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Perspective

Managing the financial risks of climate change and pandemics: What we know (and don't know)

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SUMMARY

The COVID-19 pandemic is generating the largest shock in the global economy since 1929. Although the pandemic has been unprecedented in scale and type, such complex, compounding shocks are not uncommon and are more likely in our modern, interconnected world. Our ability to assess and anticipate compounding risks is limited. Here, we propose a framework for assessing the economic losses associated with compounding climate, economic, and pandemic shocks. We propose a new metric, the *compound risk multiplier*, to measure the scale of the amplification effect and find that this can peak at over 150%; that is, the GDP impacts of the compound shock can be 50% larger than the sum of the individual shocks. Our results suggest that ignoring compounding risks could be a major blindspot in our ability to prepare for future crises. This underlines the urgency of accounting for compounding shocks within financial, fiscal, and crisis risk management.

INTRODUCTION

The COVID-19 pandemic is generating the largest shock in the global economy since 1929 with negative implications for economic development, poverty alleviation, and widening social inequalities. Although the COVID-19 pandemic has been unprecedented in scale and type, such systemic, complex, compounding events are far more likely in our modern interconnected world.[1,2] Importantly, these types of complex, compounding environment-economic-social risks are not explicitly included in most fiscal or macro-financial risk management frameworks to date. Despite a recent surge in scientific and policy interest in this type of systemic risk, there is little qualitative or quantitative evidence on their economic, fiscal, and financial implications. This means that we also do not know in economic terms how big a blind spot this is in our ability to prepare for future crises. Without this evidence, it is difficult to make a case to account for such shocks within risk management frameworks. In this perspective, we propose a preliminary framework for addressing this gap. Our focus is particularly on compounding climate, environmental, and social risks, which come with unique challenges given the complex and cascading nature of such risks, and are expected to become more common with climate change and environmental degradation.[3,4] We argue that missing these risks within our current risk management frameworks could undermine our ability to build resilience.

The scientific community has proposed a set of definitions and approaches for studying compound events.[5–7] Frameworks also exist to incorporate compounding economic and financial risks into bank stress testing.[8] But there is no widely accepted framework for assessing and quantifying complex, compounding risks associated with climate, environment, and social drivers in the economic terms suitable for integrating them into financial risk management frameworks used by governments and financial institutions. As we describe in this perspective, our standard toolkit of climate and economic models is also not well suited for such complex, non-linear events. Our ability to measure, monitor, and anticipate compounding risks is currently limited. To resolve these gaps, the economic and financial modeling communities need to step up, and work collaboratively with the scientific communities to develop a framework and appropriate toolkit to assess such risks.

In this perspective, we propose a preliminary framework for assessing the economic losses and fiscal impacts associated with compounding climate, economic, and pandemic shocks. As part of this, we propose a new indicator, the *compound risk multiplier* (CRM) to compare the impact of compounding events across event types, geographies, and over time. We discuss the challenges of quantifying the economic impacts of complex, compounding shocks within the current economic modeling toolkit. Finally, we illustrate the framework through application to two representative countries, quantify the CRM for each, and draw initial conclusions for policies to support building back better.

Risk assessment is a first step to better risk management.[9] In this perspective, we focus particularly on integrating risk into government's fiscal and wider risk management frameworks. This reflects the important role of government both in emergency response, critical infrastructure, and social protection during crises, as well as in setting an enabling environment for broader "whole of society" resilience through policy, regulation, and incentives.[9] Ensuring financial preparedness of governments for shocks is critical both to reduce the impact of crises on government balance sheets (including public debt) and to ensure finance is available in emergencies to facilitate speedy recovery across society.[10] This focus is timely given the massive fiscal impact of COVID-19. The perspective aims to help catalyze future research and also inform the active debate within many governments post-COVID on how to integrate such risks more explicitly into government financial planning and preparedness and strengthen resilience.[11] In this perspective, we argue, given the important economic and fiscal implications of compounding risks, there is a strong rationale for them to be more explicitly considered in governments assessments. The conclusions also have relevance for climate-related financial risk management as well as wider societal risk management.

COMPOUND RISKS AND COVID-19

Learning from COVID-19

The COVID-19 pandemic has led to the largest economic contraction since WWII. In response to the unprecedented social and economic shock associated with COVID-19, governments and central banks around the world have provided massive fiscal and monetary stimulus[12] to tame the near-term and long-term impacts of the pandemic and speed recovery. Total spending on COVID-19 response and recovery as of June 2021 totals almost $17 trillion across the 50 largest countries alone.[13] The International Monetary Fund (IMF) is making available more than $1 trillion in lending capacity to support more than 90 countries to manage the resulting fiscal shock, in addition to the up to $160 billion financing made available to developing countries over the last 15 months by the World Bank Group to address the health, economic, and social shocks.[14]

Importantly, such a massive shock from pandemics—including, the compounding effects with economic disruption and underlying social vulnerabilities—was not explicitly anticipated or prepared for within countries' fiscal and macro-financial frameworks.[15] In a 2020 survey of practice across five OECD countries, OECD[15] finds only one (New Zealand) that explicitly included pandemics within its fiscal risk reporting prior to COVID-19. Although our focus here is on governments, fiscal and macro-financial risks cannot be treated in insolation; financial crises create some of the largest contingent liabilities on government balance sheets.[16] Schönauer et al.[17] find that the consideration of so-called long-term environmental and societal risks (including pandemics and climate change) is limited in the communications of eight major Central Banks.

One result is a significant and long-lasting fiscal shock on government balance sheets. Average public debt worldwide reached an unprecedented 97% of GDP in 2020 and is projected to stabilize at around 99% of GDP in 2021, with lower-income countries facing challenges in financing large deficits.[18] There are also early signs that the fiscal impact of COVID-19 is impacting spending in other areas necessarily to build resilience to future disasters, particularly in the most vulnerable countries, thus potentially contributing to longer-term vulnerabilities.[19,20] If such shocks had been better anticipated, and integrated into government fiscal and financial preparedness frameworks, could these fiscal impacts have been lower? And could this have contributed to greater whole of society resilience and so lower impacts on people and firms?

One important lesson from COVID-19 is that different types of shocks can interact in complex ways, with systemic global, fiscal, economic, and social implications. In 2020, many countries saw record-breaking extreme weather concurrent with pressures on health systems and economies related to COVID-19, leading to compounding climate, health, and economic crises.[21] Take, for example, the wildfires, hurricane damage, and the cold wave in the southern US states and Typhoon Vamco in the Philippines to name a few. Compounding risks were not unique to COVID-19 nor are they particularly uncommon. Take, for example, the interplay between drought and oil prices that drove the food price shocks in 2007–2008 and 2010,[22] or the combination of drought, economic change after WW1, and the Great Depression, which led to severe economic and social impacts in the US during the 1930s Dust Bowl. Zscheischler et al.[23] reviewed historical instances of compound risk events related to weather extremes and concluded that, indeed, many major catastrophes bear the hallmark of being caused by compounding events. Pescaroli and Alexander[7] included several case study examples, including Hurricane Sandy in the US, which involved compounding and cascading risks.

Defining systemic and compound risks

Systemic risk has different definitions in different communities. In the context of financial crises, it is "the risk of widespread disruption to the provision of financial services that is caused by an impairment of all or parts of the financial system, which can cause serious negative consequences for the real economy."[24–26] More broadly, it can be defined as an event that can trigger a severe instability or collapse of an entire economy with significant economic losses and developmental impact.[27] Schweizer and Renn[27] identify several key characteristics of systemic risks: firstly, high *complexity* driven by the interdependencies between systems; secondly, transboundary and global nature, with ripple effects (*cascading risks*) across many subsystems, including economy, political, and civil society; thirdly, *nonlinearity and tipping points* that can be difficult to identify in advance, yet lead to drastic changes and potentially collapse if a threshold is breached; and fourthly, stochastic (chaotic) relationships between triggers and impacts, meaning that small changes lead to different outcomes. Each of these contributes to difficulties in quantifying probabilities of such events. Such events are popularly known as "Black Swan" events; a deep literature exists on the challenges associated with their quantitative prediction and estimation.[28]

Compound risks are one potential driver of systemic risks. Following Zscheischler et al.,[5] we define compound risks as "a combination of multiple drivers and/or hazards that contributes to societal or environmental risk" and, after Pescaroli and Alexander,[7] such risks could be: "(a) extremes that occur simultaneously or successively; (b) extremes combined with background conditions that amplify their overall impact; or (c) extremes that result from combinations of 'average' events." Pescaroli and Alexander[7] provide a holistic framework for the interrelated concepts of compound, interconnected, interacting, and cascading risks and several case study examples. Such cases show that, when different shocks combine, or when shocks interact with existing vulnerabilities (i.e., *compounding*), this can amplify the impacts and lead to *complex*, *cascading effects* (as noted above), increasing the potential for systemic, long-term implications. Such compounding events can set back or even reverse progress on poverty alleviation. Even in the US, COVID-19 is demonstrated to have slowed recovery efforts from disasters and intensified mental health impacts, thus increasing overall impacts.[29] Although systemic risks and compound risks are new, as noted above, the lessons from COVID-19 raise the importance and urgency of scientific, political, economic, and societal questions about how we can integrate such risks more explicitly into risk management frameworks.

Emerging discourse on compound risks

The pandemic accelerated research and interest on compound hazards, particularly those related to extreme weather events and climate change within the scientific community. For example, Phillips et al.[30] identified the potential hot spots for climate and COVID-19 to compound hazards and Zscheischler et al.[23] reviewed historical occurrences of compounding climate-related risks. Several studies highlighted the need for new research in this area and a new approach. For example, Zscheischler et al. argued that a systematic research program focused on these systems is overdue and is necessary to improve risk management for vulnerable communities. They further argued for the need to adopt an impact-centric perspective to identify the most important risks, rather than focusing on hazards themselves. Raymond et al.[31] called for a multi-disciplinary approach to tackling these compound risks and underlined the need to focus such collaborations on determining major feedbacks between physical processes and societal decisions that most affect the final impact. Kruczkiewicz et al.[32] similarly stressed the need for more combined natural and social scientific core research on the dynamics of compound risks to inform actions to increase preparedness for such shocks. There is growing evidence on the increasing likelihood of compounding weather shocks with climate change,[33,34] but there is little evidence on how shocks of different nature, such as climate and pandemics, combine, or the economic, financial, and fiscal implications.

We argue that there needs to be greater attention to the economic, financial, and fiscal implications of compound risks, particularly now as the attention of policy makers is focused on learning from COVID-19 and building back stronger. For governments and Central Banks, the lessons from COVID-19 raise urgent questions about how can we strengthen economic, fiscal, and financial resilience to these more complex, compounding shocks, particularly given the growing risks of climate change. What does this mean for governments today planning for future pandemics and for climate-related risks? These are questions that we raise in this perspective, and propose an initial analytical framework.

TOWARD A NEW TOOLKIT: COMPOUNDING PANDEMIC AND CLIMATE SHOCKS

To date, shocks tend to be seen in isolation within risk management frameworks. In addition, the toolkit routinely used to assess and manage the financial risks associated with natural catastrophes, such as the catastrophe risk models used by the insurance industry, include only the first-round direct impacts of shocks, and certainly exclude the cascading, global nature of major catastrophes. To resolve this gap, there is a need to bring together expertise and existing approaches from across the scientific, economic, and financial modeling communities to build a new integrated framework for risk assessment relevant to policy makers, in particular those in Ministries of Finance and Central Banks who play a central role in setting the enabling environment for policies, financial instruments, and investments in resilience.

Assessing compound risks: An initial framework

To raise the importance of this issue and help to catalyze further research, we propose an initial framework for analyzing the economic, financial, and fiscal implications of compound risks, and present initial research findings through applying them to two large middle-income countries that are highly exposed to flooding and tropical cyclones, respectively. This preliminary application of the framework aims to provide an insight into the scale of the potential blind spot in our current risk-management frameworks. Although the focus here was on climate and pandemics, the goal was to develop a framework that could be applied to different combinations of shocks and stresses, and importantly to explore the mechanics of how shocks of a different source and nature can combine and interplay within an economic system to generate impacts on government balance sheets, the real economy, and the financial sector.

We took a three-step approach. Firstly, we develop a framework for capturing compound shocks within a macroeconomic risk assessment by using a scenario-based approach and propose a new indicator for measuring the compounding effect in economic terms. The scenario-based framework learns from tried and tested approaches to scenario planning and stress testing that are common when dealing with complex, non-linear, and potentially systemic risks.[13,27] Secondly, we map the potential transmission pathways of shocks and identify where they could interact and lead to potential amplifying or cascading effects. Thirdly, we simulated the impacts of different scenarios by using one macroeconomic model, EIRIN,[35] modified to capture the transmission pathways identified in the analysis described above. This last step enabled us to quantitatively assess how climate (physical) shocks are (directly and indirectly) transmitted, and how they compound other shocks, such as a pandemic or economic shock.

As a demonstration, we took the case of a major climate shock occurring during a pandemic and applied it to two middle-income countries structurally similar to Southeast Asian or some larger Latin American countries. We design scenarios of individual and compounding COVID-19 and natural hazards, i.e., floods, which seasonally hit individual case study countries and that are worsened by climate change. In a similar way to stress-test exercises, we identify severe but plausible scenarios based on the country's exposure to natural hazards and COVID-19. Figure 1 illustrates the construction of four scenarios. The four scenarios combine climate shocks of different magnitudes, with COVID-19 scenarios based on empirical observations and test different timings of the compounding events. The scenarios are designed to assess risks that could happen tomorrow (rather than a future projection) and therefore are highly relevant to decision makers now and to COVID-19 recovery planning.

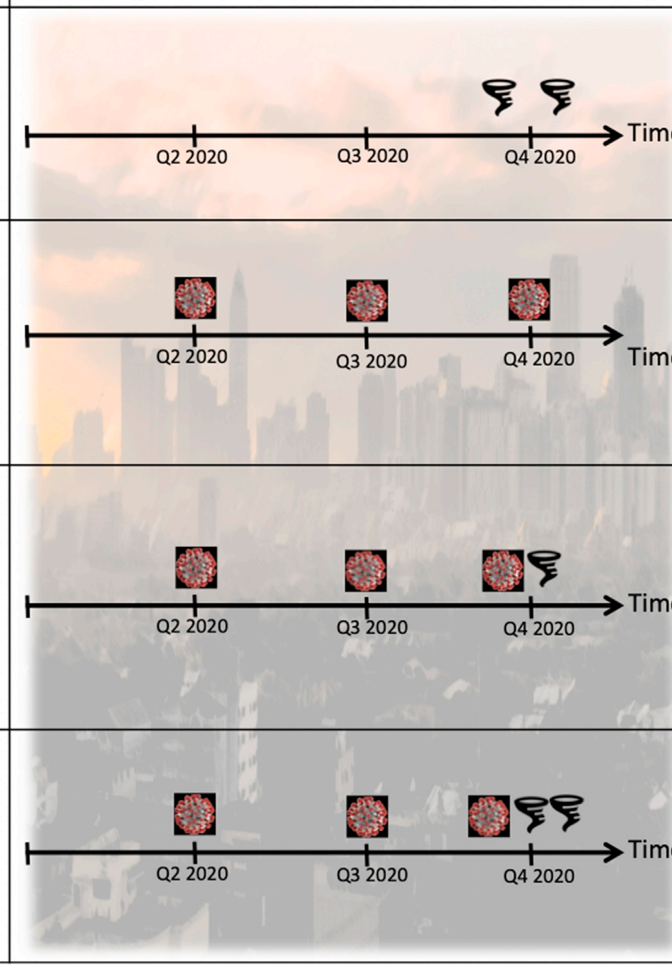
Scenario No	Natural Hazard Occurrence	Graphical Representation
1 Strong hazard (typhoon)	Timing: Q4 2020 Impact Size: $\varsigma_H = 1.63\%$ Agriculture = 0.147%, Industry = 0.5058% Service = 0.978%	
2 COVID-19 emergency	No	
3 Compound COVID-19 and mild hazard	Timing: Q4 2020 Impact Size: $\varsigma_L = 0.46\%$	
4 Compound COVID-19 and strong hazard	Timing: Q4 2020 Impact Size: $\varsigma_H = 1.63\%$	

Figure 1. Illustration of scenario of a framework for one middle-income country
Scenario 1 (SC1) is characterized by the occurrence of typhoons that hit late in the typhoon season, but no COVID-19 shock.
Scenario 2 (SC2) is characterized by the COVID-19 shock (no typhoon).
Scenario 3 (SC3) considers the case of the COVID-19 shock followed by a low-impact (mild) typhoon that occurs late in the typhoon season.
Scenario 4 (SC4) considers the case of the COVID-19 shock followed by a high-impact (strong) typhoon that occurs late in the typhoon season. COVID-19 scenarios were based upon actual data available for the countries at the time of the study. The impact of natural hazard is estimated as relative loss of capital stock by economic sector, based on a fitted Findex damage function relevant to the country, calculated by using World Bank in-house catastrophe risk models. For a comprehensive discussion of scenarios design and analysis, see Dunz et al.[36] for Mexico.

The second step is to qualitatively and quantitatively analyze the transmission channels from pandemic and natural hazard risks to the agents and sectors of the real economy and to the banking sector, including the implications on firms' lending conditions and cost of capital, and the subsequent impact on the economic recovery. This combined analysis of empirical evidence from (in this case) the current pandemic and climate-related shocks, as well as evidence from the empirical and model-based macroeconomic literature, identify and characterize the most relevant transmission pathways in terms of the materiality of their outcomes. We find that such analysis of transmission channels is an essential step to fully understand where feedbacks between different types of shocks can lead to cascading impacts that can cause severe economic disruption and macro-financial impacts (Figure 2). Such analyses are essential for scenario construction but can also enable decision makers to identify where to intervene to reduce impacts and prevent shocks escalating into crises.

In the final step, we provide a macroeconomic and financial risk analysis of the scenarios by using the EIRIN macroeconomic model.[35,37] For this analysis, we focus on the role of governments' policies (fiscal spending) in the aftermath of the pandemic and natural hazards, analyzing the conditions for its effectiveness on the economic recovery, as well as the analysis of the interaction of credit and labor market constraints with the effectiveness of government spending. This analysis can inform recommendations for the design of economic and financial policy to strengthen resilience as part of COVID-19 recovery.

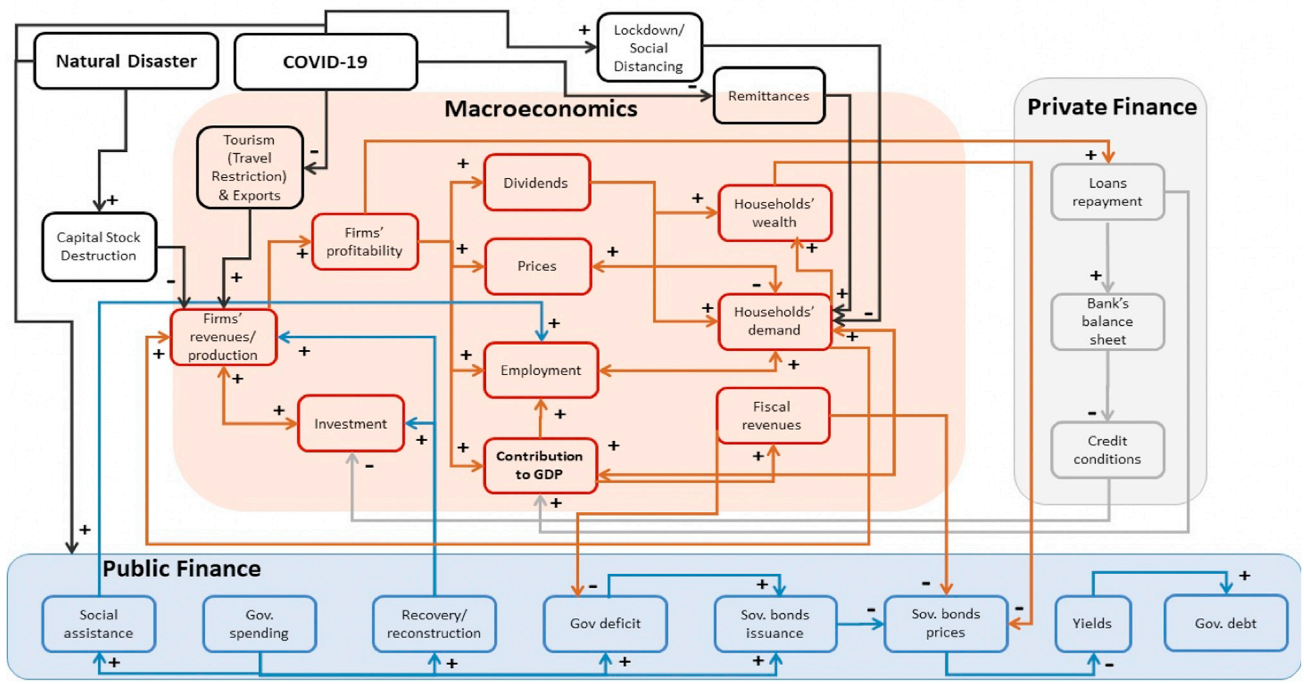


Figure 2. Compound risk transmission channels

The COVID-19 and natural hazard shock entry points (black lines) and transmission channels to the main variables of the real economy (red), public (blue), and private finance (gray). A directionality is indicated for each arrow: a positive sign indicates that the variables comove in the same direction (either up or down, i.e., an increase in A leads to an increase in B), and a negative sign indicates that the variables comove in opposite directions (an increase in A leads to a decrease in B).

Modeling the macroeconomics of compound risks

An important challenge identified during this research was that the current standard economic toolkit is not well suited for analyzing the economic, fiscal, and financial impacts of compound shocks. In the last decade, research in macroeconomics and finance has extended to consider climate change and systemic financial risks, as well as their transmission channels and impact on the real economy. However, the compounding of shocks of different nature (e.g., pandemics, climate change, financial instability) represents a new type of risk for macroeconomic research, policy making, and financial regulation. Compound risk represents a structural change in the economy and its implications cannot be simply deduced by the sum of individual risks. Indeed, when risks interact, they can give rise to non-linear dynamics in the economy and financial systems, generating a prolonged out of equilibrium state of the economy. Individual "agents," people, firms, and investors, behave differently in these circumstances. Deep uncertainty about the outcomes makes decision making more difficult for individuals and policy makers. This, in turn, contributes to increase uncertainty for firms and investors. When agents are uncertain about the impacts of the compounding shocks, and about the outcomes that will prevail, they cannot have perfect foresight. Risk averse firms will consequently delay the investment decisions, whereas risk averse banks will tighten firms' access to credit, by revising the cost of debt upward. This means that public policies aimed at restoring economic and financial stability will be less effective because their economic signaling might be weaker in the face of the uncertainty. Considering these dynamics is important because they can lead to long-lasting effects and slow recovery (*hysteresis*).

Recent research also highlighted the limitations of traditional macroeconomic and financial risk approaches to analyze the non-linearity and complexity of climate-related risks, and the implications of using traditional approaches for policy recommendations.[38,39] For instance, macroeconomic models commonly used by Ministries of Finance and Central Banks, such as the Dynamic Stochastic General Equilibrium (DSGE) models, typically assume that agents have rational expectations, that hysteresis plays no role, and that the evolution of the economy is driven primarily by exogenous shocks. Although some DSGEs have started to incorporate individual actors and more endogenous factors (e.g., money creation by banks),[40] they mostly relegate it to short-term "financial frictions,"[41] without considering the potential for long-term build-up of economic and financial fragility. Recent research shows that embedding investors' expectations and risk perception is crucial to avoiding underestimating risk.[42,43]

This is highly relevant in the context of compounding climate change and pandemic risk, for which we need models that are flexible enough to consider different high-end climate and compound risk scenarios, endogenously generated demand and supply side reactions, and a realistic representation of financial markets.[36] In this regard, stock-flow consistent (SFC) agent-based models have emerged as one important class of models for this type of problem, in that they can endogenize the climate-economy-finance feedback. The EIRIN model is applied here for this reason. Further work is needed to compare and refine models to strengthen the toolkit for compound risks.

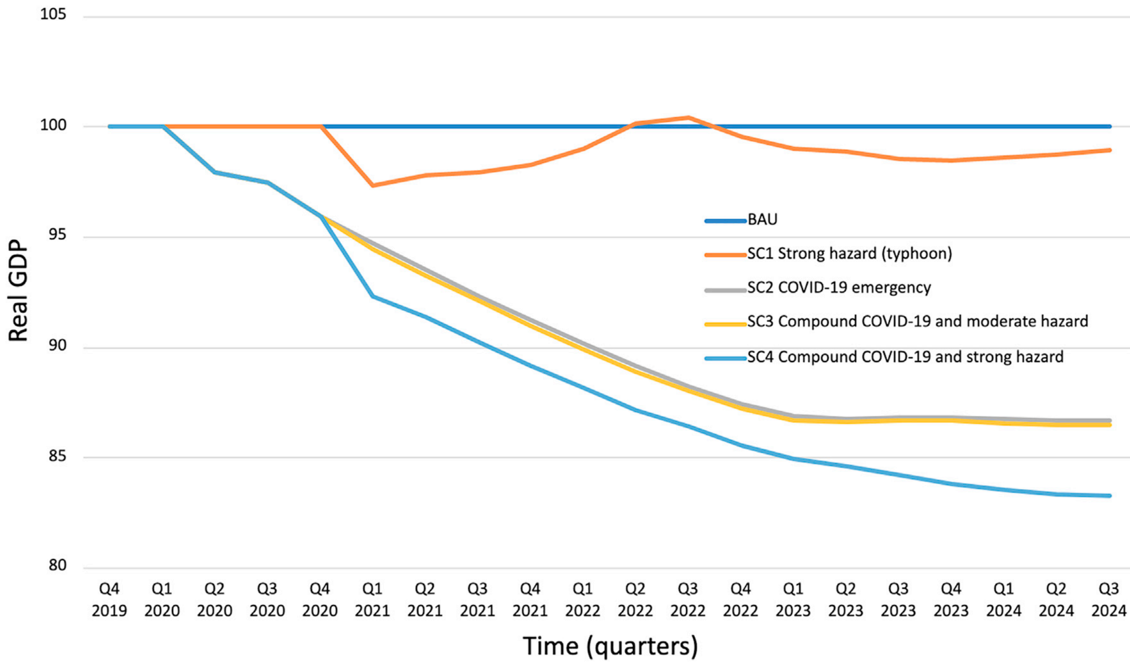


Figure 3. Real GDP indexed against the business-as-usual scenario for different shocks
Orange indicates a strong typhoon. Example: EIRIN model for a large middle-income country. The COVID-19 shock is assumed to begin in Q1 2020 and the typhoon in Q4 2020. BAU, business-as-usual.

INITIAL RESULTS: THE ECONOMICS OF COMPOUNDING SHOCKS

A primary conclusion drawn from this analysis is that, when pandemic and extreme weather events combine and interact within an economy, they generate non-linear effects that can amplify losses significantly. Indeed, the total impacts can be *larger* than the sum of the individual shocks. Figure 3 provides an illustration of the impacts of compounding shocks on GDP for the scenarios outlined in Figure 2, index against business-as-usual.

Pandemics and disasters have different direct impacts. However, by impacting simultaneously on firms' production and household demand, indirect impacts are amplified. For example, both shocks impact on firms' expectations and investment decisions. This, in turn, can increase unemployment, reduce wages, and reduce household welfare, creating a reinforcing feedback on demand, so amplifying the indirect economic impact. This can lead to long-lasting negative socio-economic effects on both firms and people and slowed growth and recovery.

This has played out in reality. For example, in Morocco, drought occurred concurrently with the pandemic, leading to major increases in unemployment among rural communities as lower-income farmers struggled to find work.[44]

We can measure this compounding effect as a CRM (Figure 4) and in this study find that it can peak at over 150%; that is, indirect impacts that can be 50% larger than the scale of the sum of the individual shocks.

But this is not one size fits all. This was evident even from comparing the findings from two middle-income countries. The transmission channels and drivers of feedbacks are risk and country specific and can combine in different ways. As illustrated in Figure 4, the scale and timing of the amplification looks different between different countries depending on the structure of the economy, the timing and nature of the shock and different vulnerabilities. In the example above, for both representative countries A and B, both large middle-income countries, GDP is strongly related to investment and capital stock is working close to capacity, so disasters can have a large indirect impact by damaging capital stock, disrupting economic activity and reducing investment. Both a disaster and a pandemic impact on production and investment so the compound effect is large. For country A, the flood shock is more prolonged. Similar risk amplification behavior was observed for Mexico in parallel research.[36]

Implications for government balance sheets

For governments, compounding shocks have implications for both sides of the balance sheet. They amplify the economic impacts of individual shocks and so impact on government revenues harder and for longer. They also increase government expenditure post-disaster, particularly in areas like social protection and recovery finance for micro-, small-, and medium-sized enterprises. In our preliminary work, debt to GDP ratios would be higher than the sum of the individual shocks (Figure 5).

Linking fiscal to financial sector resilience

We also explored the role of the financial sector in wider economic resilience to crises. Access to credit is critical during the recovery phase to enable investment in rebuilding lost assets and helping to cover lost revenues related to business interruptions. Yet, in the aftermath of a major shock, without action, credit can be constrained as banks respond to increased risks of default and withdrawals. The EIRIN model can represent these

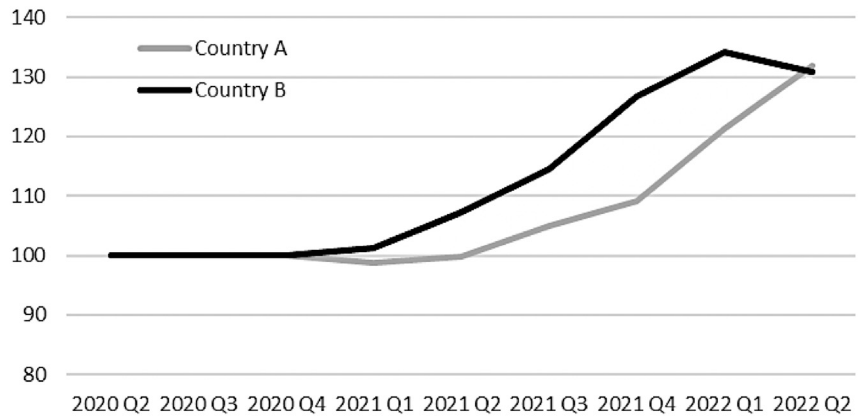


Figure 4. Compound risk multiplier for two example middle-income countries

One country is exposed to a flood shock (country A) and the other a typhoon shock (country B) during a pandemic. The compound risk multiplier is computed as the ratio between the GDP loss in the compound risk scenario and the sum of GDP loss in individual pandemic and climate risk scenarios. When the compound risk multiplier is higher than 100, this indicates non-linearities emerging that cause the shock triggered to be higher than the sum of the individual shocks.

effects and shows how the impact of compounding shocks can be significantly amplified in a situation where credit is constrained, even if public expenditure is high. Figure 6 shows the impact of the compound shock on GDP under different credit constraints.

For Ministries of Finance and Central Banks, this underlines the link between fiscal and financial sector resilience—both are necessary to ensure economic resilience—as seen in the current pandemic[13] the public sector has performed a critical role in providing quick liquidity. This reemphasizes the importance of instruments such as contingent credit lines and partial credit guarantees as part of the wider disaster risk finance arsenal of governments; and the advantages of having such mechanisms in place ahead of a disaster to ensure rapid response in emergencies.

For governments, this also underlines that government balance sheets are absorbing a large part of the financial impact of compound shocks, well beyond the direct impacts often considered within current disaster risk financing strategies, such as emergency response, social protection, and reconstruction of public assets.[10] Implicit contingent liabilities from shocks like financial crises, natural disasters, and pandemics can create some of the largest fiscal risks to government balance sheets;[16] we demonstrate there that, in reality, such shocks cannot be considered in isolation.

Governments are beginning to respond to this. For example, the July 2020 report of the UK's Office for Budgetary Responsibility concluded that "it seems implausible that the financial sector could ever be totally resilient to extreme events such as a major pandemic … the Government's future fiscal strategy will need to take account of this risk."[45]

Our findings highlight the need to understand and assess these risks and put in place appropriate policy and financial mechanisms to enhance resilience. The starting point, however, is to assess the risk.

INITIAL CONCLUSIONS FOR BUILDING BACK STRONGER

This analysis is a first attempt to better understand the fiscal and economic impact of compound shocks. Our results suggest that ignoring the potential for compounding risks could be a major blind spot as we build back stronger. Compound risks are not uncommon and amplify the impacts of individual shocks markedly. This underlines the urgency of accounting for compounding shocks within fiscal and financial risk management frameworks and crisis risk management more broadly.

These results also underscore that fiscal resilience—the resilience of government budgets—and financial resilience—the resilience of financial markets and the economy—are interlinked. Both need to be considered in tandem to ensure macro-level resilience and sustainable development.

Economic and financial risks, climate change, environmental damage, and pandemics are all interconnected. Ignoring these interlinkages and their compounding effects limit long-term resilience and effective policy making and financial risk management. Building back stronger means taking a more integrated approach to risk management. Given the significant investment being made by countries in recovery from COVID-19, now is the time to address these risks to ensure our resilience to future complex, systemic crises. In agreement with Battiston et al.,[46] we argue that strengthening resilience against future pandemics, as well as climate shocks, will require resilience-aligned COVID-19 recovery measures, and the framework we propose could be an operative approach to do it. Indeed, ignoring these risks now and focusing only on short-term "business-as-usual" measures to COVID-19 recovery might jeopardize the mid- to long-term sustainability.[46]

There are still many open questions to be addressed, both in terms of the science and economics of compounding shocks and their financial and policy implications. Not tackled here, for example, are important questions of how risks are amplified globally through patterns of global trade, including importantly food systems,[47] and how shocks will interact with longer-term growing pressures on our social, economic, and natural systems resulting from chronic changes in climate and environmental degradation. We have also only addressed risk in economic and financial terms, when the social and welfare aspects are equally important for decision making. There could also be important applications to understanding compounding effects with environmental degradation and nature loss[48] that require further exploration. Further work is needed to critically assess the scenarios and economic modeling toolkit for operational applications. Addressing these questions requires a multi-disciplinary approach, in particular bringing together both scientists from multiple disciplines, economists, and macro-financial expertise.

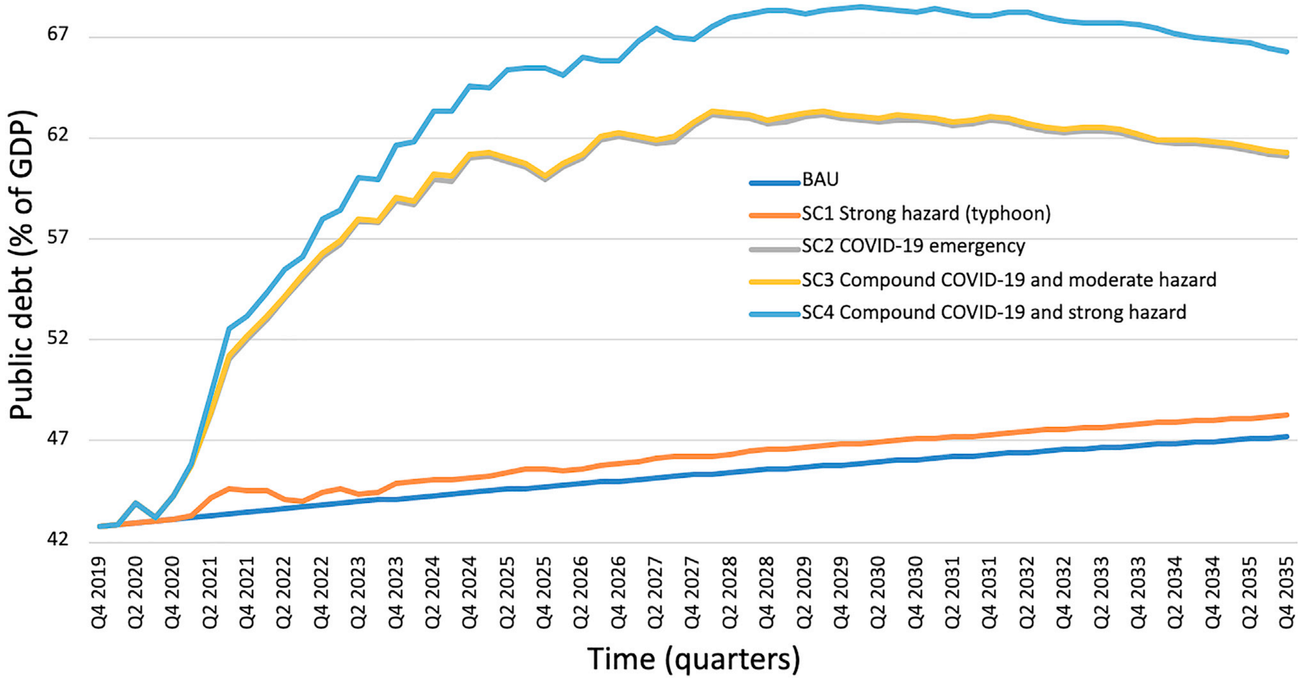


Figure 5. Debt to GDP (15 year timespan)
The x axis shows the timeline of the simulation until 2035 on a quarterly basis. The y axis shows the public debt to nominal GDP ratio.

The initial framework presented can complement standard approaches to developing future climate and impact scenarios, such as the SSP-RCP framework[49] and those of the Central Banks and Financial Regulators' Network for Greening the Financial System[50] with an added capability to assess the impacts of complex, compounding shocks linked to or happening in parallel with climate change. Specifically, existing climate scenarios could be combined with compound risk scenarios to generate a more integrated long-term risk assessment suitable for longer-term planning and decision making. Generating future scenarios would extend applications to areas such as climate-financial risk assessment and longer-term adaptation and resilience planning. Indeed, the World Bank and IMF recently already piloted such an approach in their Financial Sector Assessment Program.[51]

This analysis has also raised many important questions about the policy responses and role of financial instruments in mitigating such risks that are not addressed here. For example, what does this mean for the design of climate-resilient financial instruments, such as insurance, to better manage these risks? What are the implications for critical systems resilience, such as infrastructure systems? How can we embed these risks within investment decision making to help catalyze more investments in resilience?

This perspective also raises important questions for Central Banks and private financial institutions in considering climate (physical) financial risks.[25,52,53] How do we take account of such compounding risks within climate-related financial risk assessments? So far, shocks and stresses, such as pandemics, economic crises, and climate change, are typically considered in isolation in climate-financial risk assessment, although this has been recognized as a potential challenge.[48] Current financial supervisors' guidance on climate-related financial risks does not yet consider how climate-related risks could interact with other shocks.[54] Are we missing potentially important drivers of future risk by considering climate change in insolation? Experience and the demonstration provided in this perspective would suggest that this needs further exploration. Similar issues have been raised by others, including Chenet et al.,[55] which call for a more precautionary approach in view of the nature of the risks. But, could the impacts of physical climate-related shocks hit earlier and harder than expected because of amplifying effects as climate interacts with other risks? This important question requires further attention.

Developing simple, yet realistic, scenarios and metrics in economic and financial terms could be a meaningful first step to start answering each of these questions. Integrating such scenarios more explicitly within fiscal and financial risk management frameworks will contribute to enhanced resilience that could help to avert future crises, as well as to incentivize economy-wide investments to reduce risks.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources by qualified researchers should be directed to and will be fulfilled by the lead contact, Irene Monasterolo (irene.monasterolo@wu.ac.at).

Materials availability

This study did not generate new unique materials.

Data and code availability

This paper does not report original code.

.All data inputs to the model methodology are available in the public domain (World Development Indicators DataBank, with other sources as outlined in Dunz et al.[36]). Model outputs are third-party owned (World Bank).

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

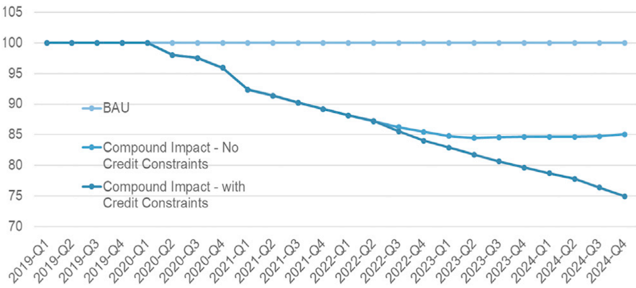


Figure 6. Illustrative example of real GDP indexed against the BAU scenario for a compound shock (typhoon plus COVID) under different credit constraints

This illustrates that, when credit constraints are strong (represented by a high regulatory CAR requirement—95% of bank CAR) the impacts of a physical climate shock on GDP are substantially amplified and more persistent (versus lower regulatory CAR—75% of Bank CAR). Such credit constraints could be generated by high demand for credit, changing policies by banks or changes in regulation.

Model framework

We tailor the macroeconomic model EIRIN[33,35] to quantitatively assess scenarios of individual climate physical (e.g., hurricanes, droughts) and COVID-19 shocks, as well as scenarios of compounding shocks, on macroeconomic aggregates (e.g., GDP, unemployment, investments) and financial variables (e.g., banks' leverage). EIRIN is an open economy macroeconomic model composed of heterogeneous agents and sectors of the real economy and finance that are represented as a network of interconnected balance sheets to increase model transparency and accountability. As a SFC model, every agent is represented by its balance sheet items, calibrated on real data (when possible), making it possible to trace a direct correspondence between stocks and flows in the economy and finance. The stock-flow consistency of the EIRIN model ensures that all the variables are initialized in a coherent way from the accounting perspective. The SFC nature of the model makes it possible to trace a direct correspondence between stocks and flows in the economy and finance, and their changes as result of exogenous shocks (e.g., natural disasters) and endogenous shocks (change in policy and financial regulation, change in investors' expectations).

EIRIN's agents are endowed with behavioral characteristics proper of agent-based models. Agents' behavioral decisions are based on empirical information and heuristics and can form adaptive expectations on the basis of historical information and risk perception. These solutions allow us to smooth strong assumptions of macroeconomic models (e.g., perfect foresight, forward-looking expectations, representativeness) and "everyone knows" that are assumed to hold true despite they are not showed by reality,[56] increasing the ability to reproduce real world dynamics.

Furthermore, not being constrained to solve to equilibrium, EIRIN explores the dynamics that drive the economy out of equilibrium and its persistence in cases of hysteresis, thus supporting the analysis of non-linearity and its impact in complex socio-economic systems noted above. This is particularly important immediate aftermath of a compound shock. These characteristics are fundamental to analyze not only the costs but also the co-benefits of climate change and policies, as well as the winners and losers from financial markets' performance.

EIRIN explicitly models money and finance, considering endogenous money creation, to capture the dynamics of amplification of financial distress, and the deriving distributive effects (inequality). The dynamics of the model are controllable, and the model is computationally efficient (i.e., a calibrated country model can be run on a laptop, including sensitivity analysis).

However, being a simulation model, it is not indicated for punctual forecasting exercises. As such, EIRIN can complement other types of macroeconomic models that are more attuned to represent longer-term, global-scale implications of shocks.

The original version of the EIRIN model[33] was developed to assess climate transition risk, and has been extended to analyze the characteristics and transmission channels of climate physical risk and pandemics risk. For a full description of the model structure, of the accounting and behavioral equations, as well as balance sheet and transaction flow matrices, and calibration, readers can refer to Dunz et al.[36] and Gourdel et al.[57]

First, we initialize the EIRIN model, focusing on the setting of parameter values that we use in the simulations, and we calibrate them at the country level, considering the characteristics and real data (national accounts) of a specific country (last 5 years) to ensure that the model and shock dimensions are quantitatively meaningful. Then, we use EIRIN to (1) identify and track the individual and compounding risk transmission channels from climate change and COVID-19 to agents' balance sheet items, (2) the implications of shocks on agents' behavioral responses, and (3) their impact on emerging macroeconomic dynamics. By embedding heterogeneous agents and sectors of the economy and finance, the model allows the analysis of the interplay between public and private finance and policies and firms' response during the shock itself, and the sensitivities. Finally, we exploit the added value of EIRIN being a simulation model to perform sensitivity analyses and test how the key model's parameters impact on relevant model outcomes. By testing different parametrizations we strengthen the robustness of the model, and we capture relevant dynamics and, to understand the role that market and scenario conditions, as well as model assumption, play in the outcomes. Model performance is validated against historical disaster damages for the two countries and were compared with COVID-19 GDP impact projections from the IMF and World Bank for those countries.

EIRIN agents and sectors

The EIRIN economy is populated by heterogeneous sectors and agents, including a working class sector; a capitalist household sector; a labor intensive consumption good producer (service sector); a touristic sector; a capital intensive consumption good producer; a capital goods producer; an energy company; a bank; a central bank; a government, and a foreign sector.[35,37]

EIRIN markets

EIRIN's agents and sectors interact with each other and with the foreign sector through a set of markets: consumption and capital goods markets; labor market; energy market; raw materials market; bonds market; and credit markets. The formation of demand, supply, and prices in each market (except for the credit market) are independent from each other at any given simulation step. In the credit market, demand depends on the demand for capital goods. The demand rationing affects the effective demand of capital goods by the consumption good producers (labor and capital intensive), and by the energy company. In each market, the prices are made by the supply side as a mark-up on unit costs, whereas in the financial market the sovereign bond price is determined on the basis of the existing stock of public debt, and on the performance of the real economy.[36]

EIRIN sequence of events

The sequence of events occurring in each simulation step is the following:

1. Policy makers take their policy decisions. The central bank sets the policy rate according to a Taylor-like rule (adapted to out of equilibrium models that do not consider NAIRU). The government adjusts the tax rates on labor and capital income, on corporate earnings, and on value added to meet its budget deficit target.
2. The credit market opens. The bank sets its maximum credit supply according to its equity base. If supply is lower than demand, proportional rationing is applied and prospective borrowers (i.e., the consumption goods producers and the energy company) revise down their investment and production plans accordingly.
3. Real markets open in parallel. Prices of the exchanged goods or services are determined, the nominal or real demand and supply are provided by the relevant agent in each market. Finally, transactions occur generally at disequilibrium, i.e., at the minimum between demand and supply.
4. The sovereign bond market opens. The capitalist household and the bank determine their desired portfolio allocation of financial wealth on sovereign bonds. The government offers newly issued bonds to finance a budget deficit, which includes the COVID-19-related expenditures. Then, new asset prices are determined.
5. All transactions and monetary flows are recorded, and the balance sheets of the agents and sectors of the EIRIN economy are updated accordingly.

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AUTHOR CONTRIBUTIONS

Conceptualization, N.R., I.M., and O.M.; methodology, N.R. and I.M.; supervision, O.M.; formal analysis, N.R. and I.M.; writing – original draft, N.R. and I.M.; writing – review & editing, N.R., O.M., and I.M.; resources, I.M.; validation, I.M.; funding acquisition, O.M.

DECLARATION OF INTERESTS

N.R. and I.M. contributed to the World Bank research project upon which this perspective draws in their capacities as consultants to the World Bank.

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