Global Monitoring of Upstream Determinants of Health Emergencies

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INTRODUCTION

The increasing number of disease outbreaks in the last 50 years, and, most recently, the devastating consequences of the COVID-19 pandemic, have shed light on the multi-faceted dynamics of health emergencies from infectious threats that defy overly simplistic and narrow conceptions of risk and countermeasures. The COVID-19 pandemic has demonstrated a myriad of shortfalls in global preparedness to confront pandemics, in large part owing to skews in science and policy that overlook foundational structural forces shaping health and wellbeing. In response, there has been growing awareness of broad array of challenges such as: info-tech mediated misinformation, mistrust in science, and vaccine hesitancy; racial and socio-economic clustering of risk; occupational insecurity and informality; medical industrial structures that distribute goods based on ability to pay rather than on need; and the dangerous convergence of agriculture/livestock practice, climate change and microbial unification. In view of their importance in the current pandemic and their likely importance in future events, there is an important opportunity now to make sure this broad spectrum of issues no longer remains on the fringes of pandemic risk frameworks and our monitoring and surveillance systems.

Creating a healthier world, one that addresses foundational forces and broader determinants of health, is creating a world that is better able to prevent, prepare for, respond to, and recover from health emergencies. This report is in direct response to the need to better identify and understand these foundational and dynamic forces, as well as the measures that are currently in place – or missing – to monitor them.

At the request of the Global Preparedness Monitoring Board, this report aims to strengthen efforts to manage the risk of infectious disease health emergencies by incorporating upstream determinants of health and health equity more centrally to pandemic risk management. More specifically, this report presents initial thinking in identifying relevant variables that may play a significant role in a risk monitoring framework for infectious health emergencies across the spectrum of prevention, preparedness, response, and recovery (PPRR), with an explicit focus on broader or more upstream determinants[1] across five pillars: social, technological, economic, environmental and political. The focus on upstream determinants exclusively is deliberate, as further downstream determinants related to health systems and front-line prevention and care are the focus of work being undertaken by another team.

Objectives

The objectives of this project are three-fold:

- Identify relevant determinants of health emergencies across social, economic, political, environmental, and technological pillars;

[1] "Broad" and "upstream" are used interchangeably to describe the more structural and macro-level variables that exacerbate risk.

- Assess available indicators of these determinants in terms of their measurability and other prioritization criteria;
- Provide recommendations on how pandemic risk management models spanning prevention, preparedness, response and recovery (PPRR) can incorporate these determinants with a view to promoting more equitable outcomes.

Frameworks

Social Determinants of Health

The social determinants of health (SDH) Framework[i] (Figure 1) developed by the WHO Commission on Social Determinants of Health in 2008, provides a good entry point to understand the broader factors that shape risk related to health emergencies. The SDH framework factors in the unequal distribution of opportunities for health arising from structural and systemic forces that stratify risk inequitably across populations. The structural and social determinants of health therefore differentiate levels of exposure to risks, and shape downstream or more proximal determinants such as individual material circumstances, behavior, biological, and psychological factors. The resulting social hierarchies in risk are closely associated with the widespread observation that constituencies that cluster in the lower rungs of the ladder most often face significantly greater risks and worse outcomes.

These systemic inequalities permeate infectious diseases risk as has been seen in the COVID-19 pandemic as well as other infectious diseases emergencies. For example, equity concerns with respect to vaccine coverage for COVID-19 are not simply a short-term supply side failure, but rather a reflection of a broader set of structural factors that characterize the inequitable skew of the global pharmaceutical industry, the design of intellectual property regimes, the purchasing power of low-income countries, and the segregated distribution mechanisms. Addressing these issues transcends the window of an acute emergency and extends to the medium and longer-term actions that will promote more equitable access to life saving commodities at the time of a future emergency.

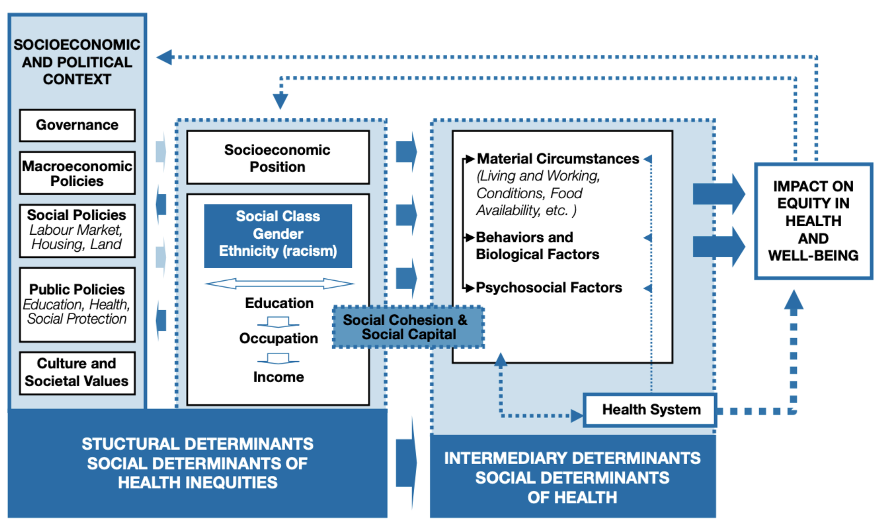


Figure 1. WHO Commission on Social Determinants of Health Framework

STEEP Framework

Building on the SDH framework, this report embraces a broader set of determinants organized by the acronym "STEEP": Social, Technological, Environmental, Economic, and Political. This framework is employed in many scenario planning exercises and has previously been used to analyze drivers of infectious diseases such as Ebola in West Africa. Definitions of each of the five "pillars" of the STEEP framework is a daunting task and can vary substantially depending on the purpose of the exercise. For this report, rather than attempt a comprehensive mapping of the economic or technological pillars, we opted to identify indicative areas within each pillar emerged from the various literature reviews and the consultative process with experts. More specifically, the working definitions for each of the five STEEP pillars are as follows:

- the social pillar draws on the social determinants of health framework (Figure 1) including well-established systemic barriers to health such as dominant gender, poverty, racism, limited education, food insecurity, malnutrition and inadequate housing;
- the technological pillar includes the medically-oriented innovation industries including R+D as well as communication and transportation sectors;
- the economic pillar considers descriptors of the economy in terms of growth, employment, income distribution, public sector expenditure, as well as other economic influences on health;
- the environmental pillar includes dimensions of the physical and built environment such as air, water, sanitation, temperature, housing, workplace and recreational spaces as well as the intersections with land-use and the agro-forestry sector; and
- the political pillar assesses the governance environment including policies, laws and regulations at different levels including public perceptions of trust and accountability.

While the STEEP framework is helpful in pointing to the wide array of broader determinants that need to be considered from a pandemic risk perspective, the breadth of each of the pillars i.e., economic, or technological, is so broad that they defy practical sub-frameworks that facilitate comprehensive assessment. From a bottoms-up perspective, literature reviews tend to raise broader determinant variables linked to pandemic risk that may not necessarily have a direct connection to a specific STEEP pillar but rather encompass them, e.g., inequity as a factor of risk. This renders meta-analysis, or review efforts, such as this scope of work, quite limiting when attempting to identify evidence that would be useful for a more technical audience.[ii] Nevertheless, STEEP offers a helpful preliminary framework for identifying some of the possible variables for monitoring broader determinants of risk.

Drivers and Amplifiers

Although it was suggested we consider a linear framework of pandemic risk from spillover to outbreak to pandemic that categorizes broader determinants into drivers (incubators, accelerators, and disseminators) and amplifiers (Figure 2), we did not find strong enough evidence from the literature nor the consultative process that supported this step-by-step model of risk. Attempts to distinguish the nature of determinants as either incubators, accelerators or amplifiers was conceptually ambiguous and therefore not pursued.

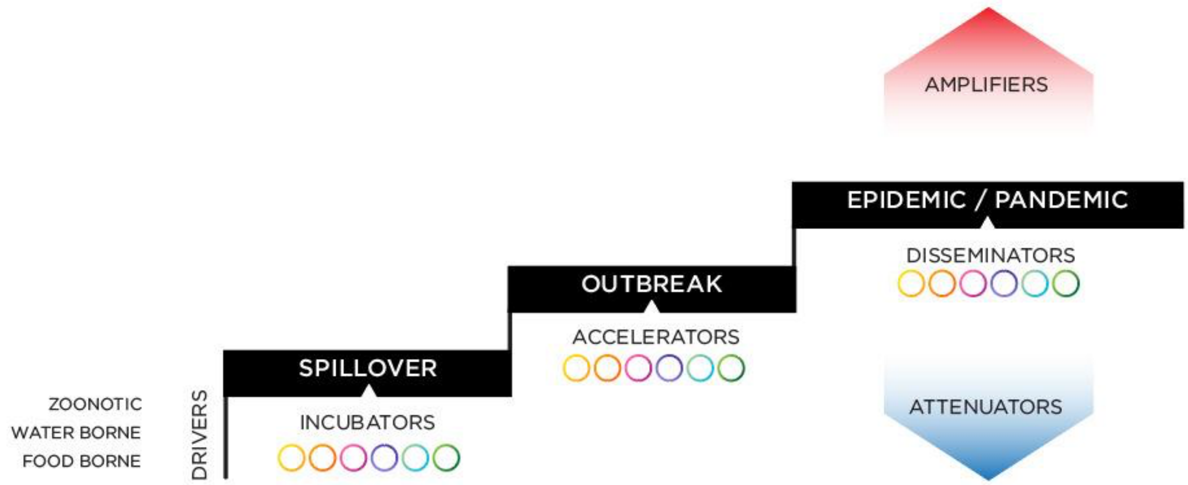


Figure 2 Understanding risk through drivers and amplifiers

Health Emergency Risk Framework: Prevent, Prepare, Respond, Recover (PPRR)

In the context of health emergencies, we have decided to define risk broadly across four discrete areas that follow the life cycle of an emergency: prevention, preparedness, response and recovery, or PPRR (Figure 3). These four areas of risk are defined as follows:

- prevention refers to factors that decrease the probability of an event or an emergency occurring (e.g., spillover, climate action) and/or that reduce the severity of such an emergency, should it occur (e.g., water and sanitation management, food safety);
- preparedness refers to factors enhance that enhance local, national and international capacities to detect or respond to various forms of disease outbreaks or other health emergencies;
- response is defined as activities taken to react to an emergency or an outbreak/pandemic that bring it to an end more quickly and minimize its health and social impacts;
- recovery is defined as strategies enacted after the acute stage of an emergency or an outbreak is declared over to bring existing systems (health, and otherwise) back to baseline and to learn lessons to build more resilient capacity

This PPRR Framework[iii] is similar to other frameworks used for crisis management, and disaster risk reduction alike and captures the multi-dimensionality of risk. The framework also helps to curb the tendency to (over-) focus on the “response” or “recovery” dimensions of emergencies, and emphasize the relatively neglected yet important areas like prevention where broader determinants may be disproportionately important. The PPRR framework thus allows us to be more inclusive of our understanding of risk.

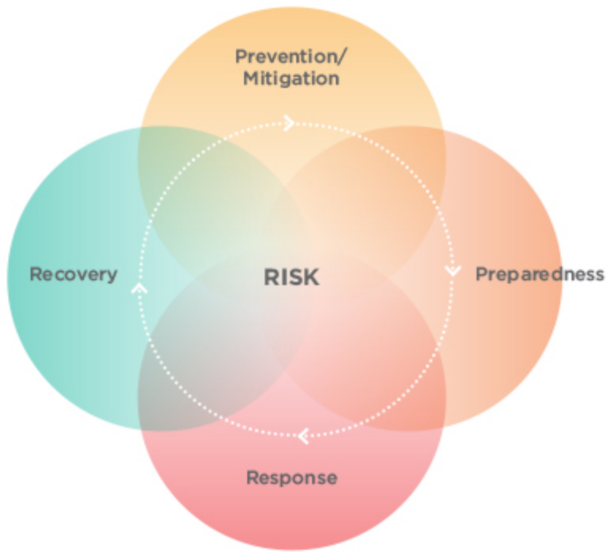


Figure 3 Health Emergency Risk Framework: PPRR

Taken together, these three frameworks, SDH, PPRR, STEEP, help conceptualize and frame some (but not all) of the important variables that interact with different dimensions of risk, but that may not be sufficiently integrated into our current assessment of risk. The SDH framework gives us some understanding of the unequal outcomes to structural factors, the STEEP framework pushes us to explore indicative areas within each pillar that are likely to be significant in risk monitoring, and the PPRR framework helps to keep the multi-dimensional landscape of risk in focus.

METHODOLOGY

Our methodology employs a four-pronged approach and involves: 1) a two-step review process of the literature on infectious-disease derived health emergencies consisting of literature scans and more formal rapid scoping reviews by STEEP pillar; 2) a review of COVID-19 models to identify upstream determinants and measurable indicators currently in use; 3) consultative exercises on broader determinants and pandemic risk with experts through a Delphi process; and 4) an iterative identification, triaging and filtering process of determinants and associated indicators across each of the pillars to move towards 40 broader determinants that bear on risk, as well as a parsimonious initial list of baseline indicators (a "Clean 15") that can be used for monitoring immediately.

Rapid review of literature

The rapid review of the literature consisted of two sections and was guided by the following research questions:

- What are the upstream factors that bear on pandemic prevention, preparedness, response and recovery?
- Why are these factors important?
- How can these factors be measured and monitored?
- What are the relative importance of these factors in terms of reducing risk?

The first part of the rapid review of literature consisted of literature scans iteratively conducted at the preliminary stage of the project to identify key determinants that may be associated with the risk of infectious disease threats. This was conducted via PubMed and the search of grey literature as well as drawing on the database of the Epistemonikos Foundation in Chile. The determinants identified from this scan were presented to experts during the Delphi process for additional input.

The second part of the rapid review consisted of five scoping reviews representing each of the pillars of the STEEP framework. Methodological details regarding the individual scoping reviews, their search strategies, and the results of the reviews are included in Appendix 5.

Rapid review of COVID-19 risk models

In order to identify measurable determinants (or indicators) related to the STEEP determinants, a rapid review of existing international and country-specific COVID-19 models was conducted. The following 6 models were identified from a systematic review of international forecasting models of COVID-19[iv] and assessed: 1) IHME 2) Youyang Gu; 3) DELPHI-MIT; 4) Imperial; 5) LANL-GR; and 6) USC SIKJalpha. We also assessed country-specific models that included the following 7 USA-based forecasting models: 1) JHU_IDD-Covid_SP; 2) DeepCOVID; 3) MOBS-GLEAM_COVID; 4)

Umich_RidgeTfReg; 5) Google_Harvard-CPF; 6) MIT_CritData-GBCF; and 7) JHU_CSSE-DECOM.

Delphi process

To triangulate findings and add additional context that may not have been captured or available in the literature, consultative exercises were conducted over the course of several months via a Delphi process. Team members identified experts with relevant areas of expertise in one or more of the pillars. More specifically, rapid literature scans led to the identification of relevant areas of expertise and appropriate experts, while ensuring geographic, gender, and sector (e.g., public, private, NGO, government) representation. The Scientific Advisory Group for the World Report on Social Determinants of Health Equity was used as a starting point to identify relevant experts, with snowball sampling used to select additional individuals. Formal expert input through surveys and interviews were conducted from December 2021 to March 2022. Validation of the final indicators and determinants were conducted thereafter until July 2022 with additional consultative exercises among pillar-specific experts.

During this consultative process, experts were requested to provide input on key determinants that had been identified during the literature review as well as others that had not emerged through the literature. Additional in-depth key informant interviews occurred with several experts from each pillar to further discuss the Delphi survey findings, the determinants identified (or missing), and how the determinants inform PPRR efforts to infectious disease threats. More specifically, the three phases in the Delphi process included:

- Phase 1. Identification of Experts
    - Identify relevant areas of expertise and experts, with geographical representation across all five pillars
- Phase 2. Assessment of Determinants
    - Experts validate and add to the consolidated list of upstream determinants identified through literature review
- Phase 3. Interviews with Select Informants
    - Experts discuss determinants in more depth, their relationship within the PPRR model, as well as important indicators

Process of identifying key determinants and filtering associated indicators towards the "Clean 15"

The scope of work from the GPMB explicitly asked that we identify an initial list of indicators broadly representative of the five STEEP pillars that could be used to monitor broader upstream determinants immediately. We utilized a multi-step identification, filtering and triaging process to develop this baseline list.

First, throughout the methodology (parts 1-3), important but complex determinants that increased risk of health emergencies emerged from the literature reviews, the review of models, and the Delphi process. We categorized these into 40 broad determinants across the 5 STEEP pillars. Concurrently, a master list of corresponding indicators that illuminate dimensions of these 40 determinants was also compiled. These 341 indicators, each associated with one of the 40 determinants, were gathered from the literature reviews, indicator databases, and through expert input. By definition, these indicators are meant to act as proxies to assess a dimension of the broader upstream determinants.

Next, to help guide our triaging process of the indicators, we developed a set of prioritization criteria (Table 1) that informed the filtering of the 341 indicators.

Table 1. Prioritization framework for triaging indicators

Criteria	Description of Criteria	Assessment
Scale appropriateness	Alignment between the scale at which the indicator is measured (i.e., global through local) and the scale at which indicator is used	High alignment
		Medium alignment
		Low alignment
Data availability	is this data currently collected? Is it available for all regions/nations?	Full coverage
		Partial/incomplete coverage
		Unavailable
Trust in data source	How rigorously is data collected and reported?	Highly trusted
		Moderately trusted
		Not trusted
Pathogen Specificity	Applicability of indicator to a particular pathogen, a subset of pathogens, or pathogen-agnostic	Pathogen-agnostic
		More relevant to certain pathogen classes than others
		Specific to pathogen or pathogen class
Proximal/Distal	How closely related is the indicator to risk of the health event? Far or near on the causal chain?	Proximal
		Intermediate causality
		Distal
Measurement difficulty		High quantifiability and feasibility

	Quantifiability combined with difficulty/feasibility of measurement	Low quantifiability but high feasibility
		High quantifiability but low feasibility
		Low quantifiability and feasibility
Actionability	The extent to which the indicator enables and informs data-driven actions to be taken	High actionability
		Medium actionability
		Low actionability
Modifiability	Responsiveness to action/ease by which the indicator can be influenced	Modifiable in the short-term
		Modifiable in the long-term
		Somewhat modifiable in the short-term
		Somewhat modifiable in the long-term
		Very difficult to modify

Each indicator from the master list of indicators was assessed for each of the eight criteria by at least two members of the research team. Large discrepancies in initial assessments were resolved through discussion in subsequent review. This exercise was not meant to be a quantitative stand-alone scoring exercise, but rather an opportunity for the research team to reflect on each of the separate components of the prioritization framework for every indicator in the master list, with a particular emphasis on data availability given GPMB's emphasis for immediate monitoring. The scoring and the insights collected during this process was complimented by the literature reviews, expert input, and research team discussions, which ultimately led to the selection of one indicator per broader determinant (n=40). This was done iteratively using team discussions, the information received during the Delphi process by experts, as well the evidence detailed by the scoping reviews and the assessment of COVID-19 models.

The final 40 indicators (one per determinant) were further filtered, using a de-duplication process that sought representation across pillars and that eliminated redundant, collinear, or irrelevant indicators given the reviews and the Delphi process in order to curate the final list of 15 indicators, a balanced "clean 15".[2] Expert judgment was also used to categorize indicators and determinants into the PPRR risk spectrum, illustrated with heat maps.

[2] This was initially initiated as the "dirty dozen" (12 baseline indicators) that transitioned iteratively into the "clean fifteen", as we felt that it was better to have at least three indicators for each of the five pillars.

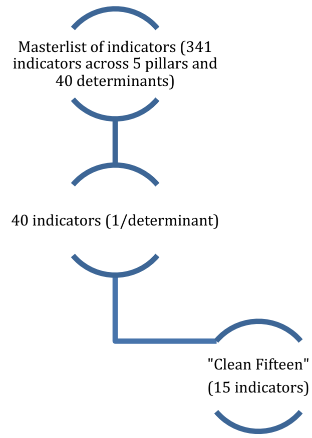


Figure 4. Process towards the "Clean 15"

Because the scope of work identified that a priority was rapid implementation for monitoring – the final list or “clean 15” placed special importance on prioritizing indicators with existing datasets across a multitude of countries, with reasonable data collection frequency to the extent possible. To acknowledge the measurement bias in the selection process of indicators that are quantifiable and widely available, the report – using the master indicator list and the scoring system - also identifies determinants that do not have readily measurable indicators, where efforts to strengthen measures and monitoring capacity are a priority.

An important caveat is that each determinant may not necessarily provide equal value in risk monitoring due to a variety of factors such as feasibility in monitoring, measurement imprecision, lack of proxies available to monitor, or lack of data sources altogether – a common occurrence within the technological pillar. Nevertheless, this report does a first pass at identifying baseline measures that can be monitored immediately, as well as measures that need to be monitored but do not have operationalization capacity at this time.

RESULTS

Figure 5 maps the methodology used and displays the distribution of determinants and indicators across STEEP. Triage 1 and triage 2 represent the two main stages of filtering of indicators using the iterative methodology described above. An important caveat here is that the absolute number of indicators prior to the triaging process does not necessarily indicate higher or lower importance of certain pillars over others with regards to risk; rather, the numbers represent the ease of availability of indicators, the breadth of the listed upstream determinants, and the study team's ability to find appropriate indicators to act as proxy for the respective determinants.

The supplemental information section of the report includes detailed results for each of the five scoping reviews (Appendix 5), the assessment of COVID-19 models (Appendix 3), the Delphi process (Appendix 1), and the pillar-specific definitions and reasoning for the upstream determinants (Appendix 2).

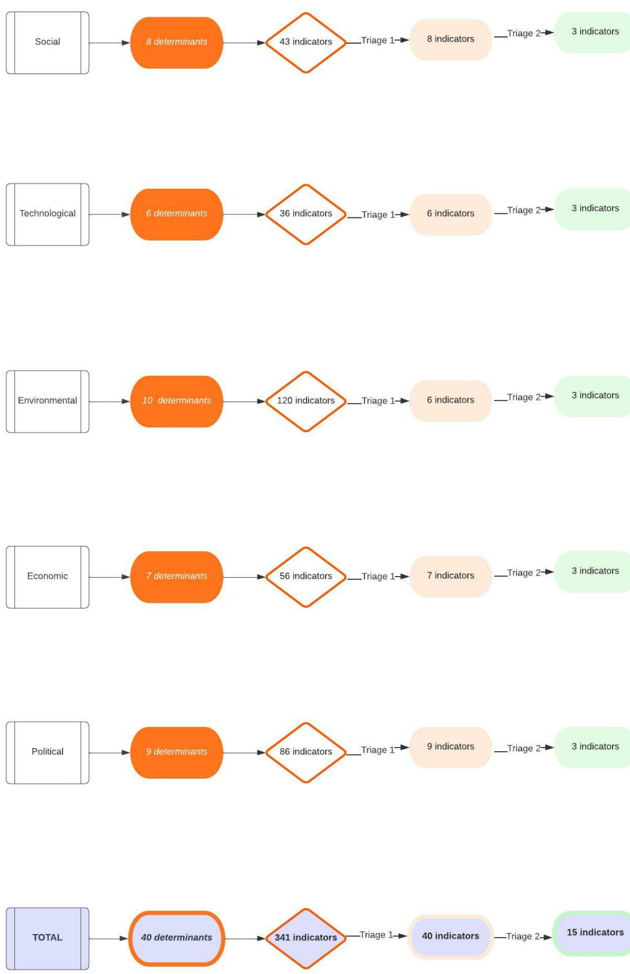


Figure 5. Mapping the process of identification of determinants and filtering of indicators across STEEP pillars

Final list of determinants and indicators

Taken together, findings from the literature reviews, the review of models and the Delphi process led to the identification of a discrete set of broad determinants (n=40) that spread across the STEEP pillars and that are thought to be important to monitor in order to manage risks associated with preparing for, preventing, responding to, and recovering from health emergencies (Table 2). Appendix 2 includes broader definitions of each of these determinants as well as the specific risk management context in which they may play a more substantive role. The master list of all indicators (n=341) associated with these 40 broader determinants are included in Appendix 4.

Table 2. The 40 STEEP upstream determinants

Social	Technological	Environmental	Economic	Political
Social inequity	Social media usage and misinformation	Meteorologic and Geographic Factors	Economic development	Governance
Racial/ethnic inequity	Technological infrastructure	Climate change and natural disasters	Economic inequity	Global health diplomacy and collaboration
Gender inequity	Digital connectivity	Air quality	Health system financing	Communications
Demographics	(Lack of) Biomedical innovations	Water, Sanitation, and Hygiene	Social program availability and financing	Political will
Underlying health status	Democratization of biotechnology	Food security, safety, and handling	Employment	Health Emergency Policies
Individualism	Interoperability of IT systems	Agricultural and farming practices	Economic interconnectedness	Systems and Institutional capacity
Human capital		Land-Use Changes	Supply chain	Public trust
Global mobility and connectedness		Human-wildlife interaction		Civic participation and advocacy
		Biodiversity		Conflict, instability, and violence
		Built environment		

Making sense of pillar-specific results

Using this large list of 40 determinants, the iterative filtering and triaging process was conducted to ultimately identify 3 indicators per STEEP pillar. To better understand how the fifteen indicators were selected, pillar-specific results are listed below. This process includes: 1) the framing of the pillar using the broader determinants that have emerged from the various inputs of our methodology (scoping reviews, expert consultations, review of models); 2) the triangulation of evidence and the rationale of filtering from the initial triage of indicators (Tables 3, 5, 7, 9, 11); and 3) the final selection of three indicators for each pillar (Tables 4, 6, 8, 10, 12) that contributed to the "Clean 15".

Social

The social dimension of risk was operationalized by borrowing the unequal outcomes to systematic and structural forces of risk observed in the SDH framework. Eight upstream determinants in the social pillar emerged as being important to monitor risk, several of which directly refer to directly to inequity including social inequity, racial inequity, and gender inequity. Underlying health status measured as under-5 mortality emerged reflecting its proxy strength as a societal measure of equity. The remaining determinants include: demographics related to age structure in the population (which may vary in importance depending on the pathogen); individualism, which speaks to the social cohesion of a society and its level of acceptance in sacrificing some individual needs for collective disease control; human capital that assesses the health and education stock of the population; and global movement and connectedness, an important factor in rate of spread of pathogens and risk-behaviors.

Table 3. Indicators for social determinants and filtering rationale

Determinants	Indicator	Evidence	Include in Clean15
Social inequity	Global Multidimensional Poverty Index	Yes Index assesses acute deprivation across health, education, and living standards, variables that play a significant role in risk. High evidence from both literature and experts demonstrating the role of social factors and social inequity – of which poverty is a proxy - that magnifies and exacerbates risk across all pillars for multiple pathogens (Zika, COVID-19, Dengue).	Yes Slight correlation possible with the climate change index which includes one aspect of social inequity, measured as the poorest quintile's share in national income or consumption. Additional investments in measuring inequity needed as there was no expert consensus on best measure. Even then, high evidence and consensus among all that this (pathogen-agnostic) determinant should be included, with additional thinking required to identify the most appropriate indicator.

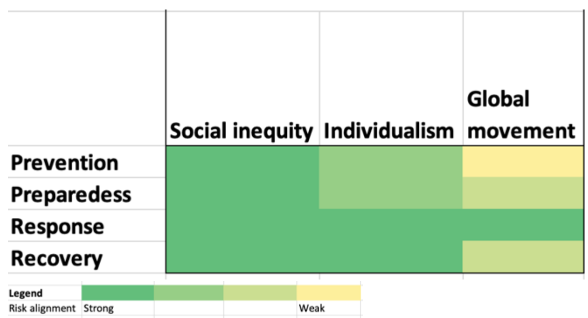
Racial/ethnic inequity	Life expectancy by racial/ethnic group	Yes Evidence demonstrating unequal COVID-19 outcomes (or other pathogen-specific outcomes) among certain racial communities over others.	No Social inequity captures many dimensions of racial inequity. GINI coefficient captures some levels of broader inequality. Better indicators to capture racial inequity needed.
Gender inequity	Gender inequality index	Yes Some evidence on women's increased risk due to employment and caregiving capacities, increased direct and indirect effect of risk (e.g., unpaid care, increased job loss). Mixed evidence from experts as to its relative importance compared to other determinants.	No Social inequity captures many dimensions of gender inequity. GINI coefficient captures some levels of broader inequality.
Demographics	Age Dependency ratio	Yes Age has been shown to be an important risk factor for COVID-19.	No While age is important for the COVID-19 pandemic, this may not necessarily be the case for others. Age is not necessarily pathogen agnostic.
Underlying health status	Under 5 mortality	Yes The health of a population - and access to care - does impact risk and recovery trends. Variation in under five mortality is likely to be an outcome of unequal distribution of risk and speaks to other structural health system barriers such as access to care.	No While the evidence is there, this determinant is likely an outcome variable due to inequities, and appears to be slightly more downstream, which is outside of our scope. In addition, there is high correlation with the inequity determinants.
Individualism	Individualism (Hofstede Index)	Emerging evidence in the literature of its importance, particularly when individualism incudes adherence towards non-pharmaceutical interventions as a component, which has direct risk implications. Expert input stressed the importance of social cohesion in risk, which can vary based on level of individualism.	Yes More explicit assessments of indicators for the opposite of individualism, e.g., social cohesion, are needed. Hofstede Index does not appear to update their data regularly. However, this is an important emerging (pathogen-agnostic) indicator that should be monitored more deliberately.
Human capital	Human capital index	Mixed While evidence on the components of human capital index as being important to risk exists, mixed evidence on the HCI itself in predicting risk. Multiple discussions with	No While important, uncertain evidence about its potential in predicting risk. Other indicators are arguably of more importance using evidence and expert input.

		experts and the study team led to downgrading the HCI.	
Global movement and connectedness	Inter- and intra-national mobility	Many of the COVID-19 models assessed as well as evidence (particularly from studies conducted early during the pandemic) include mobility as being an important risk factor.	Yes Strong evidence, pathogen agnostic, available data source.

The three social indicators selected for initial monitoring in the Clean 15 are listed in Table 4. As expected, because the social pillar represents the social fabric of a society, we envision that social determinants bear on all four dimensions of risk, with some variations in alignment between variables. For example, while mobility and individualism likely play a larger importance during the response stage (i.e., more movement increases risk, high individualism may increase risk through low adherence of non-pharmaceutical interventions), social inequity speaks to the social culture and cohesion, impacting all four PPRR dimensions.

Table 4. Social indicators included in the Clean 15 and their alignment with the four dimensions of risk

Determinant	Indicator	Level of measurement
Social inequity	Global Multidimensional Poverty Index[v]	Country (n=109)
Individualism	Individualism vs Collectivism (Hofstede Index)[vi]	Country (n=116)
Global movement and connectedness	Inter- and intra-national mobility[vii]	Country (n=135)[3]



The global multidimensional poverty index was selected as the most appropriate indicator to represent a dimension of social inequity. This indicator assesses three different areas, namely health (nutrition, child mortality), education (years in schooling, school attendance), and standard of living (cooking fuel, sanitation, drinking water, electricity, housing assets) as well as more explicit poverty dimensions (intensity of poverty, headcount ratio). There was strong consensus in the consultations on the imperative of including social inequity in the Clean 15 given the depth of the relationship between inequities and risk, though selecting the most appropriate indicator to measure a broad and complex social phenomena remains a challenge. In addition to the multidimensional poverty index, additional indicators mentioned during the Delphi process include human rights measures, the inequality-adjusted human development index, and differential health outcomes based on social class.

[3] Depending on the source of anonymized data, level of measurement can vary and can be collected at the individual, sub-regional, regional, or national levels.

The individualism index compares individualism – a loosely-knit social framework - to collectivism – a tighter knit social framework with higher social cohesion, whereby individuals look after each other, or are willing to go through personal sacrifices for a collective good (e.g., disease control). The Hofstede index does not appear to regularly update this data; however, because societal levels of individualism are unlikely to change rapidly, an absolute assessment is likely to be sufficient (e.g., cross-sectional monitoring at one time point). Even then, additional datasets or indicators that can better capture social cohesion – perhaps adherence to non-pharmaceutical interventions as a proxy – should be further explored.

Inter- or intra-national mobility refers to population movement within and across borders, which can directly exacerbate spread of a pathogen or risk-behaviors. The review of the COVID19 models suggests that anonymized data from technological companies (Meta, Google, Apple) are likely to be most accurate, and can be monitored frequently. A secondary indicator that can also capture this determinant would be the average number of domestic and international air travelers per day (International Air Transport Association).

Technological

The technological dimension of risk was broadly operationalized by assessing the strength of some innovation industries (biomedical, biotechnology), the availability of the technological infrastructure (including the interoperability of technological systems), as well as digital technology and communications (with upstream determinants assessing digital connectivity, and social media usage & misinformation). These six determinants attempted to capture a pillar that appears to have many data gaps, despite its emergence, according to experts, as a strong determinant of risk.

Table 5. Indicators for technological determinants and filtering rationale

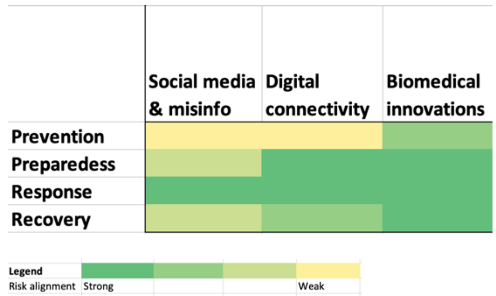
Determinants	Indicator	Evidence	Include in Clean15
Social media usage and misinformation	Number of monthly active social media users	Yes Highly favoured by experts to include in the final list. Literature also indicates that social media usage and misinformation plays a role in risk perception & perception of behaviour. Evidence demonstrates correlation between misinformation and increased cases.	Yes Correlated with digital connectivity but experts stressed the need to highlight misinformation specifically as an important driver of risk. Indicators assessing misinformation more explicitly need to be further investigated.
Technological infrastructure	Electrical grid capacity	Mixed Determinant is too broad – no direct evidence linking technological infrastructure to risk, though components of the infrastructure alleviate or worsen risk.	No Difficult to measure, correlated with an included determinant - digital connectivity - which is an important component of the technological infrastructure.

Digital connectivity (or digitization)	Internet Inclusive Index	Yes Evidence of digital access leading to greater access to services (e.g., telemedicine, digital economy, response to risk). Evidence on digital divide in terms of access to technology and internet and its consequences in terms of risk. Highly favoured by experts to include.	Yes Strong evidence, pathogen agnostic, available data source.
Biomedical innovations	Global innovation index	Yes Evidence that COVID-19 vaccines have saved 14.4 million lives in the first year, and continue to save lives.	Yes Strong evidence, pathogen agnostic, available data source.
Access & democratization of biotechnology	R&D expenditures (imperfect proxy) Other more specific indicators necessary but unavailable: number of bioweapon programs, ease and availability of material (e.g., for DNA synthesis)	Yes Emerging evidence on high biological risks due to human activities (accidental or intentional).[viii] Expert input identified this as an important high-risk driver needing immediate infrastructure for monitoring.	No Difficult to measure and monitor, unavailable datasets that can be used for immediate monitoring. Need additional investments to develop appropriate indicators and operationalize the monitoring. Some of this can be captured by the biomedical innovations determinant.
Interoperability of informational technological systems	Presence of AI infrastructure or machine learning capacity (More explicit indicator unavailable but needed.)	No No specific evidence linking this as this is more on the operational side of a (health data) system's functionality.	No Determinant speaks to the operational side which can speed up collaboration and response (e.g., data sharing agreements). Correlated with emergency policies and governance in the political pillar. Missing appropriate indicator/ dataset. Likely to be found in the "downstream" monitoring pathways.

Table 6 points to the three technological determinants and indicators included in the clean fifteen. The indicators capture different dimensions of PPRR, with biomedical innovations being important throughout, and social media and digital connectivity playing a larger role during crisis response.

Table 6 Technological indicators included in the Clean 15 and their alignment with the four dimensions of risk

Determinant	Indicator	Level of measurement
Social media usage and misinformation	Number of active social media users[ix]	Global[4]
Digital connectivity	Inclusive Internet Index[x]	Country (n=100)
Biomedical innovations	Global Innovation Index[xi]	Country (n=132)



We captured social media usage and misinformation by the number of active social media users, under the assumption that usage leads to exposure of misinformation. We suggest directly obtaining anonymous usage data from social media companies here to be most accurate but if the latter proves to be challenging, global measures are released annually by Statista.[5] We were unable to find an indicator and corresponding dataset that explicitly measured misinformation and urge the GPMB to further investigate and invest in this increasingly significant risk factor.. Measuring the credibility of social media posts was one approach mentioned during Delphi discussions.

The inclusive internet index assesses the accessibility and affordability of the internet – central to digital connectivity – through a number of indicators that measure use, connection quality, infrastructure, availability of electricity, cost relative to income and others. It also captures the extent to which the internet enables social and economic mobility through its “readiness” dimension, which measures whether communities are ready to be connected by using literacy, educational levels, existing web accessibility, privacy regulations, and national female e-inclusion as indicators. The dataset has been updated in 2022, with scores for 100 countries, representing 97% of the global GDP and 99% of the global population.

The Global Innovation Index (GII) is updated annually and assesses recent global innovation trends. Innovation is defined comprehensively across sectors and therefore includes a large list of indicators (n=81). Starting in 2021, it also includes a new Global Innovation Tracker section that provides an assessment of the impact of COVID-19 specifically on global innovation performance. More broadly, the GII includes a variety of indicators including scientific publications, R&D expenditures, international patent filings, and venture capital deals in the science and innovation investments among others.

Economic

The economic dimension of risk was operationalized by assessing some of the

[4] Depending on the source, data can be collected at varying levels of measurement (individual, regional, national).
[5] https://www.statista.com/statistics/278414/number-of-worldwide-social-network-users/

economic and financing factors with social structural influences on health, as well as other factors that determine health (health systems, governance etc.) Seven economic determinants have emerged as being important for risk monitoring, including several that directly assess the economic health of a society (e.g., economic development, economic inequity, employment). The remaining determinants assess the intersection of economic factors and health (e.g., health systems financing, and social program availability & financing to measure social protection spending) and the interconnectedness of the global economy (e.g., economic interconnectedness, and capacity of supply chain).

Table 7 Indicators for economic determinants and filtering rationale

Determinants	Indicator	Evidence	Include in Clean15
Economic development	GDP per capita	Yes Clear evidence from scoping review indicating multiple that linked risk of infection spread and/or transmissibility to GDP per capita or a country's wealth.	Yes Strong evidence, pathogen-agnostic, data source available
Economic inequality	GINI index	Yes Evidence that states higher GINI index had higher COVID-19 deaths, and that larger wealth disparity is linked to higher COVID-19-related mortality. Strong relationship between inequality and COVID-19 outcomes using GINI index based on the scoping review, and expert input.	Yes Note, poverty and inequality are distinct metrics, which is why both GDP per capita and GINI index made the final selection. Strong evidence, pathogen-agnostic, data source available
Health system financing	Total health expenditures (% of GDP)	Mixed Mixed evidence that higher per capita expenditure on health is associated with reduced risk of poor COVID-19 outcomes. Some evidence that health care planning and spending contributes towards social equity to decrease risk.	No Variable touches directly on the health system component and is therefore more downstream and outside of our scope. Correlated with other more upstream variables (e.g., governance).
Social program availability and financing (social protection spending)	Public health and social protection expenditure (% of GDP)	Yes Evidence demonstrating that public health spending is linked to decreases in poor COVID-19 outcomes (new cases). Experts stressed the importance of social protection mechanisms.	Yes Strong evidence, pathogen-agnostic, data source available
Employment	% Employment in the informal sector	Yes Emerging evidence that employment and social inclusion characteristics are	No Though evidence is there for labour market flexibility and sector-specific risk, some

		linked to susceptibility, infection risk, and fatalities with regards to COVID-19. Evidence that labour market characteristics are likely to be important from the scoping review.	correlation with income inequity/GINI index.
Economic interconnectedness	Trade in goods and services (balance of imports and exports)	Some Evidence that economic openness, as measured by volume of imports of goods and services, including high volume of trade is linked to COVID spread from the scoping review.	No Correlation with economic development.
Supply chain	Surge manufacturing capacity (tracer commodities)	No Limited evidence recorded on supply chain specifically and its risk dimensions.	No Correlation with economic development, economic interconnectedness. Variable can also be considered to be slightly more downstream than the final 3 selected.

The three economic indicators included in the Clean 15 are listed in Table 8. Though the economic pillar bears on all four risk dimensions (PPRR) to some degree, economic inequality is likely to play a more significant role during the response and recovery stages of risk, whereas economic development and social program availability and financing speak to the health of the country's economy, and are likely influential during the initial stages of risk.

Table 8 Economic indicators included in the Clean 15 and their alignment with the four dimensions of risk

Determinant	Indicator	Level of measurement
Economic development	GDP per capita[xii]	Country (n=189)[6]
Economic inequality	GINI index[xiii]	Country (n=189)[7]
Social program availability and financing	Public health and social protection expenditure (% of GDP)[xiv]	Country (n=187)[8]

To illustrate the economic development determinant, the GDP per capita measures a nation's economic output per person and assesses the prosperity of countries based on the size of its economy. We suggest that like many other indicators in the Clean 15, monitoring the growth of the indicator might be even more useful here. This can be directly done by utilizing the GDP per capita growth rate (annual %) indicator, also developed by the World Bank.

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[6] The World Bank also provides values at the regional and global level.
[7] The World Bank also provides values at the regional and global level.
[8] The ILO also provides values at the regional and global level.

The GINI index was chosen to be the most appropriate indicator to assess economic inequality, and is a measure of income distribution across a population. While some limitations exist with this indicator – for example, wealth inequality is not necessarily captured by income inequality – it is a staple measure of societal inequality and critical complement to GDP per capita. Additional indicators to consider here would be the gender wage gap (ILO), the ratio of female-to-male labor force participation rate (World Bank) and extreme poverty (World Bank).

Public health and social protection expenditure is meant to capture a country's investment in social health protection – i.e., mechanisms that promote health directly and indirectly to alleviate burden of disease and disability as well as its costs. This particular indicator assesses social protection by looking at three different components: total expenditure on social protection (excluding health), expenditure on social protection systems including floors for different age groups, and domestic general government health expenditure.

Environment

The environmental dimension of risk was operationalized by determinants pertaining to both the physical and the built environment. On the physical environment dimension, these determinants include meteorologic and geographic factors including air quality; processes of managing the physical environment (such as water, sanitation, and hygiene; food security, safety, and handling), as well as the intersection of human activity and the physical environment (climate change & natural disasters; agricultural and farming practices; land use changes; biodiversity; and human-wildlife interaction). On the other side of the environmental spectrum, the built environment refers to the conditions in which communities live, work, or host their recreational activities.

Table 9. Indicators for environmental determinants and filtering rationale

Determinants	Indicator	Evidence	Include in Clean15
Meteorologic and geographic factors	Seasonality	Scoping review pointed to seasonality being one of the drivers for COVID-19, with mixed evidence as to its importance. Seasonality patterns of pneumonia were also included in the review of COVID-19 models.	No Seasonality may not necessarily be pathogen-agnostic given mixed evidence.
	Altitude (% of population living below 100 m above sea-level)	Lower respiratory infection shown to be increased with greater altitude, from the review of COVID-19 models as well as the literature.	Climate change global adaptation index includes altitude (as the population living under 5 m above sea level), the projection of sea level rise impacts, as well as the projected change of warm periods (temperature) as some of their measure indicators.
	Temperature	Scoping review demonstrated increased air temperature inked to	

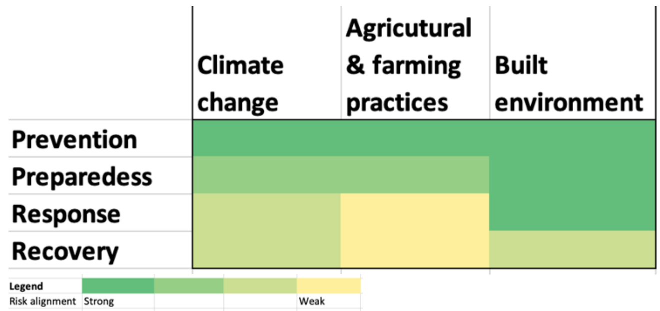
		increases in hospital admissions due to cholera, increases in cases of salmonellosis.	
Climate change and natural disasters	Climate change global adaptation index	Plenty of evidence from both the scoping review as well as expert input that increasing vulnerabilities associated with climate exacerbates infectious disease emergencies. Important driver stressed by expert consultations.	Yes Strong evidence, pathogen-agnostic, available data source.
Air quality	Air quality measures	Yes Evidence from the review of COVID-19 models and scoping reviews that air pollution may be a driver of COVID-19 transmissibility.	No Pathogen-specific, strength of evidence limited compared to selected indicators, does not capture as much of the environmental pillar as some of the other selected indicators.
Water, sanitation, and hygiene	% of population using safely-managed drinking water services	Yes Evidence on lack of access to WASH services was identified as a COVID-19 risk in the literature.	No Not in the top three environmental determinant selected by experts during the Delphi process. Not pathogen agnostic. Components of WASH are also included in climate change index, which includes several indicators such as access to reliable drinking water, water dependency ratio, change in annual groundwater runoff etc.
Food security, safety, handling	Number of moderately or severely food insecure people	Yes Evidence of increased risk due to food insecurity, concerns for food-borne illnesses in food processing and other mass congregate settings.	No Not mentioned by the experts in the top 3 during the Delphi process. Not pathogen-agnostic. Included in the climate change index, which includes indicators such as child malnutrition, and projected population change.
Agricultural and farming practices	Livestock density (per agricultural land area)	Yes Evidence that points to mass populations of livestock creating conditions that drive zoonotic spillovers. Expert input identified this determinant and indicator as being particularly significant given its potential in initiating spillovers.	Yes Though the climate change index includes "agricultural capacity" as an indicator, which assesses fertilizer, irrigation, and pesticide use, it does not explicitly go into livestock density, which has important evidence. This is also a pathogen-agnostic indicator, with an easily accessible data source.
Land use changes	Terrestrial protected areas	Yes Evidence suggests that the largest environmental cause of risk for infectious diseases are due to land use changes, and their subsequent effects on breeding sites for vectors of	No Climate change index contains indicators for "ecosystem service" which includes "projected change of biome distribution", and "protected biomes".

		disease, biodiversity of these vectors as well as reservoir hosts. Require deforestation (correlated to biodiversity), indicators between land use changes and biodiversity are also very similar	
Human wildlife interaction	Global wildlife exports (more explicit indicators unavailable, or only available in academic papers: e.g., spillover risk, bushmeat consumption and safety)	Yes Much of the evidence points to infectious disease as having a wildlife origin. No specific evidence on the indicator, hard to capture "spillover risk" – more investments in this indicator needed (only academic papers for now)	No Despite the strength of the evidence, this is somewhat correlated with agricultural and farming practices. It is also difficult to measure 'wildlife trade', particularly because illegal trade and unregulated wet markets are likely to be a large contributor towards potential spillover events. Further investments in developing indicators to more explicitly capture spillover risk, or behaviour of risk such as bushmeat consumption and safety are needed. Large scale datasets or built indices for these two potential indicators have not been found (beyond academic papers).
Biodiversity	Coverage of protected areas	Yes Plenty of evidence on the role of deforestation altering host environments, suggesting it can be a driver for outbreaks.	No Very similar indicator to the land use changes determinant. Climate change index contains indicators for "ecosystem service" which includes "projected change of biome distribution", and "protected biomes".
Built environment	Population density, captured by urban population (% of total population)	Yes Evidence from review of models and the literature pointing to the significance of congregate and dense settings as contributor to higher risk (e.g., slaughterhouses, dense areas). Evidence on city infrastructure (e.g., sewage treatment, indoor ventilation standards, drinking water infrastructure) was also found. Expert input highlighted built environment as one of the three most important determinants of risk.	Yes Though the climate change index includes urban concentration as an indicator, this indicator is nevertheless included in the final list to explicitly emphasize the importance of the non-physical environment in all spectrums of risk.

The three environmental determinants and indicators included in the Clean 15 are listed in Table 10. Because the environmental determinants can exacerbate spillover risk, physical environment indicators play a more prominent role in the prevention side of the risk spectrum. Comparatively, the indicator for built environment - population density - is likely to play a role across all spectrums of risk: denser populations may point to higher likelihood of wildlife interaction and thus spillover risk (prevention), but can also point to higher likelihood of spread and exacerbation of said risk (preparedness, response).

Table 10. Environmental indicators included in the Clean 15 and their alignment with the four dimensions of risk

Determinant	Indicator	Level of measurement
Climate change and natural disaster	Climate change global adaptation index[xv]	Country (n=182)
Agricultural and farming practices	Livestock density (per agricultural land area)[xvi]	Country (n=194)[9] Geospatial[xvii]
Built environment	Urban population (% of total population)[xviii]	Country (n=189)[10]



The climate change global adaptation index is a large, composite index that assesses climate vulnerability and adaptation readiness using 45 indicators. Vulnerability measures a country's exposure, sensitivity, and capacity to adapt to the negative effects of climate change across several sectors: food, water, health, ecosystems, human habitat, coastal, energy, and transportation infrastructure. Adaptation readiness is measured by the ability of a country to leverage investments to enhance adaptive capacity in terms of economic opportunity, governance, and social structures. 182 countries were assessed in 2020. Frequency of updates are unknown, but the index lists all of the indicators and their individual data sources, allowing users to calculate the global scores themselves, if needed.

Livestock density per agricultural land area stems from FAO's livestock patterns data consisting of livestock numbers, shares of major livestock species, and livestock densities in the agricultural land area. Country-level data are available, with annual updates. Additional indicators that can be used to assess agricultural and farming practices are fertilizer use, livestock trade volume, number of livestock facilities, some of which are also included in the climate change adaptation index.

Population density is captured by the World Bank's urban population indicator (as a % of the total population), i.e., people living in urban areas, as defined by national statistical offices. To assess trends and rates of change, we recommend specifically monitoring World Bank's urban population growth (annual %).

[9] The FAO also provides values at the regional and global level.
[10] The World Bank also provides values at the regional and global level.

Political

The political dimension of risk was operationalized by assessing some elements of governance (e.g., diplomacy and collaboration, communications, political will, health emergency policies) as well as the outcomes of the resulting political environment (e.g., public trust, systems & institutional capacity, civic participation & advocacy, and conflict, instability, and violence).

Table 11. Indicators for political determinants and filtering rationale

Determinants	Indicator	Evidence	Include in Clean15
Governance	Government effectiveness (from the Worldwide Governance Indicators)	Yes Numerous studies indicating the importance of government effectiveness in risk management by evaluating regional and national response, pointing to confrontation and conflicts between central and lower governments, showcasing the variability in a nation's response due to the way political systems function.	Yes In addition to literature, experts identified governance as being key in crisis management.
Global health diplomacy and collaboration	Percentage of funding goals met for international organizations and partnerships (More explicit indicator unavailable but needed.)	Yes Evidence suggesting that the opposite of diplomacy and collaboration – e.g., western nationalism, is a driver in increased risk, with global solidarity being jeopardized during the COVID-19 pandemic (e.g., vaccine nationalism). More broadly, large wealth of evidence on how international organizations and collaboration are essential for proper preparation and response towards emergencies with COVID-19, Ebola and other pathogens.	No Correlated within the broader umbrella of governance. No specific indicator available to explicitly measure the level of collaboration, diplomacy, and global solidarity. Further investments in building appropriate indicators necessary given evidence on broader international collaboration and need for global solidarity instead of nationalism in global risk management.
Communications	Percentage of countries with presence of WHO's risk communications team, material, content (More explicit indicator unavailable but necessary)	Some Some evidence between (risk) communications and its role in adherence of non-pharmaceutical interventions, as well as trust in governments – factors that are key to risk management.	No Correlated with government effectiveness, as well as trust in government. Appropriate indicator not available to assess communications across different countries, which are likely to be very variable.
Political will	Political will for disaster risk reduction index Index is a composite of risk knowledge, disaster governability, risk reduction investment,	No Evidence is more closely linked to governance, no specific evidence emerged explicitly assessing political will.	No Political will captured by the governance indicator. Political will specifically towards disaster risk reduction is captured by this indicator – but data is limited.

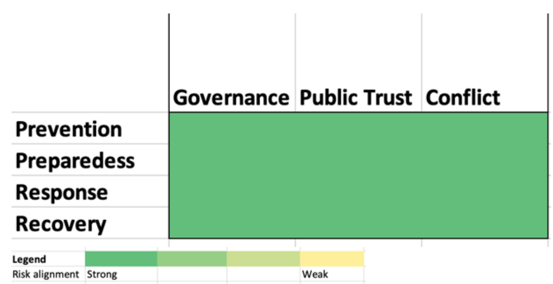
	bureaucratic preparedness, early warning systems, risk level.		
Health emergency policies	Several indicators found but flawed: GHSI (found to not necessarily be predictive of risk) IHR State Party Annual Reporting Scores Joint External Evaluation (JEE) (but only conducted in 4-5 year intervals, only cover 1/3 of countries) Government Response Index (Oxford) which includes health system policies (testing regime, emergency investment in health care), economic policies (income support, foreign aid), containment and closure (restrictions in movement etc.), vaccination (but selected indicators have stopped being updated since August 2021).	Yes Evidence on better policies resulting in better health outcomes, though limited evidence on the specific indicators listed. Evidence that there is no difference between GHSI index scores among countries that did and did not experience Ebola cases.	No Some indicators assessing preparedness for health emergencies available but mixed evidence in terms of their predictability. Lack of updated data is also an issue (for example, for Oxford's Government Response Index). No specific indicator explicitly assessing health emergency policies, but this is likely because health emergency policies fall under the broader umbrella of governance.
Systems and institutional capacity	Epidemic Preparedness Index (Oppenheim et al.) consists of an index assessing a country's economic resources, public health communications, infrastructure, public health systems, and institutional capacity to detect and respond to infectious diseases.	Yes EPI scores correlated with proxy measures for preparedness including timeliness of outbreak detection, investigation, reporting, and population vaccination rates during the H1N1 influenza pandemic. No evidence on the usefulness of EPI with respect to other pathogens such as COVID-19.	No Correlated with governance; the broader determinant is likely to be affected by the other indicators selected. Epidemic Preparedness Index does not appear to have a dataset available. Contingency financing may also be a useful indicator here but no explicit dataset or indicator found.
Public trust in government	OECD Trust in government (Additional indicators encompassing more countries needed.)	Yes Wealth of evidence making the link between messaging of governments, and public reaction and trust, corruption of governments leading to disregard of public health measures, thereby increasing or exacerbating risk. Evidence of trust in crises, particularly stressed as being of vital importance by experts.	Yes More investments in better quantifying or monitoring trust are necessary, particularly for countries that are not part of the OECD. Some levels of trust captured in the governance indicator - which includes perceived satisfaction with the government -, but expert consultations stressed the need for trust to be explicitly listed in the final 15.
Civic participation and advocacy	Voter turnout (OECD Better Life Index)	Yes	No

		Plenty of evidence of local, civil, grassroot, community responses, more broadly defined as civic participation and advocacy, being central in pandemic response, and deal with consequences or outcomes that go beyond the government's capacity, particularly when there is low level of trust in national institutions (COVID-19, HIV/AIDS etc.)	Highly correlated with trust in government. No specific indicator found to measure this, though evidence points to its importance in managing risk.
Conflict, instability, violence	Global peace index rank	Yes Presence of political unrest and conflicts hinders response to infectious diseases (e.g.,. presence of guerrilla groups complicated Ebola interventions). Particularly stressed as being important during the Delphi process.	Yes Some correlation with the governance indicator but was stressed throughout the expert consultations that it needed to be explicitly highlighted in the final list.

The three political determinants and indicators included in the Clean 15 are listed in Table 12. Political indicators are all encompassing and affect all STEEP pillars in substantive ways through institutional design, policy and political choices, and their repercussions, based on a government's ability to assess and respond to risk. It therefore is not a surprise that all four levels of risk dimensions are aligned strongly with political indicators.

Table 12 Political indicators included in the Clean 15 and their alignment with the four dimensions of risk

Determinant	Indicator	Level of measurement
Governance	Government effectiveness (Worldwide governance indicators)[xix]	Country (n=200) [11]
Public trust in government	Trust in government[xx]	Country (n=38)
Conflict, instability, and violence	Global peace index[xxi]	Country (n=163)



The worldwide governance indicators from the World Bank assesses governance as the "traditions and institutions by which authority in a country is exercised", and report governance across six broad dimensions, namely, voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. The government effectiveness dimension was specifically selected as the most appropriate indicator for monitoring and captures, the "perceptions of the quality of public services, the quality of the civil service, and the

[11] 200 includes countries and territories. The World Bank also provides values at the regional, income-group, and global level.

degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies." A wide range of sources and indicators make up this particular component of governance, including quality of bureaucracy and infrastructure, and satisfaction with public goods.

Trust in government refers to the confidence of individuals towards their national government – key during health emergencies – and was highlighted as a particularly important indicator during the Delphi process. The indicator selected in our Clean 15 utilizes OECD's dataset, where trust is captured using cross-sectional surveys. Finding global databases that captures this abstract and complex variable is a challenge and will require additional thinking and investments. A starting point for this might be to add to the World Values Survey, which touches on some components of trust through value and belief assessments conducted longitudinally across almost 100 countries.[xxii]

The global peace index measures global peacefulness across 99.7% of the global population, utilizing 23 qualitative and quantitative indicators that touch upon the level of societal safety and security, the extent of ongoing domestic and international conflict, and the degree of militarization. Annual updates of country rankings by most peaceful to least peaceful are available.

An initial set of indicators to monitor risk - the Clean 15!

The final list of the "Clean 15" – the initial list of determinants and indicators that broadly capture key elements of each STEEP pillar and that can be used to initiate a global monitoring process, based on importance, evidence with respect to risk, and operationalization capacity (availability of multi-country datasets, usability, trustworthiness of data) are listed in Table 13.

Table 13. Clean 15 - an initial list of indicators for monitoring broader determinants of pandemic risk

Pillar	Determinant	Indicator (Data Source)
Social	Individualism	Individualism (Hofstede index I)[xxiii]
	Global movement and connectedness	Inter and intra-national mobility (Google)[xxiv]
	Social inequity	Multi-dimensional poverty index (Oxford)[xxv]
Technological	Social media usage and misinformation	Number of active social media users (Statista)[xxvi]
	Digital connectivity	Inclusive Internet index (Economist & Meta)[xxvii]
	Biomedical innovations	Global innovation index (WIPO)[xxviii]
Economic	Economic development	GDP per capita (World Bank)[xxix]
	Economic inequality	GINI index (World Bank)[xxx]

	Social program availability and financing (social protection)	Public health and social protection expenditure (% of GDP) (ILO)[xxxi]
Environment	Climate change and natural disasters	Climate change global adaptation index (Notre Dame)[xxxii]
	Agricultural and farming practices	Livestock density (unit/agricultural land area) (FAO)[xxxiii]
	Built environment	Urban population (% of total population) (World Bank)[xxxiv]
Political	Governance	Government effectiveness (World Bank)[xxxv]
	Public trust (in government)	Trust in government (OECD)[xxxvi]
	Conflict, instability, violence	Global peace index (Institute for Economics and Peace)[xxxvii]

DISCUSSION

Strengths and limitations

While this report raises many unresolved issues, it does nevertheless provide a first pass at explicitly identifying broader determinants of pandemic risk that can be monitored with indicators that can be measured at scale, regularly, now. This has been facilitated by providing a credible mapping of the broader determinant space via the STEEP framework as well as identifying the four conceptual dimensions of risk i.e. PPRR. The five pillars of broader determinants and the four dimensions of risk help to avoid over-simplifying the linkages as well as discourage gravitating to narrow associations that exaggerate specific associations and miss others entirely such as focusing on singular determinants of response and ignoring determinants of prevention entirely. The diverse methods drawn upon – scoping review, synthesis of existing models, and expert review – were complimentary and appropriate given the early state of the science. The two-stage filtering process supplemented by discussions with groups within and beyond WHO working in this space has also yielded a practical set of initial indicators i.e. the clean fifteen that GPMB can begin to work with in the near term. Therefore, as a result of this exercise, there is now a practical opportunity to shine the light on broader determinants of pandemic risk with this set of initial indicators.

It is important, however, to underline the early state of the science and practice on monitoring these broader determinants and their links to pandemic risk. With respect to the STEEP framework, the clarity of conceptual frameworks and the ontology to navigate clearly and comprehensively these five pillars are in need of further attention and development. In many respects, the social determinants of health framework represents the most developed and well thought out conceptual mapping of the social pillar. Other pillars such as the economic or technology pillars would benefit from similar conceptual development. Moreover, a more comprehensive conceptual mapping of how they link together and overlap would be helpful to further work.

Beyond further conceptual development, in this report, the results encountered a variety of biases. Most importantly, and not surprisingly, is the issue of last-pandemic bias. In this analysis, the literature reviews, the model synthesis and the expert views were all skewed towards efforts to understand broader determinants associated with the current pandemic despite our pillar-specific search strategies that included other pathogens beyond COVID-19 (Zika, H1N1, Ebola etc.). This last pandemic bias is further accentuated by a disproportionate focus on one dimension of risk namely response with relative inattention to other dimensions of risk especially prevention and recovery. To address this bias, in our triaging process towards the Clean 15, special attention was paid to ensure that the final list included more pathogen-agnostic indicators that are linked to infectious health emergencies more broadly.

A further bias – the measurability bias - relates to the extent to which some important broader determinants such as trust or political will can be measured across contexts with comparable indicators and sufficient representativeness and appropriate periodicity. For less well-developed areas of the STEEP framework e.g. technology, this bias leads to skews in the literature on, or models of, broader determinants and pandemic that overlook determinants in this area. The upshot is that many important broader determinants of pandemic risk may be missed simply because they are not measured.

Cutting across all STEEP pillars and dimensions of risk, is the challenge of adequately capturing unfair or inequitable distribution. This reflects measurement bias to some extent insofar as many indicators either in their design or measurement protocols fail to incorporate/capture systemic inequalities that stratify diverse contexts so pervasively. With respect to the Clean 15 indicators identified in this report an explicit effort has been made to incorporate equity through distribution sensitive indicators such as the GINI coefficient, the multi-dimensional poverty index and the climate change global adaptation index.

An additional challenge in this report was the exclusive focus on broader or upstream determinants with no attention to downstream determinants. While this was part of the instructions from the GPMB, it is important for the future of this work to engage the full spectrum of determinants from upstream to downstream recognizing that broader determinants often condition downstream determinants of risk. This multi-level intersectionality is increasingly where the science is headed and will be critical to embrace in any global monitoring framework of pandemic risk. To that end, GPMB has indicated that both upstream and downstream determinants, informed by our work and that of another team, will be embedded in their final global monitoring framework.

Opportunities for operationalizing the Clean 15

Though this report points to key indicators that can be monitored to better understand upstream determinants of pandemic risk, there are important challenges in their operationalization related to technical considerations, information systems capacity, ownership and trust.

Beyond the suggestion in this report of what indicators of broader determinants to monitor, there are a set of technical issues related to how monitoring would be performed including:

- The frequency of monitoring: biannual, annual or more frequently in the context of a crisis?
- The level of monitoring: global, regional i.e. GBD super-regions, country or sub-national?
- The level of aggregation with respect to STEEP pillars: none i.e., 15 different indicators, an aggregate of the 3 indicators for each STEEP pillar, or a single broader determinants composite?
- Establishing a normative framework to assess and calibrate the direction of change of each of the broader determinant indicators with pandemic risk i.e., what is associated with more or less risk?
- Framing the linkage of the broader determinants with pandemic risk either as an aggregate across all four dimensions or focused on each of the four risk dimensions? For example, environmental pillar indicators appear to be especially important with respect to the prevention dimension of risk.

With reference to the final bullet above, Figure 6 illustrates how the Clean 15 indicators across the STEEP pillars may have differential importance to the PPRR dimensions of risk.

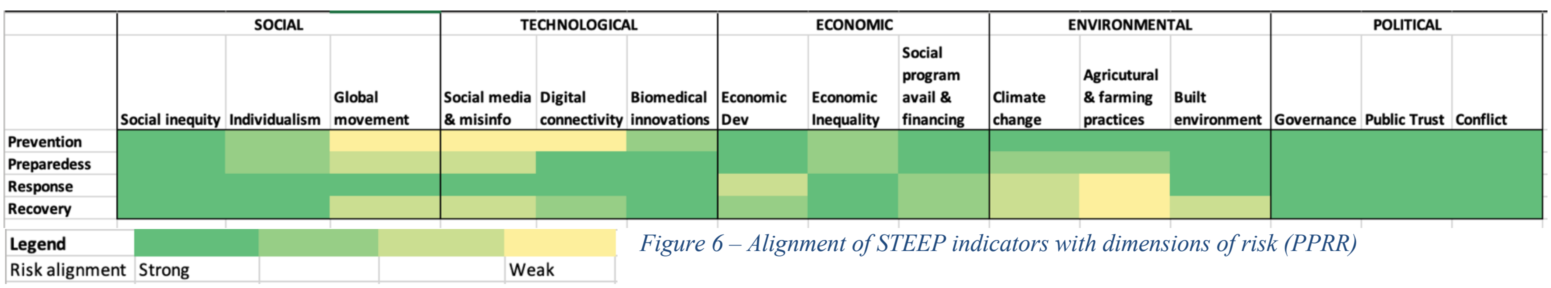


Figure 6 – Alignment of STEEP indicators with dimensions of risk (PPRR)

In addition, operationalization of monitoring needs to be sensitive to the uneven state of information systems required to generate the data for these diverse indicators of broader determinants. There are a host of issues likely to be encountered on this front including: a fragmented or absent (global) surveillance infrastructure for these broader determinants, variable frequency of data collection, data sharing barriers, financing challenges, and at the center of it all, inequities persistent throughout the development to the implementation of surveillance systems that bring into question issues of ownership and communication. Collection of key data for indicators may also be halted in certain settings during a crisis, adding additional challenges in our ability to monitor the determinants that are most helpful in the "response" phase. For these reasons, there is an urgent need to understand the state of the information systems that generate these data such that these issues can be addressed with strong and sustainable local governance. Given that these indicators are mostly outside the ambit of the health sector, there will be a need for GPMB to establish functional relationships and articulate improvement agendas with diverse non-health agencies and actors responsible for the stewardship of these data resources.

Effective operationalization must reach beyond regular and reliable reporting to ownership and action on the front lines. This raises further issues related to the availability of appropriately trained in-country human resources who can process and synthesize the data, and elevate a signal when risk is deemed to be significantly high to decision makers.

In addition, operationalizing monitoring requires a high level of trust within and between countries. Generating trust requires that benefits of surveillance systems be spread equally – and visibly – across all countries, and that most importantly, countries are not penalized for reporting information regarding new pathogens, new spillovers, or any other potential risk. Transparency in how data is shared (where is it stored, who has access to it, how is it transmitted between stakeholders) will also make or break trust – and subsequently a working global surveillance system.

Observations on the emerging science of risk assessment

It is still early days for the emerging science of global risk monitoring, and our understanding of both the broader determinants of pandemic risk. The work undertaken in this report has shed some light on some of the issues that may be important in advancing this science. Very simply, there are three important frontiers to embrace: i) the measurement of risk; ii) the measurement of broader determinants; and iii) the models of risk that include broader determinants.

First, despite much attention to pandemic risk in the last few years, the definition of the dimensions of risk from prevention, to preparedness, to response, and to recovery remain fuzzy and without sufficient international agreement on any standardized measures. Shoring up definitions and measures of these dimensions of risk and whether and how they can be aggregated will be an important foundation to strengthening the science of pandemic risk assessment.

Second, as noted above, a concerted effort is also required to generate more consensus on how best to characterize and measure broader determinants that bear on pandemic risk. This includes not only making sure that measurement biases are addressed but also involves technical discourse on how best to measure these determinants as single or composite variables, and whether they are measured as a simple average, with attention to distribution or as a rate of change.

Finally, bringing risk outcomes together with their determinants (not only broader determinants) embraces a further set of issues related to the nature/specification of risk models that might be developed to understand and predict/monitor risk more effectively. There are a myriad of issues on this front including but not limited to the types of models, the extent to which they are sensitive to different types of pandemic pathogens, their ability to accommodate different spatial-temporal contexts, the degree to which they capture dynamic and differential rates of change, and their timeliness with respect to real-time unfolding of crises. It will also be important that the development of the science is not naïve to the reality that some of what needs to feed into models of emerging risk may well constitute politically sensitive information, e.g., data on technologies that have dual use capabilities[xxxviii], or on the state of biotechnology.[xxxix]

Given the nascent state of the science in global pandemic risk assessment, it will be important for the GPMB to provide stewardship on this front be it by fostering the development of a network of global monitoring centers (with country buy-in and active participation), advocating for an IPCC-like process of open-source science, and/or encouraging a National Academies consensus process. Inclusion of efforts to develop this science as part of broader pandemic risk management efforts such as WHO and UN treaties will help advance this science more sustainably.

Conclusion

To address public health emergencies such as pandemics more effectively, monitoring and surveillance strategies would benefit from developing the science of risk assessment further with attention to the inclusion of upstream determinants. Improved capacity to engage with these determinants will not only improve PPRR related to pandemic risk, but also will recognize the broader imperative of other cross-sectoral health challenges such as health equity and the urgency of addressing other threats such as climate change and systemic inequality. Ultimately, we will need to keep lessons learned from previous epidemics and the ongoing lessons we are learning from COVID-19 at the forefront of political decisions, such that political leadership maintains momentum in implementing solutions that promise more effective pandemic risk management.

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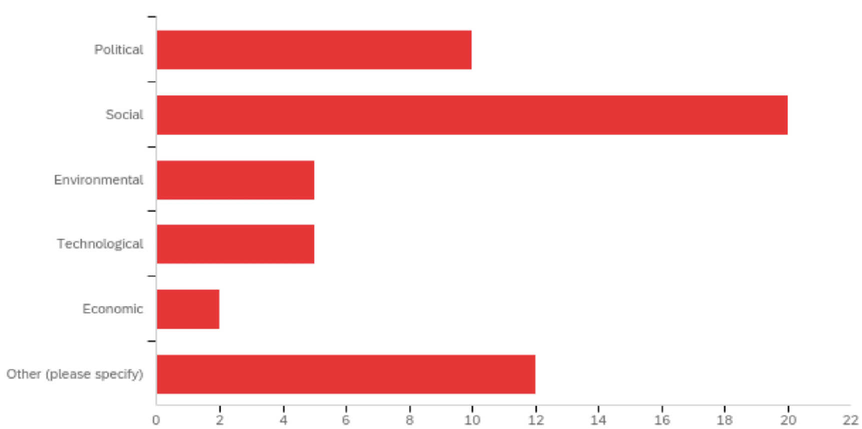
SUPPLEMENTAL INFORMATION

APPENDIX 1

Delphi Process

A total of 54 expert inputs were received through the online survey. To preserve anonymity, respondents were not required to submit personally identifiable information. Among the 34 respondents who chose to divulge their gender, 16 self-reported as male, and 18, female. Geographically, among those who chose to self-report their primary residence, 11 respondents chose the United States of America, 4 Chile, 2 Malaysia, 2 Philippines, and 2 Vietnam. A handful of respondents also self-reported being based in each of the following countries: Belgium, Brazil, China, Egypt, Hong Kong, Italy, Norway, Singapore, Thailand, Timor-Leste. Altogether, among those who chose to disclose their primary residence, 16 countries were represented. Among those who self-reported their type of employment, 15 were in the academic/research sector, 11 worked in non-governmental organizations, 1 in a think tank, 1 in a multilateral development bank, 1 for the United Nations, 1 in the private sector, and 5 in the public sector. In terms of pillar-specific expertise (Figure A2.1), respondents were able to choose more than one area of expertise, with 37% of respondents identifying their expertise within the social sphere, followed by 19% in the political sphere, 9% in the environmental space and technological space each, and 4% in the economic space. While 22% of respondents indicated that their expertise fell in the "other" section, most specified the "other" as

Figure A2.1. Pillar-specific expertise, self-reported by participating respondents



being the cross-cutting fields of public health, health or global health - which encompass all five pillars. A few (4%) indicated that they preferred to be identified as generalists.

Our preliminary list of pillar-specific determinants included in the Delphi survey were identified through initial literature scans, expert input, and through iterations within the study team. (Tables A1-5). Ranking ranged from most important to least important, with a score closer to 1 indicating a respondent's perception of the determinant being of higher importance with regards to exacerbating risk of health emergencies.

Within the social pillar, these included demographic composition, gender inequity, health inequity, human capital, individualism, mobility, racial/ethnic inequity, as well as social class and cohesion. The survey identified health inequity, human capital, and demographic composition as being ranked as the top three most important social determinants in their potential to exacerbate risk of health emergencies. (Table A2.1)

Table A2.1 Social determinants identified with the Delphi process

#	Social determinant	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	**Demographic composition (e.g. age distribution)**	**1.00**	**8.00**	**3.94**	**2.78**	**7.75**	**33**
2	Gender inequity	1.00	8.00	4.64	2.10	4.41	33
3	**Health inequity**	**1.00**	**6.00**	**2.73**	**1.50**	**2.26**	**33**
4	**Human capital (e.g. composite measure of health, nutrition, and education in a country)**	**1.00**	**7.00**	**3.70**	**1.62**	**2.64**	**33**
5	Individualism (e.g. health as a personal choice, vs. collectivism)	1.00	9.00	5.00	2.04	4.18	33
6	Mobility (forced or voluntary)	1.00	9.00	6.15	1.84	3.40	33
7	Racial/ethnic inequity	2.00	8.00	5.67	1.77	3.13	33
8	Social class and cohesion (e.g. social capital, ethnic diversity and multiculturalism, population under the national poverty etc.)	1.00	9.00	4.91	2.78	7.72	33
9	Other (Please explain and/or include additional determinants not listed)	2.00	9.00	8.27	1.97	3.90	33

Within the economic pillar, these determinants included employment/occupation, interconnectedness of economies and critical economic sectors, public and private financing of social sectors including health and wealth inequality. The survey identified all four of the identified determinants to be more or less equally important in significance in exacerbating risk for health emergencies. (Table A2.2)

Table A2.2 Economic determinants identified with the Delphi process

#	Economic determinant	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Employment and/or Occupation	1.00	4.00	2.55	0.97	0.94	29
2	Interconnectedness of economies and critical economic sectors (e.g. logistics, transport, and supply chain, production of diagnostics, tourism and air travel)	1.00	4.00	2.69	1.21	1.46	29
3	Public and private financing of social sectors including health	1.00	5.00	2.45	1.16	1.35	29

4	Wealth inequality	1.00	4.00	2.38	1.19	1.41	29
5	Other (Please explain and/or include additional determinants not listed)	3.00	5.00	4.93	0.36	0.13	29

In the political pillar, these included civic participation and advocacy, communications, governance, political will/culture, public trust, response policies, as well as systems and institutional capacity. The survey ranked governance, political will/culture, and public trust as being the top three most significant in exacerbating risk for health emergencies. (Table A2.3)

Table A2.3 Political determinants identified with the Delphi process

#	Political determinant	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Civic Participation and Advocacy	1.00	7.00	4.31	2.21	4.91	26
2	Communications (e.g. risk and science communications, independent media)	1.00	7.00	4.27	1.81	3.27	26
3	**Governance (e.g. leadership, science diplomacy)**	**1.00**	**7.00**	**2.88**	**1.69**	**2.87**	**26**
4	**Political will and/or culture**	**1.00**	**7.00**	**3.85**	**1.90**	**3.59**	**26**
5	**Public Trust (in science, government, public health)**	**1.00**	**7.00**	**4.12**	**2.01**	**4.03**	**26**
6	Response policies (e.g. economic support, containment strategies, One Health integration)	1.00	7.00	4.15	1.94	3.75	26
7	Systems and Institutional Capacity (e.g. health systems resilience, global health security)	1.00	8.00	4.50	2.08	4.33	26
8	Other (Please explain and/or include additional determinants not listed)	6.00	8.00	7.92	0.38	0.15	26

In the environmental pillar, these included air temperature seasonality, altitude, air quality, agricultural and farming practices, biodiversity, climate change, physical habitats, and water and sanitation. The survey ranked climate change, agricultural and farming practices, and physical habitats as being the top three most significant determinants exacerbating risk for health emergencies. (Table A2.4)

Table A2.4 Environmental determinants identified with the Delphi process

#	Environmental determinant	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Air Temperature Seasonality	1.00	7.00	4.95	1.94	3.76	21

2	Altitude	2.00	8.00	6.67	1.75	3.08	21
3	Air quality (indoors and outdoors)	2.00	9.00	4.52	1.89	3.58	21
4	**Agricultural and farming practices**	**1.00**	**7.00**	**3.57**	**1.73**	**3.01**	**21**
5	Biodiversity	1.00	9.00	5.67	2.21	4.89	21
6	**Climate change**	**1.00**	**8.00**	**3.43**	**2.38**	**5.67**	**21**
7	**Physical habitats (e.g., appropriate housing and working conditions, overcrowding)**	**1.00**	**8.00**	**3.67**	**2.23**	**4.98**	**21**
8	Water and sanitation	1.00	8.00	4.29	2.19	4.78	21
9	Other (Please explain and/or include additional determinants not listed)	1.00	9.00	8.24	2.35	5.51	21

In the technological pillar, these determinants included air biomedical innovations, digital connectivity, social media usage and misinformation, and technological infrastructure. The survey ranked social media usage and misinformation, and digital connectivity as being the top two most significant determinants in exacerbating risk for health emergencies. (Table A2.5)

Table A2.5 Technological determinants identified with the Delphi process

#	Technological determinant	Minimum	Maximum	Mean	Std Deviation	Variance	Count
1	Biomedical innovations	1.00	4.00	2.86	1.08	1.17	21
2	**Digital connectivity**	**1.00**	**5.00**	**2.19**	**1.01**	**1.01**	**21**
3	**Social media usage and misinformation**	**1.00**	**4.00**	**2.05**	**1.05**	**1.09**	**21**
4	Technological infrastructure (e.g. electric grid capacity)	1.00	4.00	2.95	1.13	1.28	21
5	Other (Please explain and/or include additional determinants not listed)	4.00	5.00	4.95	0.21	0.05	21

In addition to these survey assessments, pillar-specific expert interviews were conducted as phase III of the Delphi process to fill gaps and add contextual understanding to the relationships between determinants, indicators, and health emergencies. The evidence synthesis presented in the report reflects the additional thinking contributed by the broader Delphi process, and the scoping reviews.

APPENDIX 2

Evidence Synthesis of Determinants across STEEP

Social determinants

Using both the literature and the Delphi results, we have identified several social determinants that are most significant in driving and amplifying health emergencies such as COVID-19 (Table A3.1). Among the listed determinants, the concept of solidarity and the level of individualism present in a society was attributed to be most significant by experts in how social context is shaped, with all other determinants being derivative expressions of this broader concept. Societies that frame health as a collective problem fundamentally are better prepared and respond better to a crisis. A systematic monitoring of the determinants will be helpful to better understand what the status quo looks like, as well as strategize implementation strategies that target these determinants within the PPRR model.

Systemic, structural inequities that are so often associated with fewer opportunities for health and health care in all societies, emerge as pervasive risks in the context of pandemics. Specifically, if the baselines for health, gender, race or other important factors are inequitable, health emergencies are likely to amplify these gaps across each of the PPRR risk domains. It should be noted that there is vast collinearity between many determinants identified which assess various forms of inequities. For example, gender and racial inequities stem from social inequities, and are associated with poorer health outcomes; as long as these social pathologies are neglected, health disparities will persist. For the sake of comprehensiveness, we have highlighted all forms of inequity - but we would suggest picking the appropriate indicators depending on the phase of the crisis, and the appropriate PPRR quadrant that is need of monitoring, recognizing that these inequities measure different aspects of the broader foundational force that is inequity.

Table A3.1 Social determinants identified as being important in their potential or perceived role in exacerbating health emergencies

Social determinant	PPRR	Measurability	Rate of Change
Social inequity [xl] [xli] [xlii] [xliii]	Prevention Preparedness Response Recovery	Easy	Slow
Racial/ethnic inequity [xliv] [xlv]	Prevention Preparedness Response Recovery	Easy	Slow

Gender inequity [xlvi] [xlvii]	Prevention Preparedness Response Recovery	Easy	Slow
Demographics	Preparedness Response	Easy	Moderate
Underlying health status	Prevention Preparedness Response Recovery	Easy	Moderate
Individualism[xlviii] [xlix] [l]	Response Recovery	Difficult	Fast
Human capital[li]	Preparedness Response	Moderate	Slow
Global mobility and connectedness	Preparedness Response	Moderate	Fast

Social inequity
Socioeconomic inequities and marginalization or the persistent "othering" of certain groups has led to stigmatization of disease and lack of trust towards the scientific establishment and health care systems. In many ways the antithesis of social cohesion, social inequity is a key determinant in the social pillar, and captures the variability in important factors such as educational attainment, and healthcare utilization.

Racial/ethnic inequity
Similarly, communities of color have been disproportionately affected by the pandemic; such divides are not new to COVID-19 and are deeply rooted in our societal structures. In the United States, in the first year of the pandemic, Indigenous communities were 3.3x more likely to have died of COVID-19 when compared to white Americans; Latino Americans were 2.7x more likely, and Black Americans 2.7x more likely.[lii] Given the pervasive stratification along racial and ethnic lines, **racial inequity** is a key amplifier of health emergencies, and a primary stratifier to outcomes of interest to PPRR.

Gender inequality
The pandemic has also demonstrated the persistent gender inequality, with women dropping off the labor force, holding many informal or lower-paying jobs as well as the unpaid caregiving roles, and the spike in domestic violence targeting women, girls and LGBTQIA communities. Expert insights indicated that the differentiated impact within gender also requires a differentiated preparedness and response, best measured through a composite measure that recognizes that gender inequity measures are variable by different social groups. In addition, the relationship between gender inequity and education or health-seeking behaviour for example further complicates the

measurement of this determinant. Typically, an assessment of female education is most predictive of social outcomes rather than broader measures of gender inequity.

Demographics
Demographic composition has illustrated differences in the overall susceptibility of countries to the impact of the COVID-19. Countries with higher population densities, larger elderly populations, often with high levels of co-morbidities, such as most OECD countries, have had much higher levels of hospitalization and deaths compared with countries with younger demographic profiles such as those in Africa. Investigating and monitoring the differentiated impact is crucial here to better prepare for and respond to emergencies with appropriate demographic-specific interventions and strategies.

Underlying health status
Inequitable access to health care remains one of the main contributors to a population's underlying health status, and speaks to the prevalence of health inequity within the community. The availability and accessibility of health care, particularly to members of communities that are marginalized or below a certain socioeconomic threshold, will go a long way in reducing health inequities that have persisted for decades, but have been particularly exacerbated by the pandemic.

Individualism
While we had initially attempted to capture cultural and societal values through the concept of social cohesion, we felt through our Delphi discussions that nuances associated with cohesion would not be easily measurable. For example, cohesion can be positive or negative for health emergencies: cohesive in opposition of non-pharmaceutical interventions or in-support of them. We have therefore embedded this concept within the notion of individualism (as compared to collectivism), which plays an important role in crises. Countries with a focus on individual liberty portray the belief that health can be determined by personal lifestyle choices and access to health care. As a result, investments have often been on the treatment side of health, rather than investments in structural causes. When it comes to an infectious disease like SARS-CoV-2, collective cohesion is necessary to directly break chains of transmission and protect each other (e.g., masks and vaccines, adherence to non-pharmaceutical intervention) and is therefore an important social determinant that must be better understood. Measurability here is likely to be quite challenging however, particularly in a consistent way across different settings, or even in a global sense. Initial attempts to quantify these have been done by Hofstede, where individualism is selected as one of six dimensions that attempts to capture "culture." Hofstede defines individualism as a "preference for a loosely-knit social framework in which individuals are expected to take care of only themselves and their immediate families". In contrast, collectivism is assessed as a "tightly-knit framework in society in which individuals can expect their relatives or members of a particular ingroup to look after them […]."[liii]

Additional work in validating this measure would need to be conducted for the appropriate indicators associated with this determinant to be most meaningful. This determinant is also highly correlated with other social factors, as noted by Hofstede.

COVID-19 responses in Japan and South Korea, when compared to the USA and the UK highlight this difference in response and health outcomes.

Human capital
While the pandemic has had negative effects on human capital,[liv] it may be that greater stock of human capital enhances prevention, preparedness, response, and recovery. While this determinant does combine a social determinant (education) with impact, we felt like it captured an aggregate measure that was more helpful than simply monitoring the two variables separately. An assessment of human capital is in many ways the first barrier to better understanding the interconnectedness of social determinants of health because higher levels of education usually lend themselves to better health outcomes, and together, influence a population's resilience in the face of a health emergency.

Global movement and connectedness
This determinant captures the concept of mobility, either voluntary or forced, which amplifies the risk of outbreaks becoming epidemics and pandemics.

And finally, it should be noted that within our list of determinants, measuring inequity in and of itself might be less valuable, suggesting instead that the degree of inequity and level of attainment be monitored. For example, during the response stage of the crisis, health inequity at lower achievement levels, e.g. low health inequity in the population but lower vaccine coverage, might fare worse outcomes than high levels of health inequity broadly but with an overall high level of vaccine coverage.

Economic determinants
We have identified several economic determinants that are most significant in driving and amplifying health emergencies (Table A3.2).

Table A3.2 Economic determinants identified as being important in their potential or perceived role in exacerbating health emergencies

Economic determinant	PPRR	Measurability	Rate of Change
Economic development[lv]	Prevention Preparedness	Easy	Slow
Economic inequality[lvi]	Response Recovery	Easy	Slow
Health system financing[lvii]	Prevention Preparedness	Moderate	Slow
Social program availability and financing[lviii]	Prevention Preparedness	Moderate	Moderate
Employment[lix]	Response Recovery	Easy	Moderate

Economic interconnectedness	Prevention Preparedness Response Recovery	Difficult	Fast

Economic development and inequality
Economic development and economic inequality have pervasive linkages to health risk. At the population level, countries with higher levels of revenue have more assets to distribute (should they choose to do so). At the individual level, life expectancy is observably higher among those on the higher rungs of the economic ladder. A deep economic gradient means that most people do not have access to the resources needed to mitigate the impact of health emergencies. Reducing existing gaps in wealth will lead to better economic outcomes, which lead to better health outcomes, particularly among marginalized communities. Economic inequality is also related to disparities and ability to adhere with pandemic countermeasures, be they non-pharmaceutical, or pharmaceutical interventions.

Health systems financing
Health systems financing both in terms of the level and the degree of social protection or insurance are factors that will help prevent infectious emergencies and not just mitigate them. Differentiating expenditures in health between acute care and public health infrastructure is likely to be important as well. Existing mechanisms in how health systems are financed also play a large role. Health financing that is centralized and pooled, spreading the financial risk among individuals (e.g., universal health care[lx]) increases health security and health coverage, compared to an insurance-based model or a model that relies exclusively on out-of-pocket spending.

Social program availability and financing
Adding to this, **social program availability and financing** is critical in the preparedness and prevention stage of the risk dimensions, to be better placed to respond to a health emergency. One way this can be measured is through an assessment of dependence on donor or international sources of financing, given that being overly donor or foreign-capital dependent may severely limit resources for long-term planning of social sectors.

Employment
With COVID-19, we have seen how important **employment** is in determining risk. Availability of sick leave and hazard pay for the general population can provide protection that allows individuals and employers to limit the spread of an infectious agent. At the more macro level, the share of informal employment and the percentage of workforce in the service sector for example can determine the extent at which a sub-population is at higher risk, particularly if social or other mitigating measures are not in place.

Economic interconnectedness
Interconnected economies and critical economic sectors that are directly and indirectly

related to health are captured by the determinant economic interconnectedness and need to be mobilized within PPRR. These include key sectors of the economy with fit-for-purpose including trade openness, logistics, transport, and supply chain, production of diagnostics, therapies and other health commodities, communications within and across countries, tourism and air travel etc. As has been observed with the pandemic, our existing interconnected economies influence the movement of goods and money, with the pandemic causing significant disruptions in supply chain and global trade. Macroeconomic trends, trade agreements, and governmental policies that influence them are critical in our understanding of these economies, and in turn, health crises.

Political determinants

We have identified several political determinants that emerge from the literature as significant in driving and amplifying health emergencies such as COVID-19, many of which can be placed under the wider umbrella of governance. For the sake of feasibility in monitoring, these have been broken down into smaller categories of determinants. (A3.4)

Table A3.4 Political determinants identified as being important in their potential or perceived role in exacerbating health emergencies

Political determinant	**PPRR**	**Measurability**	**Rate of Change**
Governance [lxi lxii lxiii lxiv lxv lxvi lxvii lxviii lxix lxx lxxi]	PPRR	Difficult	Variable
Global health diplomacy and collaboration[lxxii,lxxiii]	Response Recovery	Difficult	Slow
Communications[lxxiv lxxv lxxvi]	Preparedness Response	Difficult	Rapid
Political will [lxxvii]	PPRR	Difficult (arbitrary)	Variable
Health Emergency Policies[lxxviii,lxxix]	Response	Moderate	Medium
Systems and Institutional capacity[lxxx]	PPRR	Moderate (dependent on data availability and quality)	Slow
Public trust in government[lxxxi lxxxii]	PPRR	Difficult	Variable (though building trust is always slow)
Civic participation and advocacy[lxxxiii lxxxiv]	Preparedness Response	Moderate (dependent on data availability and quality)	Fast
Conflict, instability, and	PPRR	Moderate	Variable

violence [lxxxv]			

Governance

Governance is key in all aspects of society - though measuring governance as a composite is very challenging because it can include everything from the governmental structure, the centralization of power, the adherence to legal treaties, membership in consensus-reaching union for emergencies, and the level of corruption and effectiveness portrayed by various levels of government. While this determinant is difficult to measure, it is nevertheless key in understanding power differentials, and decision-making, especially in the context of policing power that may be granted to public health authorities – vital before, during and in the aftermath of a crisis.

Governance in the context of a crisis also requires that appropriate policies be developed and implemented across multiple sectors during a health emergency. Efforts have been made to characterize these policies across various categories such as containment, stringency, economic support and risk of openness and to monitor these in the context of specific and aggregate government response index[lxxxvi].

The nature of leadership has been identified in different ways as important in influencing effective response in the current pandemic. Leadership that uses the evolving scientific information to shape decisions, design policies, and prioritize those most vulnerable, even before an acute crisis is introduced, can lead to better outcomes for all. Leadership may also have important gender linkages: several analyses have pointed to countries or states where more prominent female leadership, or greater gender equality in legislatures, appears to have been more agile and effective in mitigating the impact of COVID-19. The lesson learned with COVID-19 however remains that while national leadership is indispensable, it must be combined with local solutions that generate voluntary compliance, cooperation, and trust in the authorities.

Global health diplomacy and collaboration

The pandemic has also made clear the need for global health diplomacy and collaboration – an intersection of the broader umbrella of science and international affairs that is meant to increase international and within-country coordination and collaboration to tackle different jurisdictional challenges such as pandemics. While this is an evolving and relatively new area, global health and science diplomacy in particular has the potential to be critical in delivering an equitable response to pandemics (e.g., development and equitable distribution of vaccines, investments in global surveillance systems to catch viral threats (and others) early, data-sharing agreements to monitor risks and outcomes “live”). Our discussions with experts further validated the importance of the link between geopolitics and health emergencies, citing lack of trust between countries, tagging and shaming countries for reporting (or not reporting) appropriately, and the fundamental wealth and power dynamics between countries that falsely portray the notion that wealthier countries have all solutions to address global challenges. None of this promotes cooperation and development of global solutions; instead, the blaming of countries or even individuals as being responsible for health emergencies, further inhibit trust and openness in sharing of health information for example, which can heavily exacerbate health emergencies.

Communications
Appropriate risk and science communications shapes the course of a response, the public opinion, and consequently, the public's perception and trust for the next crisis. Monitoring communications at the global level is all but impossible given that risk communications require context-specific strategies, but the presence of a global communications platform for information could be one approach in consolidating evidence during a crisis and making the information digestible to the general public. Part of communications also includes the availability and strength of an independent media, which informs the public on the changing and evolving crisis, both on the scientific and the political aspects. Partisan media can significantly shape the discourse and promote mis- and disinformation (e.g. anti-vaccines sentiments observed globally).

Political will
Closely related to leadership, the political will to act and the culture that allows this to occur, when acting early may later be perceived as over-reacting (due to a successful intervention) is critical in aspects of risk management. This may move beyond "will" alone, and may be related to the political culture for addressing emergencies that is shaped by a country's historical experience with crises ranging from very many to very few.

Systems and institutional capacity
Governance also dictates core systemic and institutional capacities which encompass the resilience of health systems, the capacity of public health infrastructure to prepare, prevent, respond, and recover from stressors, the responsiveness of the research system to mobilize knowledge in a timely and effective way and also, more broadly, the systems of social protection and welfare that are so crucial in buffering downside effects of crises.

Trust
The question of **trust** at the global level is complex but is also critical to measure within countries and communities. Trust in governments shapes the confidence that communities have on the legitimacy of public health and other governmental institutions. As observed with COVID-19, low trust - and the resulting polarization - will reduce adherence with measures (e.g., non-pharmaceutical interventions) that may be necessary to restrict or mitigate the damage of an ongoing crisis. Beyond the response side, trust is critical for the successful implementation of public policies that address both long-term and short-term challenges. Trust is also likely to be an outcome measure of the other determinants assessed - where countries with a well-equipped public health system are likely to have higher compliance and trust of authorities, allowing governments to implement population-health measures much more quickly. In that sense, trust encompasses a broad definition in this scope of work, where trust in government is closely interconnected with trust in science, particularly during crises.

Civic participation and advocacy
Civic participation and advocacy have historically and with COVID-19, indicated that engagement can result in changes in political conversations and landscape, and over the long-term, shape policies that define our priorities. An example of this includes the most recent national protests against racial injustice in the USA that coincided with the pandemic.

Conflicts, instability, violence
Conflicts, instability, and violence are an underlying threat to all of the aforementioned political determinants and can amplify the spread of infectious disease outbreaks due to deficits in determinants that are conducive to guaranteeing the health of populations, including access to functioning systems, at the health level and beyond.

Additional nuances with political determinants
Potential political global indicators are limited due to the prevailing national- and regional-level governance structures. Most indicators require analysis of national-level policies or government structures. Some indicators at the global level do remain. For example, conflicts, instability, and violence can be captured by measuring the magnitude of armed conflict, migration, refugees, internally displaced persons, and violent demonstrations. Global health diplomacy and collaboration can be measured through biomedical patent sharing or releases (e.g., through signing to and adhering to the TRIPS agreement) and signatories and adherence to international conventions such as the International Health Regulations which legally mandate reporting of and response to PHEICs. (See Appendix 4 for the master list of potential indicators corresponding to these determinants.)

Another key issue with evaluating political determinants at the global level is the context-specific nature of the evidence. With COVID-19, some authoritarian regimes were better able to control spread just like some democratic nations (e.g., New Zealand), though with different approaches. This was not the case for nations like the United States or Brazil. Similarly, mis- and disinformation ran rampant in the United States despite the existence of independent media whereas some nations without such media (e.g., China) fared better. As a result, indicators must be analyzed together for a full picture. More detailed analysis is required to understand the most important political indicators and their inter-relationships.

Environmental determinants

We have identified several environmental determinants that are most significant in driving and amplifying health emergencies.

Table A3.5 Environmental determinants identified as being important in their potential or perceived role in exacerbating health emergencies

Environmental determinant	PPRR	Measurability	Rate of Change
Meteorologic and Geographic Factorslxxxvii[,lxxxviii,lxxxix,xc]	Response Recovery	Easy	Fast
Climate change[xci,xcii,xciii,xciv,xcv] and natural disasters[xcvi,xcvii]	Prevention Recovery	Difficult	Variable
Air quality[xcviii,xcix,c,ci]	PPRR	Easy	Variable
Water, Sanitation, and Hygiene[cii,ciii]	Prevention	Difficult	Slow
Food security, safety, and handling [civ,cv,cvi]	PPRR	Difficult	Variable
Agricultural and farming practices[cviicviii,cix]	Prevention	Difficult	Slow
Land-Use Changes[cx,cxi,cxii]	Prevention Preparedness	Easy	Slow
Human-wildlife interaction[cxiii,cxiv,cxv,cxvi,cxvii]	Prevention Preparedness	Moderate/ Difficult	Variable
Biodiversity[cxviii,cxix,cxx,cxxi]	PPRR	Moderate	Slow
Built environment[cxxii,cxxiii,cxxiv,cxxv]	PPRR	Moderate	Variable

Air quality & temperature

Air quality and temperature variation as expressed through seasonal trends is observed to have a significant influence on infectious diseases spread especially in the current pandemic context i.e. cooler weather appears to increase transmission. Sustained changes in ambient temperature, linked to climate change are associated with changes in vector habitats that facilitate spread of infectious diseases and increase pandemic risk. Air quality – both indoor and outdoor is also important in facilitating epidemic spread – as measured by levels of CO2 and ambient particulate matter (APM) respectively. Water availability and quality are critical components for preventing spread of infectious diseases as is appropriate wastewater disposal or sanitation systems. Land use particularly through agriculture, forestry and livestock/pisciculture practices can enhance the risk of zoonotic spillover through a combination of factors including a loss of biodiversity, habitat degradation, production conditions that facilitate the emergence of pathogens with epidemic potential i.e., antimicrobial resistance and direct contact between pathogens and humans.

Human-wildlife interaction

Emergence of an infectious disease outbreak is often an environmental matter. Many infectious diseases of concern are zoonotic, foodborne, and/or waterborne and are thus closely linked to environmental health. Many recent major epidemics have been of zoonotic or vector-borne origin, as demonstrated with recent high-profile epidemics including HIV, Ebola, Zika, malaria, and COVID-19. A key environmental determinant that derives health emergencies therefore has to be the human-wildlife interaction for its role in spillover and spillback.

Climate change and natural disasters

Another determinant moves beyond the direct interactions of humans with other species but the broader ecological stability overall. Climate change and increasing wildlife trade have been identified in the literature as global-scale drivers of infectious disease emergence, with ecological changes for example (due to agricultural and food-handling practices, deforestation and reforestation, and changes in the water ecosystems) considered to be critical. This was reflected in the Delphi process, in which one expert cited the importance of the often-overlooked oceanic systems and their influence on coastal areas and estuaries (e.g., HABs and microbial contamination of waters and seafood).

The most obvious global environmental determinant of concern is climate change and natural disasters, which act as a risk multiplier through increasing the frequency and intensity of natural disasters and extreme weather events (e.g., droughts, wildfires, extreme heat, floods, cyclones, extreme cold), destabilizing ecosystems, shifting weather and animal migration patterns, and increasing food and water insecurity.

Meteorologic and Geographic factors

Outside of climate change are the related but more stable meteorologic and geographic factors such as terrain, altitude, seasonality, and weather. It should be noted that these factors are valuable not necessarily on the global level, but rather as signals on the regional level, or perhaps combined with global population distribution.

Land Use, Agricultural Practices, Food Security, WASH

Given the interconnectedness of the environment, it should come as no surprise that many determinants overlap but have nevertheless been separated for higher utility. Land use change incorporates issues like deforestation and reforestation while agricultural and farming practices deal specifically with application of fertilizers, use of antibiotics, and livestock handling. Food security and safety deals downstream with foodborne disease and food access but relates as well to WASH and human-wildlife interaction, for which food insecurity may be a driver (e.g., bushmeat consumption).

Ecosystem biodiversity

One key area of debate during the Delphi process and in the literature is the importance of ecosystem biodiversity in disease emergence. The issue of the dilution effect may require nuance and regional specificity in the application of a biodiversity indicator. Furthermore, most biodiversity indicators are oriented towards and more useful for developed nations highlighting the need for the development of more regionalized indicators and metrics more useful for developing nations.[cxxvi]

Built Environment

The built environment is also a major driver of pandemic risk. Housing conditions linked to crowding and indoor air quality are established determinants of spread of infectious diseases. Plenty of literature[cxxvii] prior to and during the pandemic establishes a strong link between substandard homes and poor health outcomes, often affecting those who are already most vulnerable (lead in homes and the development of children; poor air quality and crowding leading to asthma and increased spread of viruses, segregation of older individuals in long-term care or nursing homes where quality of care and infection prevention and control are wide variable. Residential areas especially those linked to urban slums also constitute a convergence of housing, air quality, and water and sanitation conditions that amplify infectious disease spread. Workplaces can be both direct and indirectly linked to infectious diseases risk. High density work environments with poor ventilation and/or high levels of toxins in the air facilitate infectious disease spread directly (e.g., meatpacking factories in this pandemic). Indirectly, many workplace environments e.g., mines, where workers migrate to live in surrounding camps or worker residences, become conducive for the spread of infectious diseases like tuberculosis, syphilis and HIV/AIDS secondary to a convergence of insalubrious factors in the living environment and/or the absence of social supports such as paid sick leave. The recreational or cultural built environment also constitutes an important source of risk for pandemics linked for example to the high densities of people associated with religious congregations, social events like concerts and night clubs, and tourism related to congregate transport (buses, ships, planes) and hotels.

And finally, given the interconnectedness and connectivity, as discussed above, measures and policies need to take a One Health approach, one that assesses planetary, animal, and human health together in preparation and response to a pandemic. To do this, all environmental practices must be regulated with a technical lens, rather than a political one.

Technological determinants

We have identified several technological determinants that have are most significant in driving and amplifying risk. (Table A3.6)

Table A3.6Technological determinants identified as being important in their potential or perceived role in exacerbating health emergencies

Technological determinant	PPRR	Measurability	Rate of change
Social media usage and misinformation	Recovery Response	Difficult (given vast social media data)	Fast
Technological infrastructure[cxxviii]	PPRR	Difficult	Variable
Digital connectivity	PPRR	Moderate	Fast
(Lack of) Biomedical innovations[cxxix]	PPRR	Easy	Fast
Democratization of biotechnology	Prevention Preparedness	Difficult (very little data availability)	Fast
Supply chain	Response Recovery	Difficult	Variable
Interoperability of IT systems (e.g., surveillance and vital registration, health data information management, logistics information management)	Prevention Preparedness Response Recovery	Difficult	Slow

Biomedical innovations, R&D
Most attention in this domain has focused on technologies related to the health sector namely biomedical innovations and diagnostics, therapeutics, vaccines and infection prevention and control commodities such as masks. There are however other technological determinants that are of growing relevance to pandemic risk management that are not developed specifically for health purposes but have become increasingly important given their ability to be applied for health purposes. Foremost amongst these are digital technologies that are being integrated in diverse and rapid ways and that are presenting both opportunities and challenges in pandemic risk management. Recent analyses point to the importance of including digital access[cxxx] and **digital connectivity** as critical measures of societal resilience in times of

pandemics. Reliable access to high-speed internet determines people's ability to work from home, to participate in online schooling, to access necessary information on the crisis, and quickly adopt digital tools. Digital connectivity has also ensured that even when a nation closes to mitigate pandemic risk, people could stay connected with friends and family. As observed during the pandemic, digital connectivity can also provide real time assessments of mobility patterns, useful to track spread during an infectious disease.

Social media & misinformation
The other side of digital connectivity is of course social media usage and misinformation in spreading it, to devastating effects. Considered to be an "information" pandemic of its own, mis and disinformation has distorted people's behavior (e.g., anti-vaccine beliefs) and policies (e.g, anti-mask mandates), eroded trust in science and public health, and has visibly increased the negative impacts of the pandemic.

Technological infrastructure, Interoperability of IT systems
Technological infrastructure and innovation have and will continue to play a role in determining the magnitude of health crises; these include laboratory and surveillance capacity, new methods of contact tracing, research and development, biotechnology etc.) Adding to this, **the interoperability of IT systems,** including but not limited to surveillance and vital registration systems**,** health data information management systems, and logistics information management systems are critical pieces of the technological infrastructure that need to be monitored. A major challenge stems from the fact that all of these systems – both on the supply side (manufacturing, production, and distribution systems) and on the data side, are unconnected at both the country and global levels, which has been a major source of disruption during the ongoing pandemic, hindering response capacity, and exacerbating risk

Supply chain
As demonstrated with the pandemic, supply chain is also of critical importance. Availability and accessibility of medical and non-medical products is key to a functioning and healthy society. Monitoring prevalence of stockouts, medicine availability, as well as receiving insights on surge manufacturing is one potential approach in measuring various aspects of the supply chain issue.

Democratization of biotechnology
And finally, the democratization of biotechnology can be considered to be an emerging and important threat, with the potential of generating novel health emergencies, if not carefully monitored. Monitoring biohacking availability, accessibility of bioweapons, and, research conducted towards gain of function, can all be preliminary sources of information to start piecing together a mostly uncovered and unmonitored space.

Of all pillars, this pillar appears to have the largest gaps, both in the literature and in our conversation with experts, in better understanding digital transformations and the integration of technology in bettering our health and our foundational structures.

Because technology – and innovation - can both drive and mitigate risks associated with health emergencies, many unexplored areas such as AI, social media mining, civil society engagement to crowdsource, politics of data and data sharing agreements, and broader financing of technological platforms require additional investment.

Appendix 3.

Review of COVID-19 models

Review of International COVID-19 Models

Our attempt to identify measurable indicators included the assessment of 6 international COVID-19 models and 7 USA-based forecasting COVID-19 models. In general, methodologic details were lacking and when provided, often vague for any meaningful operationalization or monitoring. Most models were primarily focused on proximal determinants of epidemiologic parameters such as cases, hospitalizations and deaths. The few broader determinant variables included had limited details on their specification and operationalization or were estimated through machine learning algorithms as a 'global' variable that captured the average impact of these parameters on epidemic trajectory. Any relevant variables through this exercise were included in the master list of indicators if the study team identified them as playing a role in upstream variables. Because the final list of selected indicators included filtering criteria that assessed modifiability and actionability, variables that may be measurable may not necessarily have come up in the final list of "dirty-dozen" indicators.

Model 1: Institute for Health Metrics & Evaluation (IHME)

Primary Outcome: Predicted Mortality (global); also includes ICU, hospitalization, ventilators.

Important Note(s): The IHME model has undergone numerous iterations and updates, not all of which are well documented or easily accessible. The below table represents a composite of multiple iterations of their model and various data sources used. In some cases, operationalization of data is not specified.

Source(s): https://www.nature.com/articles/s41591-020-1132-9; http://www.healthdata.org/covid/updates;

Parameter	Data Source	How Operationalized?

Mobility (lagged data)	Measured via cell phone mobility data (anonymized data from Google, Facebook, Apple)	Operationalized to influence the frequency of human contact. Influenced also in part by vaccine coverage
Quality of death registration	Unspecified. Potentially WHO data on coverage of death registration	Unspecified. Potentially influences proportion of missed deaths and corrects for underreporting.
Average latitude	Geographic location	Unspecified. Potentially linked with seasonality trends (below).
Healthcare Access & Quality Index	Global Burden of Disease Study	Unspecified. Potentially influences mortality risk after infection.
Seasonality of transmission	Seasonal patterns of pneumonia	Operationalized to influence risk of mortality.
Altitude	Global Burden of Disease Study	Proportion of population living below 100m above sea-level. Influence on mortality, as lower respiratory infection mortality increases at greater altitudes
Ambient Particulate Matter	Global Burden of Disease Study	Population-weighted mean exposure to <2.5micrometer particles. Unspecified how it is operationalized.
Population Density	*Worldpop* total population registers	Proportion of population living in areas denser than 1000 people per square kilometer. Unspecified how operationalized.

Mask Use	Self-reported mask use outside of homes	Unspecified. Potentially influences risk of infection.

Model 2: Youyang Gu

Primary Outcome: Deaths (global); also includes USA specific estimates for cases and ICU.

Important Note(s): This model is based on a machine learning algorithm to see which variables best predict future trends. As such, many parameters included are 'composites' of different phenomena—for example, lockdown fatigue captures various things such as trust in government, adherence to public health measures, and mobility.

Source(s): https://github.com/youyanggu/yyg-seir-simulator#parameters; https://covid19-projections.com/about/;

Parameter	**Data Source**	**How Operationalized?**
Lockdown Fatigue	Unspecified	Impacts the effective reproductive number (effective number of contacts and thus potential new infections per person).
Fall Multiplier	Unspecified	A multiplier on the R-naught value based on the potential for increased contacts associated with school re-openings and seasonality of transmission.

Model 3: DELPHI-MIT

Primary Outcome: Mortality and cases; also collects hospitalization

Important Note(s): The DELPHI model seeks to use real world impacts of different policies to estimate the impact of interventions on the force of infection. There is no specific inclusion of social, economic, political, environmental, or technological determinants beyond those ‘embedded’ within estimates of effect. As such, no parameters have been drawn from this model.

Source(s): https://www.medrxiv.org/content/10.1101/2020.06.23.20138693v2.full.pdf (recent to June 2021).

Model 4: Imperial

Primary Outcome: Mortality and cases; also collects hospitalizations and ICU

Important Note(s): Targeted to low- and middle-income countries. Initially designed to model the (assumed) impact of various interventions, it now includes consideration for many other aspects, including variants of concern and vaccine rollout.

Source(s): https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-09-25-COVID19-Report-33.pdf; https://www.science.org/doi/full/10.1126/science.abc0035; https://mrc-ide.github.io/global-lmic-reports/parameters.html;

Parameter	**Data Source**	**How Operationalized?**
Health System Constraints	World Bank Data	Assumed as limited hospital capacity available so not all those who require hospitalization will receive it, impacting mortality. The constraints are greatest in LIC, as compared to LMIC and UMIC.
Mobility	Google	Differences in mobility impact number of effective contacts and opportunities for transmission (affect R-naught).
Vaccine Hesitancy	Assumed	Fixed hesitancy at 20% of the population (i.e., 80% of the population eligible for vaccination will receive it).
Population Structure	WHO, government/academic sources, others	To develop a population structure for vaccine roll-out that targets people based on occupation (i.e., health workers), older age, and medical conditions.

Model 5: LANL-GR

Primary Outcome: Mortality and cases

Important Note(s): This is a compartmental SIR-type model, which forecasts different case and death trajectories at state and country level. It has growth parameters included, but these are based on observed data and are not adjusted for social, economic, political, environmental, or technological determinants. No parameters have been extracted from this model.

Source(s): https://covid-19.bsvgateway.org/static/COFFEE-methodology.pdf; https://covid-19.bsvgateway.org/;

Model 6: USC SIKJalpha

Primary Outcome: Mortality and cases

Important Note(s): This model consists of stratifying the population into many regions and having variability in the rate of infection and mobility pattern. Other variables are drawn from epidemiologic input data to predict mortality and cases.

Source(s): https://arxiv.org/pdf/2007.05180.pdf; https://github.com/scc-usc/ReCOVER-COVID-19;

Parameter	Data Source	How Operationalized?
Mobility Patterns	Google	Based on inter-regional travel and spread of infection, increased mobility increases likelihood of contact & infection.

Review of country-specific US COVID-19 models

Model 1: JHU_IDD-CovidSP

Primary Outcome: Cases, Deaths

Important Note(s): Key aspect considered is mobility, using an online repository of mobility.

Source(s): https://github.com/HopkinsIDD/COVIDScenarioPipeline

Parameter	Data Source	How Operationalized?
Mobility	COVID-19 Mobility Data Network (https://www.covid19mobility.org/)	Links to an R package that reads repository data containing various mobility metrics that includes: social distancing, travel, and mobility data.

Model 2: DeepCOVID

Primary Outcome: Cases, Hospitalizations, Deaths

Important Note(s): For overlapping locations see: Couture, V.; et al. 2020. Measuring movement and social contact with smartphone data: a real-time application to COVID-19. Technical report, National Bureau of Economic Research.

Source(s): https://www.medrxiv.org/content/10.1101/2020.09.28.20203109v3.full.pdf

Parameter	Data Source	How Operationalized?
Mobility	Google/Apple; Tracking overlapping locations	Changing mobility patterns and frequency/duration of social exposures.
Prevalence of symptoms	Kinsa digital thermometers; Facebook survey	To estimate proportion of population with ILI.

Model 3: MOBS-GLEAM_COVID

Primary Outcome: Cases, Hospitalizations, Deaths

Important Note(s): Sources not well documented…

Source(s): https://uploads-ssl.webflow.com/58e6558acc00ee8e4536c1f5/5e8bab44f5baae4c1c2a75d2_GLEAM_web.pdf

Parameter	Data Source	How Operationalized?
Air Travel	Airline Data Patterns (daily passenger flows between locations).	Individuals in the model travel on airplanes according to an explicit dynamic that considers the probability for each individual in the subpopulation to travel on a specific route.
Short-Range Mobility	Offices of Statistics	Movement between different regions based on commuting and car travel.

Model 4: UMich-RidgeTfReg

Primary Outcome: Cases, Deaths

Important Note(s): Sources not well documented…

Source(s): https://gitlab.com/sabcorse/covid-19-collaboration

Parameter	Data Source	How Operationalized?
Mobility	Google Mobility Report	Unclear.

Model 5: Google_Harvard-CPF

Primary Outcome: Cases, Hospitalizations, Deaths

Important Note(s): Most parameters are allowed to impact contact rates (which influence rates of infection) and downstream impacts (such as hospitalization, death, and recovery).

Source(s): https://arxiv.org/pdf/2008.00646.pdf

Parameter	Data Source	How Operationalized?
Mobility Indices	Mobility changes in response to covid-19. arXiv:2003.14228 [cs.SI], 3 2020	Affects average contact rates.
Income	US Census; BigQuery (bigquery-public-data:census bureau acs.county 2018 5yr and bigquery-publicdata:census bureau acs.county 2018 1yr)	Rates of infection, hospitalization, recovery.
Population Density		Rates of infection, hospitalization, recovery.
Households on food stamps		Rates of infection, hospitalization, recovery.
Number per household		Rates of infection, hospitalization, recovery.
Population above 60y	The Kaiser Family Foundation (On BigQuery at c19hcc-infoext-data:c19hcc info public.Kaiser Health demographics by Counties States)	Average contact rates.
Hospital rating scale	BigQuery public dataset that comes from the Center for Medicare and Medicaid Services	Rates of identification, recovery, death, and re-infection

Available types of hospitals	BigQuery public dataset that comes from the Center for Medicare and Medicaid Services	Rates of identification, recovery, death, and re-infection
Air quality measures	BigQuery public dataset that comes from the US Environmental Protection Agency (EPA); (bigquery-public-data:epa historical air quality.pm10 daily summary)	Rates of recovery and death

Model 6: MIT_CritData-GBCF

Primary Outcome: Cases, Hospitalizations, Deaths

Important Note(s): Implementation not well documented.

Source(s): https://github.com/sakethsundar/covid-forecaster

Parameter	Data Source	How Operationalized?
Mobility	PlaceIQ	Exposure indices based on movement data impact contact
Hospital capacity/utilization	Department of HHS	Unclear
County-level socioeconomic data	Various (https://github.com/JieYingWu/COVID-19_US_County-level_Summaries/blob/master/data/README.md)	List of variables: https://github.com/JieYingWu/COVID-19_US_County-level_Summaries/blob/master/data/availability.csv

Model 7: JHU_CSSE-DECOM

Primary Outcome: Cases, Hospitalizations, Deaths

Important Note(s): Vague implementation.

Source(s): https://systems.jhu.edu/research/public-health/predicting-covid-19-risk/

Parameter	**Data Source**	**How Operationalized?**
Mobility	SafeGraph	Used to generate metrics related to likelihood of viral spread
Demographics	Department of HHS	Includes population size, age, sex, and others.
Health/Economic Measurements	County Health Rankings	Includes smoking percentages, poverty, rates of chronic disease and others (https://www.countyhealthrankings.org/explore-health-rankings/measures-data-sources/2021-measures)
Hospital bed availability	Definitive Healthcare Dataset from ESRI	https://www.esri.com/en-us/arcgis-marketplace/listing/products/bd5bc35bbdca41d4a9312edefb5e9ee6

Appendix 4, included as an additional attachment, consists of the master list of indicators for all determinants across the STEEP pillars.

Appendix 5, included as an additional attachment, consists of the pillar-specific evidence synthesis from the five scoping reviews.

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