0.2500\varepsilon_t^{rec} - 0.8330\varepsilon_t^{pol}$$

POLICY AND TRANSITION FUNCTIONS

	c	i	y	em	k	n	covid	spr
k(-1)	4.335745	-8.879598	0.333363	-0.002222	0.753010	0.000044	0.055560	0.185202
a(-1)	10.261239	-20.340836	0.950084	-0.006334	-0.508521	0.000127	0.158347	0.527825
lampol(-1)	-73.451440	173.399569	0.002111	-0.158347	4.334989	0.003167	-0.791315	-2.637716
n(-1)	-288.407907	686.284745	0.680060	-0.004534	17.157119	1.020091	0.113343	0.377811
covid(-1)	5.180952	-12.426988	-0.002222	0.166681	-0.310675	-0.003334	0.832963	-0.556790
rec(-1)	-17.118689	40.605591	-0.000127	0.009501	1.015140	-0.000190	-0.237521	0.158263
precond(-1)	16.035794	-38.010572	-0.002534	0.190017	-0.950264	-0.003800	-0.000422	-0.001408
lama	10.801305	-21.411406	1.000089	-0.006667	-0.535285	0.000133	0.166681	0.555605
lamprecond	16.879783	-40.011128	-0.002667	0.200018	-1.000278	-0.004000	-0.000444	-0.001482
lamrec	-18.019673	42.742727	-0.000133	0.010001	1.068568	-0.000200	-0.250022	0.166593
lamlampol	-77.317305	182.525862	0.002222	-0.166681	4.563147	0.003334	-0.832963	-2.776543

	pol	lambda1	lambda2	lambda3	lambda4	lambda5	lambda6	lambda7	lambda8
k(-1)	0.011112	23.167751	4.335745	113.629601	113.627379	94.104469	94.160029	4.335745	-212.123153
a(-1)	0.031669	49.438877	10.261239	237.559068	237.552734	195.729839	195.888186	10.261239	-443.702160
lampol(-1)	0.791737	-682.463647	-73.451440	-3608.915714	-3609.074061	-3044.269724	-3045.061039	-73.451440	6727.586540
n(-1)	0.022669	-2723.932717	-288.407907	-14419.153659	-14419.158193	-12177.737389	-12177.624046	-288.407907	26885.190146
covid(-1)	0.166593	48.985896	5.180952	258.049798	258.216479	218.191758	219.024721	5.180952	-482.422151
rec(-1)	-0.047504	-159.501304	-17.118689	-841.615488	-841.605988	-711.675552	-711.913073	-17.118689	1570.637749
precond(-1)	-0.000084	149.755909	16.035794	790.518817	790.708834	668.600997	668.600575	16.035794	-1475.345203
lama	0.033336	52.040923	10.801305	250.062177	250.055510	206.031409	206.198091	10.801305	-467.054905
lamprecond	-0.000089	157.637799	16.879783	832.125071	832.325089	703.790523	703.790079	16.879783	-1552.994950
lamrec	-0.050004	-167.896109	-18.019673	-885.911040	-885.901040	-749.132160	-749.382182	-18.019673	1653.302894
lamlampol	0.833407	-718.382787	-77.317305	-3798.858646	-3799.025328	-3204.494447	-3205.327410	-77.317305	7081.670042

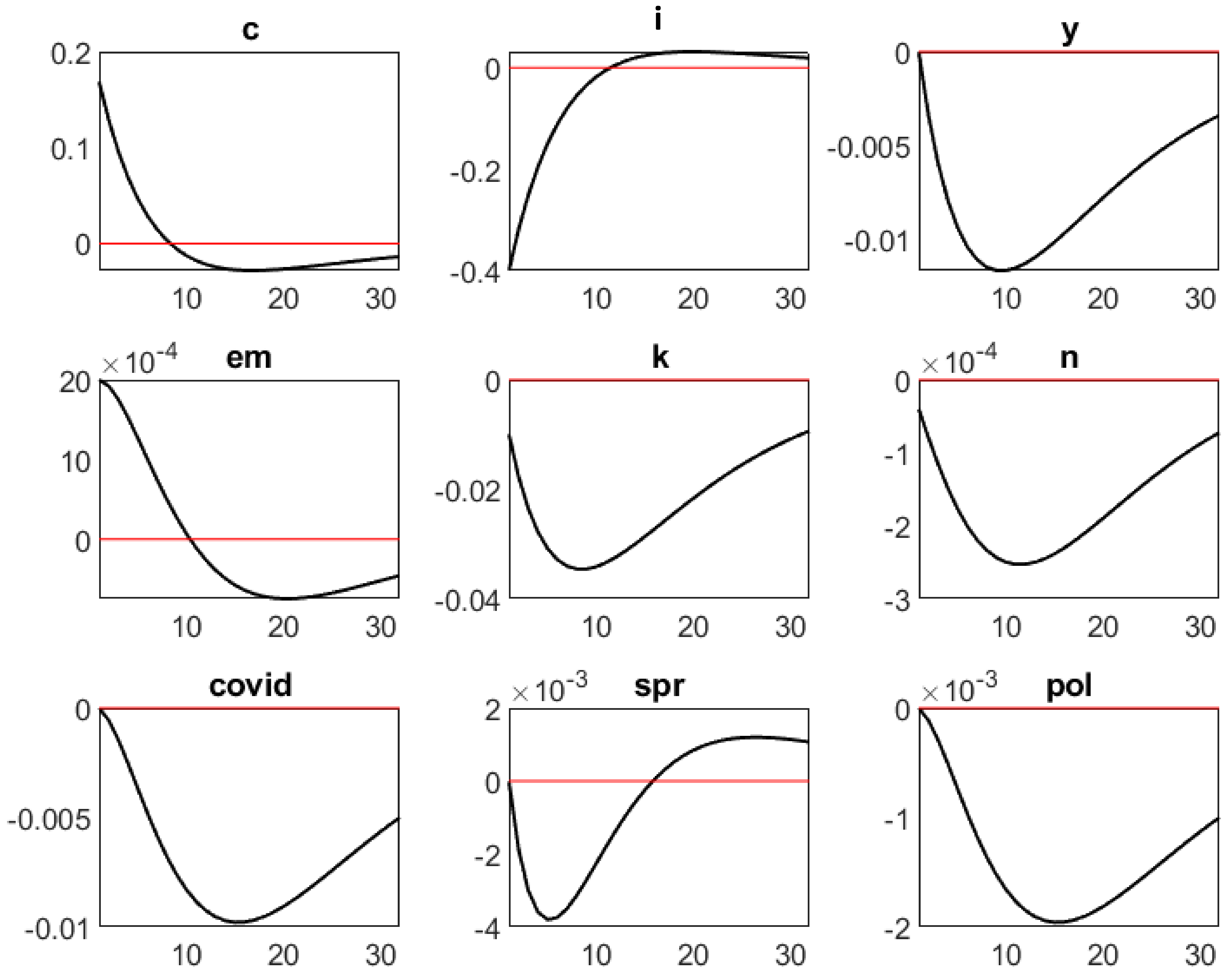
Impulse Response Functions: Technology ε_t^a



The technology shock increases the return to production and, through the assumed mechanism, in which COVID-19 spread is a positive function of production, it increases COVID-19 and therefore, increases excess mortality and lowers labor. The increase in the virus forces an increase in the anti-COVID policy.

The higher production and a drop in investment, finances the policy and higher consumption.

Impulse Response Functions: Preconditions $\varepsilon_t^{precond}$

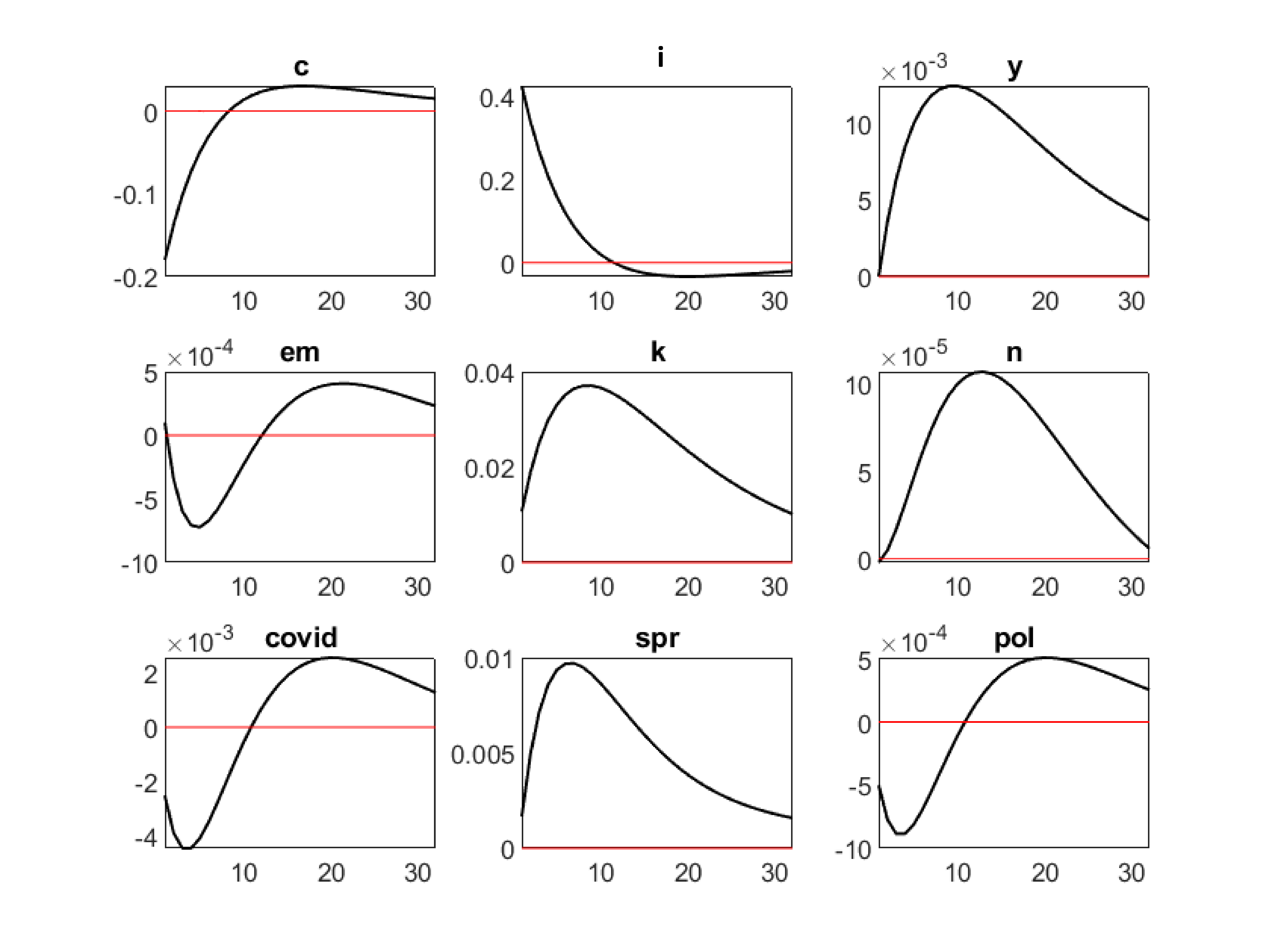


An increase in preconditions directly increases excess mortality and lowers labor input and investment, which reduces production.

The lower production reduces COVID-19 spread, which lowers COVID-19 and therefore the anti-COVID policy.

Under the current calibration, despite the drop in output, the larger reduction in investment provides resources to increase consumption.

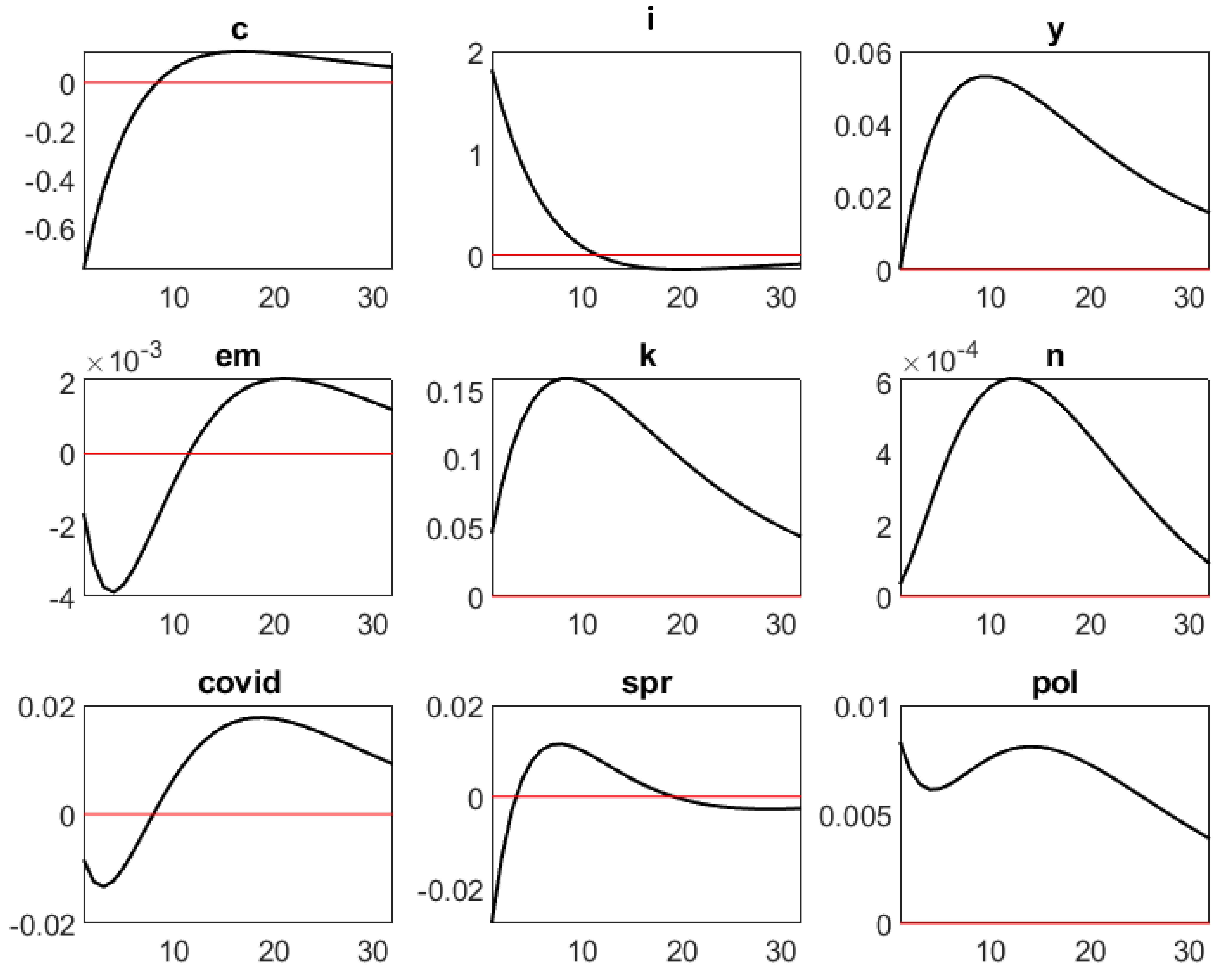
Impulse Response Functions: Recovery ε_t^{rec}



The higher recovery rate reduces COVID-19 and therefore excess mortality and the required policies. This allows an increase in workers and incentivizes investment that increases output.

Over time, the higher production increases COVID-19 spread, which gradually increases COVID-19 and excess mortality.

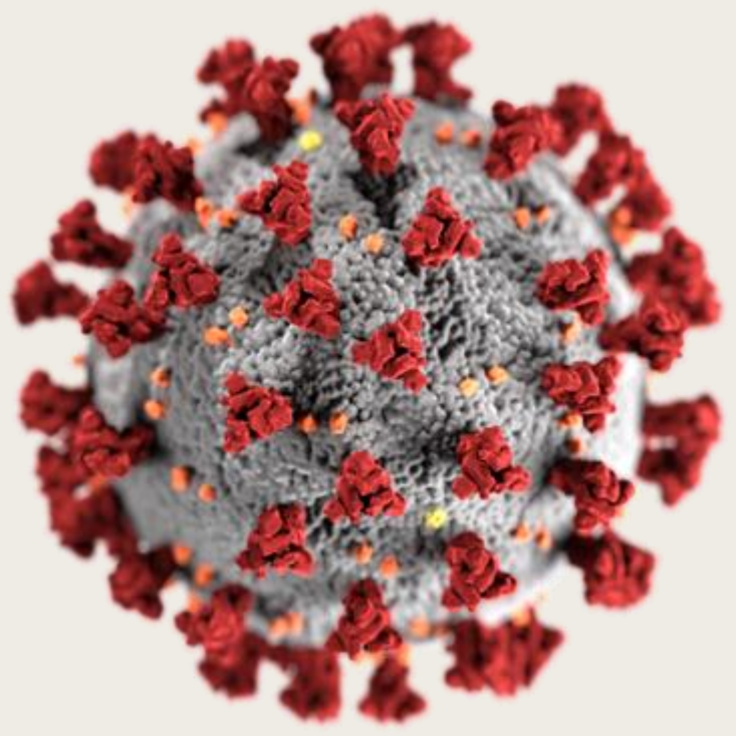
Impulse Response Functions: Policy ε_t^{pol}



The anti-COVID policy lowers COVID-19 and excess mortality. This increases available workers and incentivizes investment, yielding higher production.

Under the current parametrization, despite the increase in output, consumption declines due to the large increase in investment and the required resources to finance the policy.

A Benchmark Macroeconomic Model on Excess Deaths, Economic Production's Losses and Economic Policies During the COVID-19 Pandemic



$$\max_{\{c_t, i_t, y_t, em_t, k_{t+1}, n_{t+1}, covid_{t+1}, spr_t, pol_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t [u(c_t) - v(em_t)] \quad (9)$$

$$c_t = y_t - i_t - pol_t \quad (7)$$

$$em_t = precond_t * covid_t - pol_t \quad (4)$$

$$pol_t = (covid_t)^{\theta_{pol}} e^{\varepsilon_t^{pol}} \quad (8)$$

$$y_t = a_t k_t^{\alpha} n_t^{1-\alpha} \quad (1)$$

$$covid_{t+1} = (1 + spr_t - rec_t) covid_t \quad (5)$$

$$k_{t+1} = (1-\delta)k_t + i_t \quad (2)$$

$$n_{t+1} = (1-\mu)n_t - em_t \quad (3)$$

$$spr_t = \varphi y_t - pol_t \quad (6)$$

Arrows show the directions in which variables are related. c_t is consumption, em_t is excess mortality, y_t is output, i_t is investment, a_t is (exogenous) technology, k_t is physical capital, n_t is labor assumed equivalent to population, $precond_t$ are (exogenous) preconditions, $covid_t$ is the virus, spr_t is the spread of the virus, rec_t is (exogenous) recovery from the virus, pol_t is the anti-spread/anti-excess mortality policy, here assumed to be the same, but that could be individualized, and ε_t^{pol} is a policy shock. Equation (1) to (8) together with their eight optimality conditions related to the objective (9) and the processes for the exogenous variables are used to solve the model that describes the evolution of the endogenous variables over time.