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Original Contribution

Investing to Both Prevent and Prepare for COVID-XX

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Abstract: One cause of the high rate of COVID-19 cases in the USA is thought to be insufficient prior capital investment in national health programs to preemptively reduce the likelihood of an outbreak and in national capacity to reduce the severity of any outbreak that does occur. We analyze the choice of capital investments (e.g. testing capacity, stockpiles of PPE, and information sharing capacity) and find the economically efficient capital stock associated with mitigating pandemic risk should be dramatically expanded. Policymakers who fail to invest in public health forgo significant expected cost savings from being prepared.

Keywords: Pandemic preparedness, Health capital investments

INTRODUCTION

Infectious zoonotic diseases, such as COVID-19, capable of producing major outbreaks or pandemics result from complex ecological, socioeconomic, and epidemiological interactions. Effective prevention and mitigation requires integrating management strategies involving various interventions (e.g., reducing environmental drivers, managing human–animal contact risk, testing, quarantines, stockpiling of therapeutics, vaccine development) at local, national, and international scales to reduce the number of outbreaks and their consequences, including hospitalizations, deaths, and the potential for outbreaks to expand (Fig. 1, following a World Health Organization (WHO) classification) (World Health Organization 2018).

The COVID-19 pandemic is far from over, with over 44 million confirmed cases, close to 716 thousand deaths, and 656,699 new reported cases the week of October 17, 2021 (Johns Hopkins University and Medicine 2021) in the USA alone. But COVID-19 is only one of many possible pandemic risks, and novel diseases are emerging at an increasing rate (Morse et al. 2012; Pike et al. 2014). Indeed, unlike some other risks like wildfire, the current outbreak does not reduce fuel load or the likelihood of future outbreaks. Instead, it is a warning siren that risks—in terms of both the likelihood and costs of outbreaks—continue to grow due to environmental change and socioeconomic drivers (Jones et al. 2008; Cohen 2000; Morse et al. 2012). Programs to preemptively identify novel pathogens that could emerge so that vaccines or therapeutics could be more broadly targeted (Carroll et al. 2018; Saunders et al. 2021; Sheahan et al. 2017), or to reduce the underlying

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Decisions	Phases				
	Introduction or emergence →	Localized transmission →	Amplification: Epidemic →	Pandemic →	Reduced transmission
Strategies	Anticipation Primary prevention Early detection	Containment Preemptive protection	Control Mitigation Insurance	Control Mitigation Insurance	Elimination Eradication Reemergence control
Responses	Viral surveillance Spillover interventions Syndrome surveillance	Local testing Isolation Contact tracing Mobility restrictions	Widespread testing Quarantine Health care capacity School closures Business restrictions	All at larger scale	Vaccine Treatment Surveillance
Type	Non-pharmaceutical	Non-pharmaceutical	Non-pharmaceutical Pharmaceutical	Non-pharmaceutical Pharmaceutical	Non-pharmaceutical Pharmaceutical

Figure 1. Phases of disease emergence, strategies, and responses.

drivers of emerging diseases are considered a valid part of a preemptive strategy (Daszak et al. 2020). Making investments now based on lessons from COVID-19 could prepare society for the next potential pandemic.

President Biden recently proposed The American Jobs Plan (The White House 2021), which includes $30 billion in "infrastructure" to prevent future pandemics, as well as other major investments in research and caregiving that could provide additional support (e.g., $400 billion for caregiving to the elderly and $40 billion to upgrade research infrastructure and laboratories). It is not clear how much of the additional support would contribute to pandemic infrastructure, but here we pose the question: even if all of the originally proposed investments (which have recently declined due to negotiations with Congress) contribute to pandemic prevention, is $470 billion adequate?

We examine this issue numerically for the USA and find the expected net present value of economic gains (over an infinite time horizon after accounting for the unknown date of an outbreak; see SI) relative to current investments is maximized by an initial infrastructure investment of $511 billion ($41 billion more than the $470 billion indicated above), followed by additional investments that bring the capital stock to a steady-state value of $829 billion (for a total of $233 billion in addition to the American Jobs Plan). These investments generate $10.4 trillion in expected economic gains from investment, with each dollar spent expected to generate $12.55 in economic gains on average. Specifically, we examine investment in *ex ante* (pre-outbreak) preparedness infrastructure to prevent or reduce a novel disease's impact prior to the discovery, testing and roll-out of a vaccine or therapeutic. Such investments help contain, preemptively protect, mitigate, control and insure society against the risk. Following the economic insurance and risk reduction literature, we term the investments as self-insurance-cum-protection (SICP) (Daszak et al. 2021).

SICP includes investments that facilitate preemptive self-protection, such as rapid testing and diagnostics to detect and prevent establishment via local transmission and subsequent amplification. SICP also includes investments that promote self-insurance during amplification, such as contact tracing, capacity to develop therapeutics and vaccines, and understanding disease spread to aid in policy (Berry et al. 2015; Lee 1998).[1] These two features of SICP reflect the two components of economic risk in this context: the probability of an outbreak and the economic consequences of an outbreak, including loss of life (Perrings 2005). SICP investments involve physical and human

[1]SICP is broadly defined at the national level, given that policies associated with its generation are programmatic and initiative based—many national programs or initiatives with elements of both self-insurance and self-protection. See the SI for more details of components included in our numerical analysis.

capital elements that can address both risk components. The SICP measure we examine includes testing capacity, healthcare workers, stockpiles of PPE, hospital beds and equipment, and capacity to support widespread cooperation and information sharing to facilitate the rapid identification of and responses to novel outbreaks—hopefully before they become pandemics.

While the importance of investments in vaccines and treatments (therapeutics) is well known, arguments for investments to increase public health managers' abilities to anticipate, detect, prevent, contain, mitigate, and control a disease outbreak so that it does not become epidemic or pandemic are less obvious. Pike et al. (2014), Berry et al. (2015, 2018) all argue the importance of near-term investing to reduce long-term pandemic risks, and the broader invasive species literature finds prevention is often more cost-effective than post-outbreak control (Finnoff et al. 2007).

The CDC promotes the One Health approach, which focuses on preventing zoonotic transmission in regions of potential disease emergence (US Centers for Disease Control and Prevention n.d.). Dobson et al. (2020) find significant cost savings can be achieved in this context from restricting wildlife trade, reducing land-use change (a driver of increased risk of human contact with wildlife microbes), and promoting biosecurity to prevent zoonotic disease spillovers to humans. However, these investments do little to stop early local transmission and to contain an outbreak that does occur. Indeed, a prevention-only focus leaves the world less resilient to the pandemics that inevitably will occur—in this sense prevention alone is a risky investment. But this risk can be hedged through investments that also reduce the consequences of outbreaks (Finnoff et al. 2007). Accordingly, SICP is a broader concept than One Health's zoonotic prevention approach.

A National Research Council report (2016) produced after the 2014 West Africa Ebola outbreak emphasized the relative lack of preparedness capacity and the need for significant investments in what amounts to SICP, and this point was again emphasized just before COVID-19 struck. In the wake of COVID-19, Global Preparedness Monitoring Board (2019) argue that preparedness deficiencies were a significant factor in the economic and health impacts experienced by many developed countries. The US' COVID-19 experience suggests it was deficient in SICP resources, especially without a more coordinated Federal response that would have improved the efficiency of these resources (Daszak et al. 2021). This is in spite of the 2019 Global Health Security Index ranking the USA number one overall for health and security capabilities prior to COVID-19 (Nuclear Threat Initiative et al. 2019). The USA had a pandemic plan suitable for the smaller scales of major recent outbreaks, was working toward implementing the International Health Regulations both at home and abroad, and was investing in projects like PREDICT, an initiative to discover and preemptively categorize potential zoonotic diseases and facilitate early detection of potential pandemics (PREDICT Consortium 2020). However, an initially politicized and patchwork response to COVID-19 undermined the preventative capacity of these approaches to support institutional cooperation and information sharing and to facilitate better use of SICP resources (Colglazier 2020). US CDC Director Dr. Rochelle Walensky testified to a Senate subcommittee on May 19, 2021, that the pandemic would have been "extraordinarily different" if, prior to the pandemic, we had made investments to conduct tests "on a massive scale," if we had "contact tracers on the ground ready to go," and overall had "a more robust public health infrastructure" (Langmaid 2021) [see also (Daszak et al. 2021)].

Our analysis of SICP capital investments extends prior work calibrated based on emerging but, in hindsight, comparatively low outbreak risks of diseases such as Ebola or the Zika virus (Berry et al. 2018). Here we use information on COVID-19 impacts to consider the significantly larger risks posed by future pandemics. We also examine how optimal investment levels change with the efficiency of SICP, which may be affected by institutional and political factors.

Methods

We constructed a decision model (see *SI* for model specification and calibration) to determine how pre-outbreak US investments in SICP can be made over time to maximize the expected net present value of social benefits to the USA, given a growing hazard that a pandemic could emerge and generate significant economic costs (Berry et al. 2015; Reed and Heras 1992). These net benefits are defined as the net present value of the expected economic gains from having a larger SICP stock relative to maintaining the stock at its current value. Prior to an outbreak, net benefits are the benefits of having a larger SICP stock that might be useful right away (e.g., for non-pandemic purposes) less investment costs. Post-outbreak net benefits are the avoided expected outbreak costs from the larger SICP stock.

Outbreak costs are modeled based on Martin and Pindyck (2019), who disaggregate the expected welfare consequences of a catastrophe such as a pandemic into unavoidable (fixed) and avoidable (variable) costs. Avoidable (variable) costs are those that can be reduced by ex ante SICP healthcare investments that are available when the pandemic begins (e.g., by reducing the types of capacity constraints we have faced with COVID-19), whereas unavoidable (fixed) costs are unaffected by SICP. Some costs are due to deaths, with a portion considered unavoidable due to prior poor health (the infirm) or age (the elderly). There are also costs associated with reduced GDP via reductions in economic productivity, consumption, and other capital investments, stemming from increased sick days as well as social distancing measures to reduce spread. The magnitudes of the avoidable and unavoidable costs depend on the magnitude of the pandemic, which we take to be uncertain ex ante so that we focus on expected costs. We only focus on US benefits and costs, thereby providing a conservative value on the gains from investment, as US investments will inevitably produce benefits to other countries.

The time horizon for the investment problem is the time interval prior to the outbreak. This interval has an uncertain end date (the date of outbreak) that could come at any point in the future. Uncertainty about the timing of an outbreak is captured by a hazard rate that depends on two variables. First, it is increasing in an exogenous background hazard rate that reflects climatic, ecological, and global human socioeconomic factors over which the decision maker has no significant control, but that may influence ecological conditions and private decisions influencing disease emergence. We model the background risk to be increasing over time since changes in climate, land use, and international trade have significantly increased the frequency of emerging infectious disease events over the past 40 years (Jones et al. 2008; Cohen 2000; Morse et al. 2012). Second, the overall hazard rate is decreasing in SICP capital investments. Reed and Heras (1992) show that such a management problem under uncertainty must be analyzed over an infinite time horizon. With this in mind, the expected net present value of gains is technically defined over an infinite horizon, but they are really based on an uncertain time interval that is likely finite. The uncertainty surrounding the pre-outbreak time horizon causes society's risk-preferences to be ambiguous prior to optimization; while obviously influenced by the modeling specification, the modeling approach results in preferences not being set a priori as they are in problems with a known time horizon. Rather, optimization effectively determined both the optimal investment strategy *and* society's risk-preferences. Specifically, we find the optimal strategy involves society acting as if it is risk-averse.

Analysis

Our analysis finds it is optimal to increase the SICP stock over time to a steady state of $829 billion (assuming a 3% discount rate). The first panel of Fig. 2 presents the optimal investment response as a function of the background hazard rate (on the horizontal axis). The lower dashed horizontal line represents the current SICP level in the model, and the current background hazard rate is given by the dashed vertical line at 0.1 (together resulting in an initial hazard rate of 0.05). As the hazard rate is increasing over time, the investment response in the first panel of Fig. 2 can be interpreted as a plan that moves over time from left to right. The optimal strategy involves an immediate, large increase in SICP (vertical arrow) followed by moderate increases as the background hazard increases to a steady state of 0.4 (at the second dashed vertical line)—at which point the SICP stock remains constant at $829 billion (upper dashed horizontal line). The explicit time path is presented in the second panel of Fig. 2, where each unit of time represents one year.

The optimal strategy generates $10.4 trillion in social net benefits—again, the present value of expected economic gains from investment. On average, each dollar spent is expected to generate $12.55 in economic gains. The average expected gains are fairly consistent (e.g., in the range of $9–$15 in benefits per dollar of SICP capital) across a wide range of perturbations in the model's parameters relative to the baseline scenario presented above.

A sensitivity analysis, detailed in the SI, examines steady-state SICP outcomes and expected gains from investment when each model parameter is increased or decreased by 50%. We find that a 1% change in any given parameter generates less than a 1% change in the optimal steady-state SICP stock in all but one case (a healthcare benefits parameter), with most changes being less than 0.2%. The optimal paths to the new steady states in these cases are not substantially different from the baseline scenario unless the steady state has been significantly altered

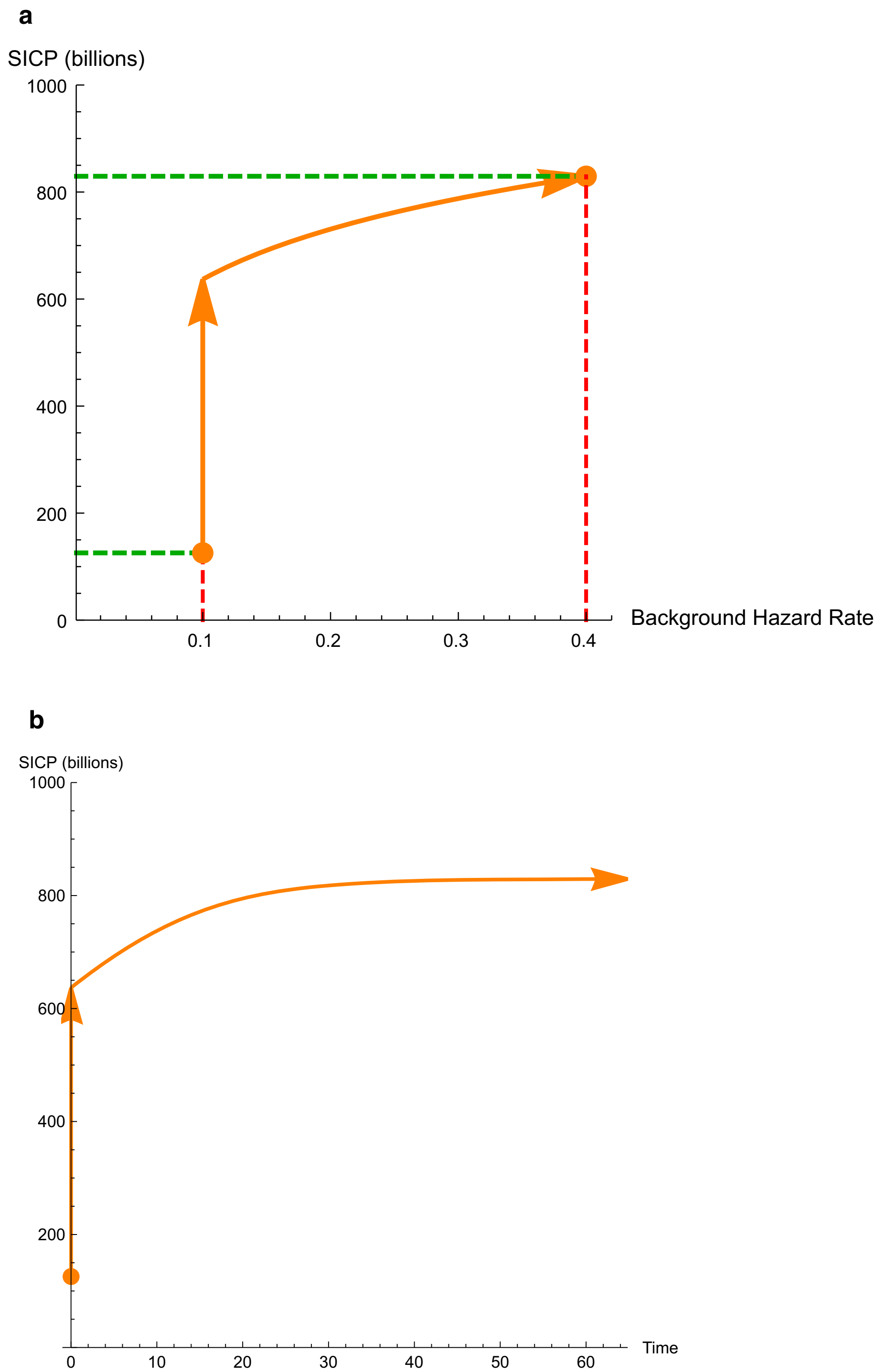

Figure 2. Top panel: optimal SICP stocks as a function of the current hazard rate. Current SICP is modeled as the lower dashed horizontal line, the current hazard rate is at the vertical dashed line at 0.1, and the steady-state hazard rate is at the vertical dashed line at 0.4. The steady-state SICP is the upper dashed horizontal line. The solid lines represent the optimal investment plan, starting from the current SICP and background hazard combination with an immediate increase (vertical arrow) followed by gradual expansion. Bottom panel: the optimal time path of the SICP stock.

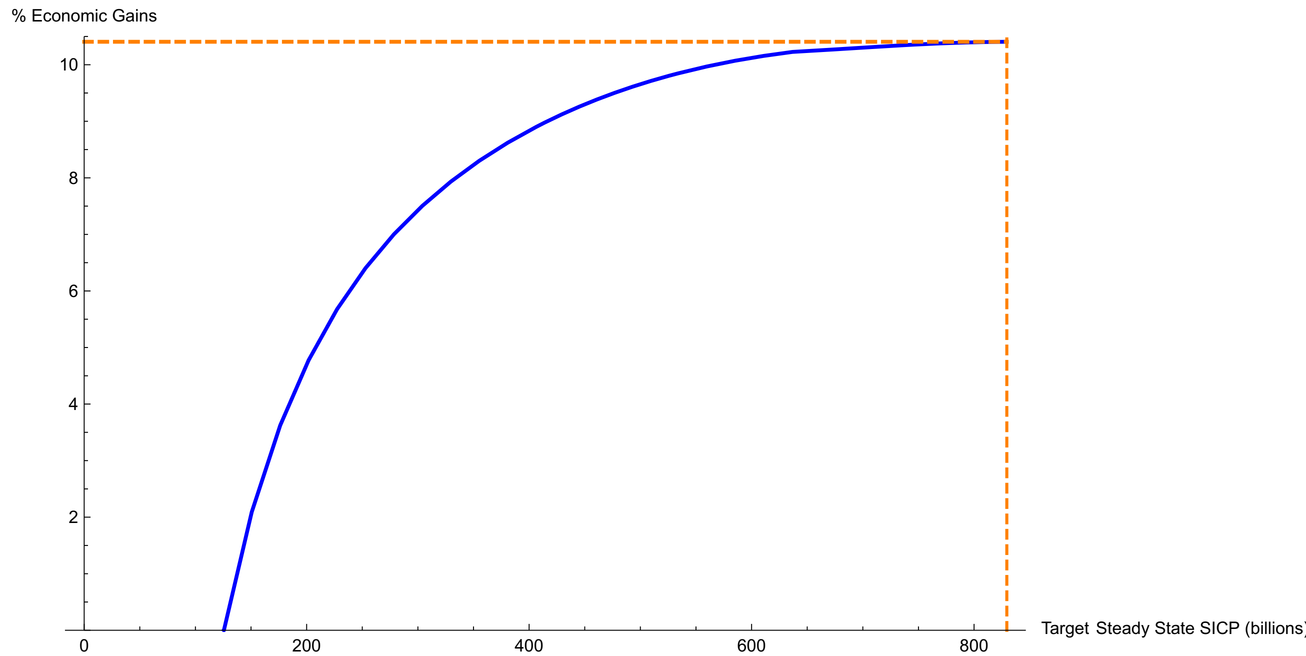

Figure 3. The percent increase in expected economic gains relative to current investments given various target steady-state stocks. The gains includes general healthcare benefits prior to the pandemic and unassociated with pandemic prevention, as well as the reduction in the probability of a pandemic occurring (self-protection) and the value of SICP in reducing damages after a pandemic occurs (self-insurance).

(the primary outliers here being healthcare benefits and SICP effectiveness parameters). We also find that a 1% change in any parameter generates less than a 0.11% change in expected net gains from investment, except for a 0.22% change associated with the healthcare benefits parameter. These small parameter impacts indicate our baseline model results are fairly robust.

Policymakers who fail to invest in public health are leaving substantial sums of money on the table. This is shown in Fig. 3. The horizontal axis indicates target steady-state SICP stocks, while the vertical axis represents the percentage gain in expected economic welfare relative to a benchmark scenario in which society simply holds SICP fixed at current levels.

The curve represents the relation between target stocks and the expected gains from optimal investment in SICP. For the socially optimal steady-state SICP stock of $829 billion, we assume an economically optimal investment strategy was used to obtain this steady state. This target stock yields maximum economic gains, expressed in Fig. 3 as an 87.8% gain in welfare relative to the benchmark scenario (holding the current stock constant). For each alternative (smaller) SICP target, calculating economic gains requires calculating economic values both along a particular path to the target and at the target. We assume society follows the welfare-maximizing strategy until the alternative target is reached, thereafter maintaining this target value into perpetuity. This assumption means any reductions in welfare gains, relative to the socially optimal strategy, stem from stopping prematurely at the wrong target. Welfare gains would be further reduced if, as might be expected, society instead pursued a sub-optimal path to the sub-optimal target. Accordingly, we view the welfare gains presented in Fig. 3 as conservative (high) relative to what might be expected in practice. No economic gains occur where the curve crosses the horizontal axis; this is the baseline scenario in which the target stock equals the current SICP stock.

Figure 3 illustrates that society stands to generate large gains from relatively small increases in the current SICP level. As investment levels continue to increase, the additional gains become smaller although they may still be quite large in absolute terms. For instance, optimal economic gains are only 3.3% larger than those arising the initially proposed American Jobs Plan investments (with $595 billion steady-state SICP), but this roughly translates to a $330 billion gain in expected cost savings. Finally, note that Fig. 3 is qualitatively similar across various assumptions about extant annual investments and damage costs, which were used to calibrate the model. Likewise, the quantitative results here related to the 20% reductions in SICP are also similar across the same assumptions about extant annual investments and damage costs.

Within the optimal investment pattern, SICP levels are chosen to ensure that the marginal rate of return to investing in SICP always equals the depreciation-adjusted social opportunity cost of capital (i.e., the discount rate, reflecting the rate of return from alternative capital investments in the economy, plus the SICP depreciation rate). Our framework is one of joint production in the sense that the single SICP capital stock jointly produces three types of benefits: general healthcare, self-protection, and self-insurance. As such, the overall rate of return generated by the stock of SICP can be examined as a portfolio of three returns, one for each type of benefit that SICP produces. Our notion of a portfolio here differs from standard notions where multiple, distinct investments are made to each generate a rate of return that contributes to an overall return. Here, we have a single investment that simultaneously generates three returns that cannot be tailored individually. The collective return determines the optimal level of SICP investment, but the individual components give insight into which effects are driving the last units of investment.

The first rate of return is a risk-free rate of return due to increased general healthcare capacity that can be broadly used prior to a pandemic. This return does not explicitly reflect pandemic risks, although it does change over time based on overall investment responses made, at least in part, due to outside forces that drive changes in the background hazard rate.

The second is a rate of return from self-protection that reduces the likelihood of a pandemic. Finally, there is a rate of return to self-insurance that reduces the costs associated with any pandemic that does occur. The risk-related returns also depend on the background hazard rate as well as society's risk responses in the form of SICP investments. Each of the risk-related returns provides incentives to expand the stock beyond that needed for general medical care and sufficient to be prepared for a pandemic. The degree to which SICP contributes to each effect can be inferred by examining the portfolio of returns.

The three rates of return are presented in Fig. 4 for different values of background hazard rates, assuming SICP investments are made optimally at each of these background rates. An optimal strategy requires the three rates to always sum to the depreciation-adjusted required rate of return (8% in our analysis: 3% discount rate plus 5% depreciation rate). We find that the risk-free rate of return is positive and small and slowly declines as the background hazard rises. With zero background hazard, the value equals the depreciation-adjusted required rate of return, 0.08. Larger background hazard rates incentivize overinvestment in SICP for the purpose of just general healthcare, reducing the risk-free rate of return slightly.

The self-insurance rate of return is zero when there is no background hazard and jumps to about 2.25% with the first nonzero units of background hazard. The self-insurance rate of return declines relatively faster than the risk-

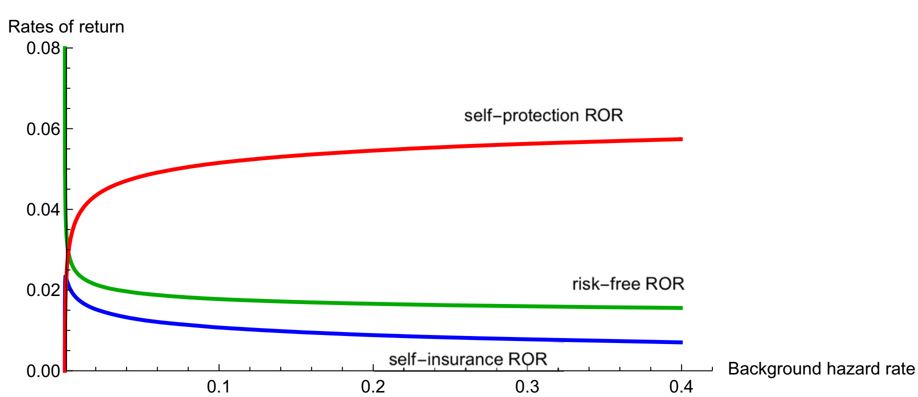

Figure 4. Rates of return (ROR) associated with various SICP stock-related benefits, given various background hazard rates of a pandemic. The risk-free ROR stems from general healthcare benefits not associated with pandemic risks. The self-protection ROR stems from self-protection that reduces the likelihood of a pandemic. The self-insurance ROR stems from self-insurance that reduces the costs associated with any pandemic that does occur. All returns depend on the current background hazard rate as well as society's risk responses in the form of SICP investments.

free rate of return as the background hazard is increased. This indicates an overinvestment in SICP for the purpose of just reducing the costs of pandemics that do occur.

Finally, the self-protection rate of return is also zero when there is no background hazard, but is positive and increasing as the background hazard increases. For most hazard rates, this rate of return exceeds the discount rate. This result means that self-protection, i.e., trying to prevent a pandemic, is the driving force of our investment pattern. The relative importance of self-protection increases when either the future is valued less (higher discount rate) or SICP capital depreciates quicker (higher depreciation rate), and increasingly so for increases in the depreciation rate. That prevention is a higher priority than mitigating pandemic costs is consistent with prior work suggesting that prevention of environmental risks is generally a better investment than investments made to mitigate economic damages associated with adverse events. We find this priority on prevention while adopting risk-averse behavior contrasts with Finnoff et al. (2007), who show the necessity of risk neutrality for prioritizing prevention (in cases where the time horizon is not uncertain, so that preferences are set a priori, prior to optimization, in contrast to the present problem).

A more complex model might consider additional types of capital stocks that are each specific to one type of benefit, in which case the portfolio of returns could be more tailored. Our results here suggest that, in such cases, we might expect a greater focus on prevention-specific capital when that is available.

The analysis above is based on a calibrated relation between current estimated SICP investments and associated economic damages from COVID-19. It is generally common knowledge that capital stocks were used inefficiently, reducing the effectiveness of both self-prevention and self-insurance activities, likely due to inefficient Federal and State oversight. We now perform an additional sensitivity analysis to examine the effects of using SICP more effectively in each of these areas. In each case, we assume the baseline results based on historical trends reflect the current, less-effective management reflected in the calibrated model.

First, suppose that, under the optimal strategy, SICP is utilized in such a fashion to be twice as effective in reducing the variable component of economic damages to provide self-insurance. We find the optimal steady-state SICP stock in this case is \$744 billion, which is a 10.3% decline: less capital is required if it is used more effectively, although the reduction is comparatively small relative to the effects on damages. The expected economic gains in this case are \$10.58 trillion, which is a 2 percent gain relative to the optimum when capital is used less effectively.

Now suppose that, under the optimal strategy, SICP is utilized to be twice as effective in reducing the hazard rate to provide self-protection. We find the optimal steady-state SICP stock in this case is \$530.9 billion, which is a 35.9% decline: significantly less capital is required if it is used more effectively. The expected economic gains in this case are \$11.2 trillion, which is a 7.7% gain relative to the optimum when capital is used less effectively. These results are consistent with our prior rate of return results: larger gains come from improving the effectiveness of self-protection.

Discussion

Current SICP stocks are unable to capture the potential gains achievable from optimal investments to manage the threats of problems like COVID-19. Not only does the current stock need to be expanded, but by an even greater extent than in recent proposed legislation (The American Jobs Plan) and maintained over time. Our sensitivity analyses here involving lower damages or hazard rates, as well as our prior work on less costly diseases for the USA (Berry et al. 2018), indicate this conclusion is robust.

To adequately face the problems of threats like COVID-19, it is important to embrace broader concepts of investment such as SICP in comparison with focusing only on investments in prevention or adaptation. SICP works not only on managing the probability of an outbreak becoming pandemic, but also on alleviating the consequences if worst-case scenario(s) occur. It is important to note that our analysis aggregates capital in a manner that effectively maintains a constant proportion of self-protection and self-insurance with each dollar invested, whereas a disaggregated (and significantly more data-intensive) model would allow us to also examine the portfolio of investments. Our rate of return results suggests the return to self-protection (prevention) outweighs that of self-insurance, and so shifting the portfolio toward self-protection might be beneficial at the margin. Some additional sensitivity analysis (not reported) suggests this result is enhanced by increases in both the opportunity cost of capital (the discount rate) and, especially, the capital depreciation rate.

Finally, it is key to manage the stock to be as effective as possible. The more effective the stock, the lower the investment needed, and the greater the gains achievable. Indeed, programs like the American Jobs Plan might be adequate if their planned investments do all contribute to SICP and if this capital stock is managed effectively in the future. As improving efficacy is also costly, our results indicate the biggest bang for the buck comes from working to improve the efficacy of self-protection, further supporting our results about the portfolio of investments.

Author Contributions

KB, RH, DF, and PD conceived of the project. KB led the project. KB, RH, and DF contributed to the analytical modeling. KB, RH, DF, and RP contributed to the numerical exercise and calibration. KB, RH, DF, and PD contributed to drafting the manuscript.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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