Pandemic Risk Assessment and its Intersection with Climate Change

Needs, Opportunities, and Design Considerations

June 9, 2025

BACKGROUND INFORMATION

The increasing frequency and severity of infectious disease outbreaks—driven by factors such as climate change, new methods of land use, urbanization, and global interconnectedness—underscore the urgent need for robust pandemic risk assessment frameworks. Future pandemics, which will likely be exacerbated by complex anthropogenic factors and inadequate systems for infectious disease surveillance and response, pose a substantial and underappreciated risk to both global health and economic well-being, with expected economic losses comparable to those of climate change (Fan et al., 2018). Despite the magnitude of these threats, pandemic risk remains poorly understood, supported by fragmented and insufficiently cumulative research, and limited quantitative assessment tools exist to understand these risks.

Against this backdrop, the United Nations Foundation (UN Foundation), in collaboration with the United States (US) National Academy of Medicine (NAM), the Fundação Oswaldo Cruz (Fiocruz), and the Global Pandemic Monitoring Board (GPMB) and with support from Pax sapiens and the Skoll Foundation, organized a workshop on October 28–29, 2024, in Rio de Janeiro, Brazil, titled *Pandemic Risk Assessment and its Intersection with Climate Change: Needs, Opportunities, and Design Considerations*. The workshop brought together a global multidisciplinary group of health leaders, scientists, and policymakers to address the pressing need to develop a pandemic risk assessment agenda, with particular attention to climate change as a driver of risk, but also considering a broader set of contributing factors. The workshop aimed to examine existing systems and methodologies for assessing pandemic risk; identify the challenges of linking climate and health data; and propose actionable steps to enhance global capacity to identify and quantify risk drivers, estimate economic and health impacts, and monitor change in risk levels.

MEETING SUMMARY

Welcome Remarks

The workshop opened with remarks from **Dr. Victor Dzau,** NAM, and **Dr. Maria de Lourdes Aguiar Oliveira**, Fiocruz. Dr. Dzau reflected on the lessons of COVID-19 and highlighted the complex interplay between climate change, human activity, and infectious disease emergence. He emphasized the need for comprehensive frameworks to monitor and mitigate pandemic threats and called for a global pandemic monitoring mechanism that would provide multidisciplinary assessments to inform policies and build resilience. Dr. Oliveira underscored Fiocruz's 124-year legacy in public health and highlighted its pivotal role in pandemic response, including the COVID-19 crisis, as well as its contributions to genomic surveillance, wastewater monitoring, and diagnostic networks. She stressed the importance of cross-sector collaboration and equitable partnerships to address the interconnected challenges of pandemics and climate change.

Workshop Objectives

Dr. Cecilia Mundaca Shah, UN Foundation, and **Dr. Ben Oppenheim,** Ginkgo Bioworks, Inc., introduced

the workshop's objectives. Dr. Shah thanked the co-hosts, sponsors, and planning committee members for their involvement in facilitating the workshop. Dr. Oppenheim outlined the workshop's focus on assessing the maturity of scientific approaches, the quality and reliability of available data, and the precision of current modeling techniques. He stressed the importance of identifying areas of scientific consensus and disagreement to guide actionable insights for policymakers.

Keynote Address

Ms. Joy Phumaphi, GPMB, framed pandemics as persistent and evolving threats that require proactive and holistic mitigation strategies. Drawing from a recent GPMB report titled *The Changing Face of Pandemic Risk*, she highlighted four high-impact drivers of pandemic risk: global movement, agricultural practices, misinformation, and trust deficits between institutions and communities (GPMB, 2024). She proposed three pillars for building global resilience against pandemics: adapt through flexible, forward-looking planning; protect by strengthening health systems and safety nets; and connect through enhanced cross-sectoral and international collaboration. She concluded by urging participants to prioritize integrated approaches and long-term investments to build this resilience.

Regional Perspectives on Pandemic Risk Assessment

Dr. Ciro Ugarte, Health Emergencies, Pan American Health Organization (PAHO/WHO), and **Dr. Lwazi Manzi,** African Union Pandemic Preparedness and Response Commission, provided regional perspectives on pandemic risk assessment. Dr. Ugarte highlighted progress in integrating climate change considerations into health systems in the Americas but noted that while some countries have improved risk assessment and surveillance, many struggle to fully connect epidemiology, health systems, and emergency response. He outlined PAHO/WHO's climate change and health efforts, including climate-informed early warning systems in eight countries, a regional action plan, and rapid risk assessments. He also stressed the critical role of national governments, supported by regional initiatives, in pandemic response. Dr. Manzi noted that the Africa Centres for Disease Control and Prevention (Africa CDC) has a legal mandate for pandemic risk assessment and highlighted its *Risk Ranking and Prioritization of Epidemic-Prone Diseases,* a decision support tool that helps identify and rank high-risk pathogens to inform regional preparedness and response efforts (African Union and Africa CDC, 2022). However, she emphasized broader factors influencing pandemic risk, including climate change, socioeconomic challenges, conflict, weak One Health capacity, and limited cross-border surveillance. She called for risk assessment tools that also inform mitigation strategies, stressing the need for regional vaccine manufacturing, stronger surveillance, and greater Global South representation in pandemic response.

Session I: Risk Assessment: Current Systems, Capabilities, and End-User Needs

The session was moderated by **Dr. Cecilia Mundaca Shah,** UN Foundation. The panel included **Dr. Abdirahman Mahamud,** Health Emergencies Programme, World Health Organization (WHO); **Dr. Ciro Ugarte,** PAHO/WHO; **Dr. Henry Kyobe-Bosa,** Ministry of Health, Uganda; **Mr. Sam Halabi,** Center for Transformational Health Law, O'Neill Institute for National and Global Health Law, Georgetown Law; and **Dr. Aïda Diongue-Niang,** National Agency of Civil Aviation and Meteorology, Senegal.

This session explored the evolving landscape of pandemic risk assessment, emphasizing the need for robust frameworks, fair and inclusive data access, and tools that translate risk insights into preparedness actions. Panelists emphasized the importance of ensuring that risk assessments translate into actionable efforts and leveraging diverse multisectoral data to enhance risk assessments. Additionally, discussions highlighted the importance of fairness and transparency in data access and decision making.

Dr. Mahamud highlighted WHO's risk assessment tools and stressed the need to link assessments to decision making, governance, financing, and policy

implementation. He called for a global pandemic accord to unify preparedness standards. Dr. Ugarte emphasized the need for action oriented risk assessments. While more than 160 Joint External Evaluations (JEE) have been conducted, funding gaps hinder national action plans. He urged improvements to tools like the International Health Regulations and Global Health Security Index (GHSI). Dr. Kyobe-Bosa, speaking as an end user of risk assessments and analytical tools, stressed the need for granular, context-specific insights and improved access to data sources to support decision making. He noted that Uganda's intensive care unit bed shortage during COVID-19 was largely unforeseen in initial risk assessments, highlighting the need for better capacity evaluations. He also suggested incorporating subnational data on risk and preparedness to strengthen responses. Mr. Halabi highlighted the potential benefits of an independent panel on pandemic risk, a mechanism similar to the Intergovernmental Panel on Climate Change (IPCC), emphasizing its ability to distill complex variables into actionable insights. He also pointed to the need for greater transparency in WHO's Public Health Emergency of International Concern determinations, arguing that clearer criteria and more open decision making processes could build trust and facilitate increasingly effective global responses. Dr. Diongue-Niang emphasized the importance of ensuring fair access to data, resources, and inclusive representation in global risk assessment frameworks. Drawing on her experience with the IPCC, she highlighted the need to balance specialized scientific expertise with broad geographic representation to ensure that diverse voices are included, even when technical capacity varies across regions. She stressed the need for geographically diverse authorship and equitable data access, particularly for low-income nations that often face institutional barriers to participation.

During the discussion, participants noted that risk assessments should extend beyond technical analyses to drive tangible improvements in preparedness and response at both global and local levels. Equity was also a central concern, with speakers stressing that health care access is a fundamental component of pandemic preparedness. Other participants underscored that risk assessments should incorporate social vulnerabilities, community-specific practices, and diverse needs to be truly effective in pandemic prevention, preparedness, and response. Key insights from this session are highlighted in *Box 1*.

Session IIA: Outbreak Risk (Pre-Emergence—Spillover)

This session explored the drivers of disease emergence, focusing on how land use, agricultural practices, and wildlife trade influence pathogen spillover risk. Panelists discussed surveillance challenges; the importance of accessing and leveraging diverse data sources; intervention effectiveness; and the need for context-specific, community-driven approaches to mitigate emerging infectious disease threats.

The session was moderated by **Dr. Louise Gresham,** Pax sapiens. The panel included **Dr. Daniel Becker,** University of Oklahoma; **Dr. Benjamin Roche,** Preventing Zoonotic Disease Emergence (PREZODE) and French National Research Institute for Sustainable Development; **Dr. Sarah Olson,** Wildlife Conservation Society (WCS); **Dr. Erik Karlsson,** Institute Pasteur, Cambodia; and **Dr. Skylar Hopkins,** North Carolina State University.

Dr. Becker highlighted how deforestation and urban expansion force wildlife into human contact, increasing spillover risks, and how climate change alters migration and food patterns, requiring better wildlife surveillance, particularly outside Asia. He called for prioritizing viral discovery in high-risk species like bats and rodents. Dr.Roche introduced PREZODE, a global initiative connecting stakeholders to prevent zoonotic disease emergence. He emphasized the need for local spillover mitigation strategies and standardized indicators to measure human exposure to zoonotic diseases. Dr. Olson stressed the importance of long-term monitoring and integrating research with surveillance to improve risk assessments. She highlighted WCS's work analyzing land use

BOX 1 | Key Insights: Risk Assessment: Current Systems, Capabilities, and End-User Needs

- Risk assessments should be linked to decision making and drive actionable solutions to strengthen country capacities, with a focus on granular, context-specific insights, particularly in capacity distribution.
- Effective risk assessment requires strong governance structures, sustainable financing, and supportive policy frameworks.
- Existing tools, such as the JEE and the GHSI, require refinement to better identify critical vulnerabilities.
- Decision making should ensure equitable access to data, technological tools, and participation for all countries.
- Risk assessments should incorporate social vulnerabilities, community-specific practices, and diverse needs to enhance pandemic preparedness.

SOURCE: Created by the authors.

change gradients and the need for community co-development to align surveillance with local priorities. Dr. Karlsson discussed the limitations of traditional surveillance, advocating for metagenomics and environmental sampling to detect multiple pathogens in high-risk areas. However, he noted, early detection should be paired with clear guidelines for policymakers, as effective risk communication depends on how data is presented. Dr. Hopkins examined the effectiveness of interventions aimed at preventing zoonotic spillover risk, particularly those designed to achieve both conservation and public health goals. She noted that while many proposed solutions target land use changes, interventions addressing climate change-related drivers are rare. She stressed the lack of robust evidence for climate change mitigation efforts, with many proposed solutions failing to account for feasibility, social acceptability, and unintended consequences. She highlighted community-led partnerships as promising models for testing and refining mitigation efforts that align with local needs.

During the discussion, panelists highlighted challenges in accessing and utilizing diverse data sources and the need for multi-source models that combine epidemiological, ecological, and social data. They noted that technical, legal, and ethical barriers hinder data interoperability, limiting comprehensive spillover risk assessments. Participants also noted the difficulty of predicting viral risk based solely on pathogen characteristics. While *in vitro* experimentation remains essential for assessing spillover potential, ongoing debate around gain-of-function research—as well as the high cost and complexity of maintaining BSL-3 and BSL-4 facilities— present challenges for advancing risk assessments. Although gain-of-function research restrictions are intended to prevent accidental release and enhance biosafety, they can also constrain certain studies on high-risk pathogens. Risk assessment should extend beyond pathogen detection and incorporate ecological and environmental factors to better understand spillover dynamics. Key insights from this session are highlighted in *Box 2*.

Session IIB: Outbreak Risk (Pre-and-Post Emergence—Climate)

This session explored the intersections between climate change and pandemic risk, focusing on how temperature shifts, extreme weather, and environmental changes influence zoonotic spillover, vector-borne diseases, and respiratory

BOX 2 | Key Insights: Outbreak Risk (Pre-Emergence—Spillover)

- Data synthesis is essential for identifying spillover drivers, with a priority on viral discovery in key species (e.g., bats and rodents) to improve understanding of spillover dynamics in tropical regions.
- Local-level identification of spillover drivers and mitigation strategies is crucial.
- Sustained investment in monitoring systems and long-term studies of frequently occurring pathogens is needed to improve spillover risk assessments.
- Surveillance innovations, including metagenomics and environmental sampling, offer promising alternatives for detecting multiple pathogens in high-risk environments such as markets and farms.
- There is a need for more robust evidence on intervention effectiveness, as many proposed solutions fail to account for feasibility, social acceptability, and unintended consequences.

SOURCE: Created by the authors.

infections. Panelists discussed the role of climate modeling, surveillance innovations, and global policy coordination in mitigating future health risks.

The session was moderated by **Dr. Ben Oppenheim,** Ginkgo Bioworks. The panel included **Dr. Rachel Baker,** Brown University School of Public Health; **Dr. Laura-Lee Boodram,** Caribbean Public Health Agency; **Dr. Luiz Augusto Galvão,** Fiocruz; and **Dr. Tulio de Oliveira,** Stellenbosch University.

Dr. Baker challenged the conventional view of climate-sensitive infectious diseases (CSIDs), noting that they include vector transmitted diseases and directly transmitted diseases, exhibit seasonal outbreak patterns, and demonstrate variation by latitude. She also highlighted how researchers use statistical models to estimate climate's impact on CSID transmission, which appears to be most evident in a disease's endemic phase. Dr. Boodram highlighted efforts in the Caribbean to merge climate, demographic, and disease data for outbreak prediction. She described a dengue prediction model co-developed with European and Brazilian institutions that provides probabilistic forecasts with a 3-month lead time for over 550 micro-regions in Brazil (Díaz et al., 2024). She also underscored the importance of data quality in ensuring model accuracy. Dr. Galvão emphasized that climate-driven health risks are changing across generations, with those born in 2020 facing significantly different risks than those born in 1950. He stressed that future generations' health outcomes will depend on the immediacy and effectiveness of current policy decisions, calling for greater alignment between global frameworks—including the UN's Sustainable Development Goals, the Paris Agreement, and the Sendai Framework—to address climate-related health challenges. Dr. de Oliveira showcased genomic surveillance as a tool for responding to climate-driven epidemics, emphasizing how real-time genetic sequencing can support epidemic response, biomedical discovery, and vaccine development. He highlighted Stellenbosch University's Centre for Epidemic Response and Innovation's role in developing Africa's first mRNA vaccine and successful efforts to track mpox and cholera strains, aiding diagnostics and vaccine distribution.

During the discussion, panelists addressed challenges in forecasting long-term climate and disease trends due to limited historical data. Accurate projections require decades of records, making it challenging to model future risks without such data. As a result, long-term models that account for climate and societal changes remain underdeveloped, limiting their usefulness in decision making. However, artificial intelligence

(AI) and large language models can potentially harness insights from diverse datasets—including climate, genomic, and surveillance data—to improve predictions. Panelists also stressed the need to incorporate climate-induced vulnerabilities into disease models, as factors like urbanization, aging populations, and global connectivity alter disease risks and require a holistic approach to risk assessment. Key insights from this session are highlighted in *Box 3*.

Session III: Pandemic Risk (Post-Emergence)

This session explored the factors influencing disease transmission after the initial outbreak, highlighting the role of human mobility, social behaviors, early warning systems, and public health interventions in controlling disease. Panelists illuminated the need for locally-tailored risk assessments, improved surveillance systems, and ethical approaches to data use.

The session was moderated by **Dr. Sylvie Briand,** GPMB. The panel included **Dr. Abdirahman Mahamud,** WHO; **Dr. Bach Tran,** Hanoi Medical University; **Dr. Iris Hunger,** Robert Koch Institute; **Dr. Thumbi Mwangi,** University of Nairobi; and **Dr. Cesar Munayco Escate,** Ministry of Health, Peru.

Dr. Mahamud stressed that pandemic response strategies should be tailored to local conditions and highlighted WHO's use of scenario modeling, short-term forecasting, and disease exportation analysis to improve response planning. He emphasized the need to integrate social science into epidemiological models, explaining that WHO deploys social scientists to study community-specific behaviors and improve intervention effectiveness. Dr. Tran showcased Vietnam's early warning system, which utilizes real-time data, a vulnerability index, and infectious disease assessments to prioritize resources and improve outbreak response. He emphasized the importance of behavioral and environmental factors in transmission modeling. Dr. Hunger highlighted the importance of non-pharmaceutical interventions (NPIs) in outbreak management while noting gaps in understanding their effectiveness. She called for stronger evidence from COVID-19 data to assess NPIs' impact and stressed the need to consider long-term health and socioeconomic impacts in risk assessments. Dr. Mwangi discussed the challenge of tracking viral spread. In Kenya, limited data on contact patterns during COVID-19 forced policymakers to rely on global datasets such as European contact matrices

BOX 3 | Key Insights: Outbreak Risk (Pre- and Post-Emergence—Climate)

- Climate change is reshaping population health risks over time.
- Climate change influences disease transmission, particularly during the endemic phase, where temperature and humidity largely determine the timing and intensity of outbreaks.
- Leveraging the combined insights of climate, demographic, and disease data is essential for improving outbreak prediction, with data quality playing a critical role in model accuracy.
- Genomic surveillance can support epidemic response, biomedical discovery, and vaccine development, with rapid genetic sequencing playing an important and growing role in responding to epidemics.
- Climate-induced vulnerabilities should be incorporated into disease risk models and should consider socioeconomic conditions and urban development factors. Increased global connectivity, aging populations, and declining birth rates are further reshaping infectious disease risks, requiring a more holistic approach to risk assessment.

SOURCE: Created by the authors.

and Facebook mobility data. He noted that insights from such data revealed the ineffectiveness of certain movement restrictions, allowing officials to adjust public health strategies accordingly. He focused on the need for greater investment in local data collection, particularly from mobile phones, credit cards, and wearable devices to improve disease modeling in resource-limited settings. Dr. Escate reflected on Peru's efforts to build modeling capacity during COVID-19. He explained how, in order to address gaps in expertise and data, the Ministry of Health created a modeling unit of university-trained professionals who are now vital to epidemic preparedness and outbreak response, including during Peru's recent dengue epidemic. He emphasized the need to strengthen surveillance systems and improve data collection on the social determinants of health and human movement to enhance predictive accuracy.

During the discussion, panelists addressed contact tracing challenges and digital innovations in outbreak response. A South African platform using WhatsApp data demonstrated how digital tools and community-driven approaches can identify outbreak hotspots. Proactive data partnerships—establishing relationships with data holders before crises—were seen as more effective than reactive, crisis-driven efforts. Furthermore, speakers stressed the importance of community health workers in building trust and ensuring public cooperation. The discussion concluded with ethical concerns about data use in risk assessment, and the speakers agreed that there is a need to balance individual privacy with public health priorities. Key insights from this session are highlighted in *Box 4*.

Day One Closing

Dr. Oppenheim summarized Day 1, emphasizing key themes from the discussions. First, he highlighted the importance of "slow science," acknowledging that meaningful progress in understanding disease spillover and risk assessment requires long-term, sustained investment. Second, he noted the complex and multidisciplinary nature of measuring risk, including the need to incorporate evolving population-level challenges. Third, he discussed the necessity of deeply integrating social science into computational models, acknowledging that this integration will likely be a gradual process involving theoretical and practical advancements. Finally, he emphasized the importance of designing research outputs that are accessible to a wide

BOX 4 | Key Insights: Pandemic Risk (Post-Emergence)

- Pandemic response strategies should be tailored to local conditions, and understanding how infected individuals spread viruses remains a challenge.
- Human behavior, mobility, and environmental factors drive disease spread, requiring the integration of social science theory and data into risk models and assessments.
- More robust and globally representative empirical evidence is needed to assess the effectiveness of NPIs.
- Strengthening surveillance systems and improving local data collection on the social determinants of health and human movement are essential for accurate risk prediction.
- Proactive data partnerships enhance outbreak response, with pre-established relationships and routine data sharing and coordination generally proving more effective than reactive, crisis-driven approaches.

SOURCE: Created by the authors.

swath of policymakers who may prioritize different metrics—such as health care capacity or economic stability—depending on their needs.

Session IV: Viral Risk Assessment

The session was moderated by **Dr. Luiz Alcantara,** René Rachou Institute, Fiocruz. The panel included **Dr. Stephanie Seifert,** Washington State University; **Dr. Nardus Mollentze,** University of Glasgow Centre for Virus Research; **Dr. Sook-San Wong,** School of Public Health, Hong Kong University; **Dr. Nicaise Ndembi,** Africa CDC; **Dr. Josefina Campos,** WHO; and **Dr. Marilda Siqueira,** Fiocruz.

This session explored the role of genomic surveillance in assessing viral risks from spillover events to human transmission. Panelists discussed the limitations of predictive models; inequities in sequencing capacity; and the need to better connect genomic, laboratory, and epidemiological data to improve risk assessments.

Dr. Seifert emphasized the importance of integrating genomic, host, and environmental data to enable better risk predictions and cautioned against overreliance on AI in data-limited settings. She noted that machine learning models can identify host–virus compatibility but often fail to explain post-entry behaviors like transmissibility. For instance, *in silico* models predicted SARS-CoV-2 compatibility with pig receptors, but the virus failed to replicate in live pigs. Dr. Mollentze discussed the challenges of using genomic data to predict the behavior of novel viruses with limited prior characterization, noting that current ranking models often perform worse than random chance at the species level. He stressed the importance of incorporating non-phylogenetic signals, such as host range data, to improve predictions. He advocated for a feedback loop where predictive models guide lab studies and new data refine models. Dr. Wong emphasized the need to look beyond genomic signatures to understand virus evolution and emergence, and highlighted immunological imprinting as one example, where past viral exposure influences lifelong infection risk. She also stressed the need to address global inequities in sequencing capacity and predicted that mapping population immunity will be key to assessing vulnerability over the next decade. Dr. Ndembi echoed the importance of global representativeness in genomic surveillance, particularly in high-risk regions such as Africa. He highlighted Africa CDC's 2022 report titled *Risk Ranking and Prioritization of Epidemic-Prone Diseases*, which provides insights on 20 high-risk diseases, but noted that these insights must be be translated into actionable public health measures like rapid diagnostics and vaccines (African Union and Africa CDC, 2022). He stressed the importance of integrating genomic tools with geographic and phylogenetic data to track disease spread, citing regional spread corridors for cholera and mpox. Dr. Campos emphasized the need for timely, geographically representative, and well-contextualized pathogen genomic data and the importance of strong pre-existing collaborations for outbreak preparedness. She then noted that WHO launched its 2022 Genomic Strategy to address these challenges and expand sequencing access, strengthen the global workforce, and improve data sharing (WHO, 2022). She also highlighted the WHO's International Pathogen Surveillance Network, which leverages existing genomic systems to promote equitable sequencing and analytics worldwide. Dr. Siqueira reinforced the importance of collaboration in pandemic preparedness, drawing from Brazil's 2003 SARS-CoV outbreak experience, among others. She emphasized shared protocols, trained personnel, and integrated surveillance systems, citing Brazil's genomic databank and development of a real-time polymerase chain reaction kit for the Oropouche virus as examples of how sustained partnerships can enhance response capacity.

During the discussion, panelists highlighted geographic biases in sequencing, noting that approximately half of SARS-CoV-2 genomes sequenced to date come from just two countries—the United States and the United Kingdom (GISAID, 2025). They also raised concerns about precision medicine gaps, such as mpox tests that screen only

for clade 2 and could therefore miss clade 1 cases circulating in Africa. Panelists and participants concluded with a call for actionable interventions beyond sequencing expansion, including investment in equitable diagnostic tools, tailored sampling strategies that reflect regional needs and populations, integration of genomics with epidemiological and clinical data, and expanded access to medical countermeasures informed by genomic insights. Panelists highlighted ethical concerns about digital sequence data sharing, emphasizing the need for inclusive genomic frameworks that ensure equitable data access, benefit sharing, and real-world public health applications. Key insights from this session are highlighted in *Box 5*.

Session V: Risk Mitigation (Pre-and-Post Emergence)

The session was moderated by **Dr. Tim Evans,** McGill University. The panel included **Dr. Rory Gibb,** University College London; **Dr. Mauricio Barreto,** Fiocruz; **Dr. Yap Boum II,** Pasteur Network; **Dr. Arminder Deol,** Coalition for Epidemic Preparedness Innovations (CEPI); and **Dr. Sheetal Silal,** University of Cape Town.

This session explored strategies to reduce pandemic risk before and after emergence, focusing on integrating ecological and epidemiological approaches, improving modeling, and ensuring equitable preparedness efforts. Panelists emphasized the need for context-specific strategies, stronger data systems, and aligning risk mitigation with economic and policy considerations.

Dr. Gibb highlighted the disconnect between pre-emergence—ecology and biodiversity—and post-emergence—epidemiology and social science—research, which leads to siloed efforts. He noted that human epidemic modeling is conceptually advanced but constrained by limited data, while ecological pre-emergence interventions face methodological gaps and surveillance biases. He called for a syndemic approach that integrates social, environmental, and economic factors to address upstream pandemic drivers and ensure equitable resource distribution. Dr. Barreto emphasized the role of health and social data in tracking disease spread, noting that social vulnerabilities shape transmission patterns. However, he said, fragmented data systems, interoperability challenges, and regional disparities hinder effective responses. He called for standardized global data collection, real-time surveillance, and improved international collaboration while balancing privacy concerns and strengthening analytical capacity. Dr. Boum

BOX 5 | Key Insights: Viral Risk Assessment

- Genomic data should be combined with host and environmental factors to improve predictive accuracy and risk assessments.
- Virus evolution research should extend beyond genomic signatures, as immunological imprinting and population immunity play critical roles in disease emergence.
- AI tools require validation in real-world settings. Machine learning improves host–virus compatibility predictions but struggles with transmissibility assessments due to environmental variability.
- Pre-established collaborations strengthen outbreak preparedness and routine data sharing and coordinated response strategies improve efficiency.
- Expanding sequencing capacity in high-risk regions is critical to ensuring globally representative genomic surveillance.

SOURCE: Created by the authors.

BOX 6 | Key Insights: Risk Mitigation (Pre-and-Post Emergence)

- Pandemic risk mitigation should integrate ecological, social, and epidemiological approaches. Siloed research limits effectiveness, so a syndemic approach should be utilized to address upstream drivers.
- Social vulnerabilities and population characteristics influence transmission patterns. Social data systems, standardized data collection, improved real-time surveillance, and stronger international collaboration are needed to better understand these patterns.
- Shared leadership, community-driven solutions, sustainable funding, and region-specific strategies enhance preparedness by building trust and strengthening interventions.
- Accelerating vaccine development requires global and regional coordination, and strong surveillance, immune research, manufacturing, and trial networks are also essential.
- Economic and environmental factors should be integrated into risk models. Cost-benefit analyses and structured decision making can help prioritize at-risk populations and long-term sustainability.

SOURCE: Created by the authors.

II underscored the need for shared leadership in global health. He cited the mpox response, where Africa CDC and WHO collaborated on a regionally-tailored plan, as a model for inclusive leadership. Effective risk mitigation, he argued, requires context-specific strategies, sustainable funding, trust building, and active community engagement in surveillance and intervention planning. Dr. Deol outlined CEPI's 100 Days Mission to develop vaccines within 100 days of identifying a pandemic threat. Modeling suggests, she said, responding to COVID-19 within 100 days could have averted over 8 million deaths and 1.4 billion infections (Barnsley et al., 2024). She detailed five priorities for achieving this goal: enhancing pathogen surveillance, identifying immune response markers, creating vaccine libraries for high-risk diseases, expanding global manufacturing, and strengthening clinical trial networks. She stressed the importance of equitable vaccine access, particularly in low-income countries, and the need for improved data sharing and regional training. Dr. Silal advocated for a systems thinking approach in epidemiological modeling, which would integrate demographic, economic, and health care factors to improve preparedness. She emphasized refining contact matrices to reflect evolving social behaviors and linking epidemiological outcomes to economic indicators like gross domestic product, unemployment, and inflation. She urged modelers to ensure that their work is actionable and accessible to policymakers.

During the discussion, panelists stressed the importance of aligning modeling with policymaking. They called for tools that are both user-friendly and sophisticated enough to capture complex disease dynamics. Panelists emphasized the need for dual approaches—one for long-term forecasting and another for real-time decision making during crises. Additionally, participants reinforced the importance of incorporating macroeconomic impacts into models. For example, in Cameroon, government officials weighed scientific and economic factors before implementing a COVID-19 lockdown. Ultimately, they prioritized economic stability, illustrating how cost-benefit analyses shape pandemic responses. Key insights from this session are highlighted in *Box 6*.

Session VI: New Research and New Methods

This session explored advancements in pandemic risk modeling, highlighting emerging methodologies, challenges in utilizing diverse data sources, and uncertainties in estimating pandemic frequency and severity. Panelists emphasized the need for diverse modeling approaches, stronger local capacity, and improved data-sharing frameworks to enhance preparedness.

The session was moderated by **Dr. Alexandra M. Schmidt,** McGill University. The panel included **Ms. Nita Madhav,** Ginkgo Bioworks, Inc.; **Dr. Manoel Barral-Netto,** Fiocruz; **Dr. Vijaykrishna Dhanasekaran,** University of Hong Kong; **Dr. Tonderai Mapako,** National Blood Service, Zimbabwe; and **Dr. Chansoo Kim,** Korea Institute of Science and Technology and University of Science and Technology.

Ms. Madhav shared insights from computational epidemiology and extreme event modeling to estimate global pandemic risks. She highlighted that key findings estimate annual global mortality of 2.5 million individuals to respiratory diseases, 19,000 individuals in sub-Saharan Africa to viral hemorrhagic fevers, and a 2–3% annual probability of a COVID-19-scale event. Over 25 years, this probability has risen to 40–53%, increasing to 72% when accounting for rising risk due to factors such as climate change (Madhav et al., 2023). While sobering, she stressed that these risks are not fixed, highlighting the need for prevention, early action, and global collaboration. Dr. Barral-Netto introduced a surveillance system developed with Brazil's Ministry of Health to detect early outbreaks (Fiocruz, Coppe UFRJ, and The Rockefeller Foundation, n.d.). He explained that the system leverages health care data, over-the-counter drug sales, and social media to model outbreak spread, and added that integrating human mobility patterns has further improved its accuracy. He highlighted key challenges, including gaps in linking diverse data sources, health system capacity constraints for implementing precision surveillance, and a lack of data on environmental drivers such as climate change. Dr. Dhanasekaran highlighted key uncertainties in pandemic risk modeling, including regional data biases, zoonotic disease knowledge gaps, and the limitations of models that fail to incorporate host–environment interactions or climate-driven changes. He noted that while statistical and mechanistic models align for well-studied diseases, discrepancies arise for emerging pathogens due to differing structural assumptions and data sources. He advocated for the use of complementary approaches to improve predictive accuracy. Dr. Mapako reflected on Zimbabwe's growing infectious disease modeling capacity, noting that COVID-19 exposed significant gaps in expertise, funding, and research collaboration. He emphasized the need for co-developing models that integrate spillover risks, climate influences, and socioeconomic factors while incorporating diverse methodologies to bridge knowledge gaps. Dr. Kim shared lessons from South Korea's COVID-19 response, highlighting the risks associated with an infodemic, where excessive data overwhelms decision making. He advocated for agent-based modeling with reinforcement learning to optimize public health policies and the use of real-world data, such as credit card transactions, to refine model accuracy. While acknowledging the challenges of implementing agent-based models in resource-limited settings, he emphasized that meaningful insights can still be gained. He cautioned against excessive data collection without clear applications and called for privacy-conscious approaches to public health modeling.

During the discussion, panelists emphasized the need to integrate dynamic factors, such as human behavior and NPIs, to improve model accuracy and predictive power. They highlighted the potential of alternative data sources, such as blood donation records, to enhance transmission models by detecting overlooked infections. They also warned against recency bias in pandemic planning, stressing the challenge of modeling unknown pathogens. Other participants cautioned against rigid pathogen priority lists, advocating

for a flexible strategy that prioritizes high-risk pathogen families while maintaining adaptability for emerging threats. Key insights from this session are highlighted in *Box 7*.

Session VII: Developing a Synthesis Agenda

In this session, participants convened in four breakout groups to identify strategies for advancing pandemic risk assessment and outlined key priorities:

- **Establish regional and global data hubs:** A central knowledge hub with regional satellites could leverage health, ecological, and social data to generate region-specific insights.
- **Develop frameworks for evidence quality and uncertainty:** Given the evolving nature of pandemic risk assessment, participants called for frameworks to capture uncertainties across models, data, and assumptions. Multi-level, multi-sectoral approaches should align research with local, national, and global decision making needs.
- **Enhance collaboration platforms:** Participants proposed an agenda-setting platform to prioritize research based on outbreak stages, climate-sensitive diseases, and regional health vulnerabilities. This platform would also support benefit-cost analysis for resource allocation.
- **Host annual conferences on pandemic science:** A recurring conference series would unite diverse scientific communities, facilitate data sharing, and integrate pandemic science into public health policy.
- **Create a collaborative, inclusive research agenda:** A research prioritization workshop was proposed to coordinate across disciplines, focusing on spillover risks, ecosystem health, and emerging technologies like AI for data synthesis. Participants also proposed an IPCC-like model for pandemics to enhance collaboration and policy integration.

AREAS OF FUTURE FOCUS/KEY THEMES

Based on the workshop discussions, several key themes and priority areas for future focus emerged:

1. **Linking Risk Assessment to Policy Processes** Risk assessment frameworks should align with policy needs and decision making processes by addressing key questions and producing actionable insights. Knowledge products like prioritization frameworks and risk estimates

BOX 7 | Key Insights: New Research and New Methods

- Multi-method approaches are crucial, especially for emerging pathogens with limited data. Combining statistical, mechanistic, and AI-driven models can improve predictions while addressing regional data gaps, zoonotic disease risks, and host-environment interactions.
- Developing context-specific models that account for uncertainty, spillover risks, climate, and socioeconomic factors while integrating diverse methodologies to better understand pathogen transmission is critical.
- Agent-based modeling with reinforcement learning should be used to refine public health decision making. Using real-world data, such as credit card transactions, while ensuring privacy-conscious approaches that consider behavioral and economic factors can assist in these efforts.
- Biases and uncertainty in pandemic planning should be reduced as much as possible, recency bias should be addressed, and existing models should be adapted to high-risk pathogen families while maintaining flexibility for novel threats in order to prepare for emerging pathogens.

SOURCE: Created by the authors.

should be tailored for policy impact. Clarifying what questions policymakers are asking and identifying what constitutes a valuable answer will enhance the applicability of risk assessment outputs. Knowledge products like prioritization frameworks and risk estimates should be fit for the purpose of effectively informing policy decisions.

2. **Advancing Pandemic Science Through a Global Risk Assessment Mechanism**
   Advancing risk assessment requires integrated research agendas that link field epidemiology, virology, and climate science while embedding social sciences into modeling and risk assessment techniques. Structuring research around key interdisciplinary questions will create a more holistic and actionable risk assessment ecosystem.
3. **Accounting for and Explaining Uncertainty**
   Policymakers need clearer guidance on uncertainty in modeling to make informed decisions. Risk assessments should transparently convey confidence levels, model limitations, and precision to improve interpretability and usability. Outputs should be tailored for different audiences to ensure that uncertainty informs, rather than hinders, decision making.
4. **Enhancing Global Inclusion and Access in Pandemic Science**
   Strengthening regional modeling capacity and ensuring fair access to data and technologies can enhance global preparedness. Equitable benefit-sharing mechanisms should be in place to ensure that data, technology, and countermeasures are accessible to all, particularly in low-resource settings.
5. **Fostering Sustainable Governance and Financing Mechanisms**
   Long-term pandemic preparedness requires sustained investment, strong governance structures, and integration with health security and climate resilience policies. Ensuring stable financing and embedding risk assessment in broader frameworks will support long-term resilience.

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REVIEWERS

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