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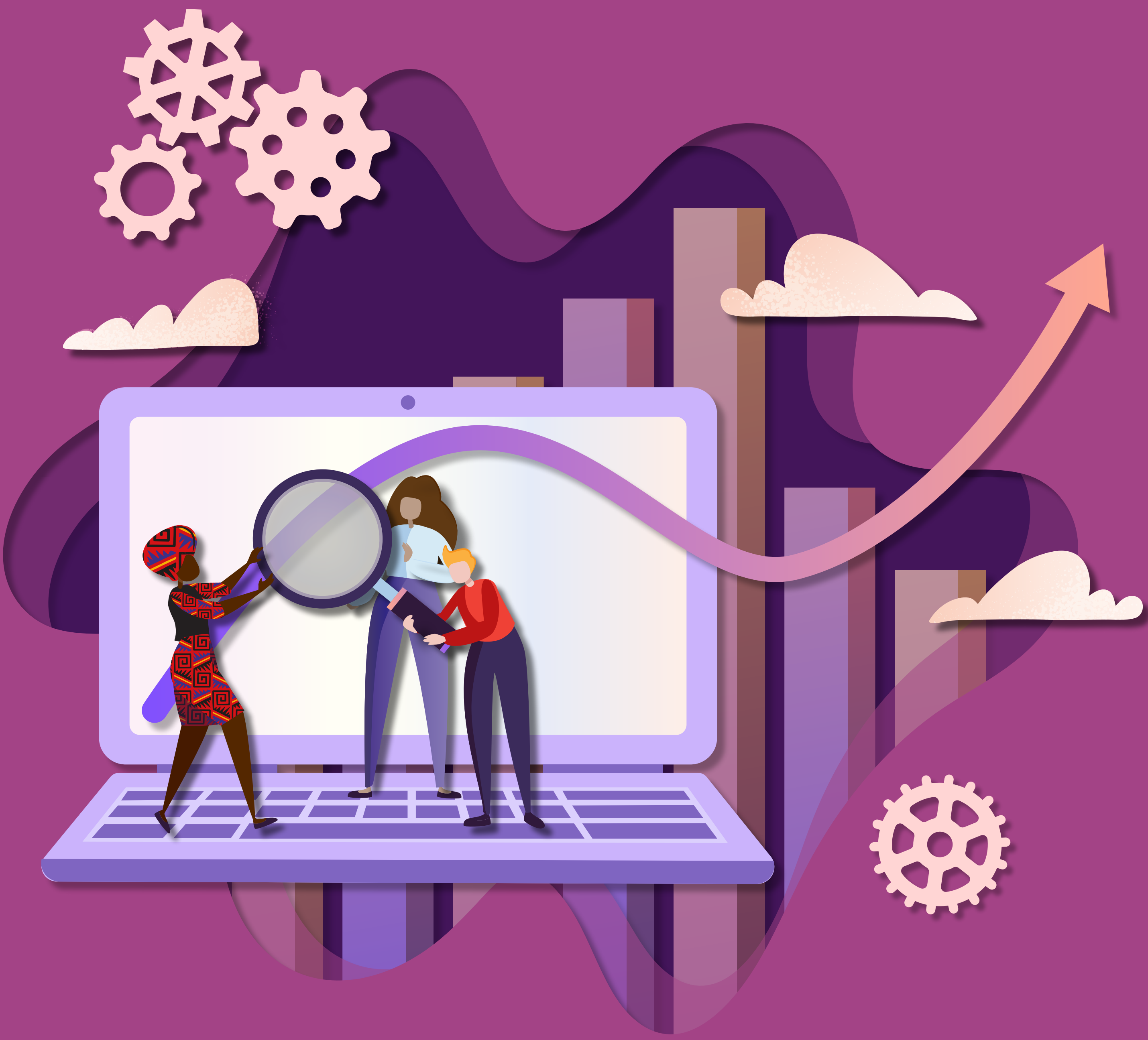
Transformations within reach:
Pathways to a sustainable and resilient world

STRENGTHENING SCIENCE SYSTEMS



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Transformations within reach:
Pathways to a sustainable and resilient world

Strengthening Science Systems

Lead Authors
Elena Rovenskaya, David Kaplan, and Sergey Sizov

This report is part of the IIASA–ISC Consultative Science Platform "Bouncing Forward Sustainably: Pathways to a post-COVID World", under the Leadership of Leena Srivastava (IIASA), Luis Gomes Echeverri (IIASA), and Flavia Schlegel (ISC).

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Executive Summary

Despite past warnings of an infectious disease that could result in a "global catastrophe," COVID-19 took the world by surprise. In the early phase of the pandemic, two organizations, the International Institute for Applied Systems Analysis (IIASA) and the International Science Council (ISC), came together to create the IIASA–ISC Consultative Science Platform "Bouncing Forward Sustainably: Pathways to a post-COVID World." One of four themes of the Platform was **Strengthening Science Systems**.

Strengthening Science Systems brought together participants drawn from key stakeholder groups engaged with the science system. Their objective was, in the light of the COVID-19 pandemic experience, to discuss and advance recommendations that would allow the science system to be better prepared to deal with future global crises. This report presents the analysis and recommendations resulting from deliberations in three online consultations which engaged 47 external participants plus members of IIASA–ISC team.

Science has moved to center stage in the ongoing COVID-19 crisis. Science was called upon to provide solutions across a very broad front—not only to the immediate challenges to health but also to the many social and economic challenges posed by the pandemic. Scientists across multiple disciplines reacted rapidly by reorienting their research to this challenge, and the COVID-19 crisis has seen a marked acceleration in collaboration and cooperation among scientists. Digital means of connecting across the globe are being used extensively, although they lack many of the advantages provided by physical meetings, such as a face-to-face networking and informal conversations.

The COVID-19 crisis disrupted the functioning of the science system. Adjusting to teaching in a virtual format put additional pressure on university-based researchers and reduced the time available for research. Work in labs, field work, and expeditions had to be postponed or canceled. The closure of childcare and other services created additional demands on scientists to support and take care of their families, thus further reducing the time and energy they could spend on research. COVID-19 also appears to have aggravated existing inequalities in science. Female scientists, and especially scientists with young children, have experienced a substantial decline in the time that they have been able to devote to research.

COVID-19 has demonstrated that the response of scientists to a new crisis is constrained by concerns regarding their job security and career advancement. This is especially critical for early-career scientists whose future employment is critically dependent on having their work published in peer-reviewed journals. There is no system for recognizing and rewarding the contributions made to addressing an urgent crisis like COVID-19, and this significantly inhibits scientists from undertaking such research. Funding incentives are also needed to encourage scientists to reorient their research to focus on crisis-related issues. Funding agencies, however, have limited freedom to establish new priorities and to expeditiously redirect funding to them.

COVID-19 has highlighted some of the weaknesses of the science system and has accelerated a number of trends. The proliferation of preprints as a more rapid way of disseminating knowledge in a fully open fashion has highlighted the limitations of the system of publishing in commercial journals and peer review in their current forms. However, there has been widespread concern with respect to the quality of information that has been put into the public domain without undergoing peer review.

In the early stages of a crisis, data and expert knowledge on the fundamentals of the phenomenon are naturally very limited. Being able to utilize existing knowledge effectively is thus critical. Currently, the science system and the planning and evaluation of research pay little attention to the importance of generating knowledge that could be applicable to future crises.

The private sector forms a large part of the research ecosystem. While, in many fields, there are effective collaborations between publicly funded science and private-sector science, much more collaboration is required.

Trust in science and its possible erosion have been long discussed. These discussions have significantly intensified with the advent of COVID-19. COVID-19 has seen an increased flood of false and fake news. The public is being exposed to massive flows of misinformation and pseudoscience which undermines trust in science. A key lesson from COVID-19 is that a policy can be rendered more or less effective depending on the degree of trust that the public has in science and in the government.

COVID-19 has brought science to the forefront of public attention and highlighted the lack of public understanding as to how science functions and what science can and cannot do. Many scientists do not consider the communication of science as part of their work. Moreover, the performance evaluation system for scientists places very little weight on the communication of scientific findings and results.

As the COVID-19 pandemic has so clearly demonstrated, crises are always multidimensional. COVID-19 has clearly been far more than a medical problem; it has had multiple implications for society, the economy, and politics. Policies to address COVID-19 should thus engage multiple scientific disciplines. However, advisory boards and task forces involved in the design of public policies to deal with COVID-19 have often engaged only a limited range of expertise. A systems-based approach, which is necessary for dealing with a complex crisis like COVID-19, has been insufficiently emphasized and prioritized.

COVID-19 has demonstrated how difficult it is for research and advisory institutions that are poorly endowed and supported to respond with agility to sudden threats. Strong and robust institutions are an essential prerequisite for a rapid and high-quality response. It is vital that adequate, reliable, and ongoing public funding is provided to institutions that undertake policy research and deliver science-based policy advice on global risks.

COVID-19 has clearly demonstrated the value of international collaboration. Some countries with very limited scientific capacities were able to draw on the experiences of other countries and international organizations to develop effective and timely policy responses to COVID-19. However, there has been a countertrend toward the "nationalization of science systems" in some countries.

Analysis of the COVID-19 crisis reveals that for the science system to be in a position to react more efficiently and more effectively to future global exogenous threats, three axes of improvement are required. First, the ability of the science system to react swiftly to newly emerging and rapidly unfolding issues at national and international levels, whichever is appropriate, must be significantly enhanced: *increased agility*. Secondly, the science system will have to further improve the quality of its output: *greater reliability*. Thirdly, the science system will need to be linked more effectively to policy and to the public: *increased relevance*. The objective is to ensure that the science system advances along all three axes simultaneously and reaches a new frontier of agility, reliability, and relevance to society.

Simultaneous improvement along all three axes necessarily entails many changes to the existing science system. Accordingly, we put forward here 38 recommendations, summarized under five interrelated major transformative changes as follows (see also Figure A):

- **Strengthen transdisciplinary research and networking on critical risks and systems resilience**

A broader definition of global and national security that includes natural and anthropogenic disasters as relevant threats should be adopted. National and international capacity for transdisciplinary research on critical risks and systems resilience, especially where this is very limited, should be enhanced. To compensate for lack of capacity, networks and mechanisms should be further developed through which scientists can tap knowledge from other countries or knowledge accumulated at the international level. To accelerate scientific progress, international networks of researchers with complementary expertise in major risk areas should be strengthened.

- **Increase capacity of science to respond rapidly to crises with quality research**

Institutions undertaking research on risk need to be developed and sustained. The potential should be explored for a system of "emergency" expert teams that can be activated on demand in response to crisis. A system of easy-to-access grants needs to be established to fund research into unanticipated and urgent challenges. To recognize the contribution made by scientists to addressing crises, the evaluation system needs to be adjusted. Special attention should be given to incentivizing young researchers. The development of easily reusable research models and data should be prioritized, and the use of general-purpose models should be expanded. New mechanisms to enhance international scientific cooperation to respond rapidly to crisis should be developed. It is important to promote standards of good scientific practice in times of crisis and to significantly strengthen those institutions that enforce a code of scientific conduct. Ways of enhancing cooperation between public- and private-sector science should be explored. The private sector needs to be incentivized to make technology platforms available and to share data and knowledge.

- **Enhance knowledge diffusion within science system**

A number of improvements to the publication review system should be implemented. These include a system of rapid post-publication peer review of preprints; a suite of material and non-material incentives for providing reviews; the possibility of open communication between authors and reviewers; accommodation of diverse research cultures and strong peer-review systems for data. Training on undertaking reviews should be promoted for scientists, especially reviews of interdisciplinary research. Researchers should be also incentivized to provide scientific reviews and perspective articles that synthesize extant knowledge relevant to a crisis and its effects.

To facilitate access to existing research, and navigation through it, researchers should be incentivized to make data, models, and computer codes open and easily accessible. Common standards for data, as well as the use of open-source software, should be promoted. A system whereby scientists make available the interim products of research (research protocols, negative results, etc.) should be examined. Depositories for data and existing research, as well as platforms aggregating research on a particular topic, should be developed and used. The effectiveness of automated knowledge synthesis algorithms and governance schemes for them should be explored.

- **Enhance communication of scientific knowledge, public understanding, and trust in science**

Easily accessible sources of scientific results and information should be created to provide reliable information to the general public. Scientists should be trained and incentivized in the communication of scientific knowledge and need to be more actively engaged in countering science denial and misinformation. The capacity and integrity of science journalism and science media should be enhanced. Automatic systems for checking scientific facts should be developed and used widely. Active engagement between science and citizens at appropriate research stages should be facilitated to enhance the relevance and legitimacy of scientific research. The scientific literacy of citizens should be improved.

- **Improve quality and efficacy of science–policy interface at national, regional, and global levels**

Robust national and multinational institutions engaging in science–policy advice should be developed, as should effective networking among such institutions. The social impacts of the different candidate policy options need to be assessed prior to implementation, together with likely responses to these options across different communities and interest groups. Policymakers should have the chance to interact with a wider academic community to interrogate and integrate different pieces of science advice. Science advice should engage a wide number of scientific disciplines. A systemic approach to policy advice should be adopted. Governments should consider the full range of science advice offered, and the reasoning behind the policy choices should be made transparent. It would be very useful to examine the COVID-19 experience to investigate which models of the science–policy interface have proved to be most effective and under what circumstances.

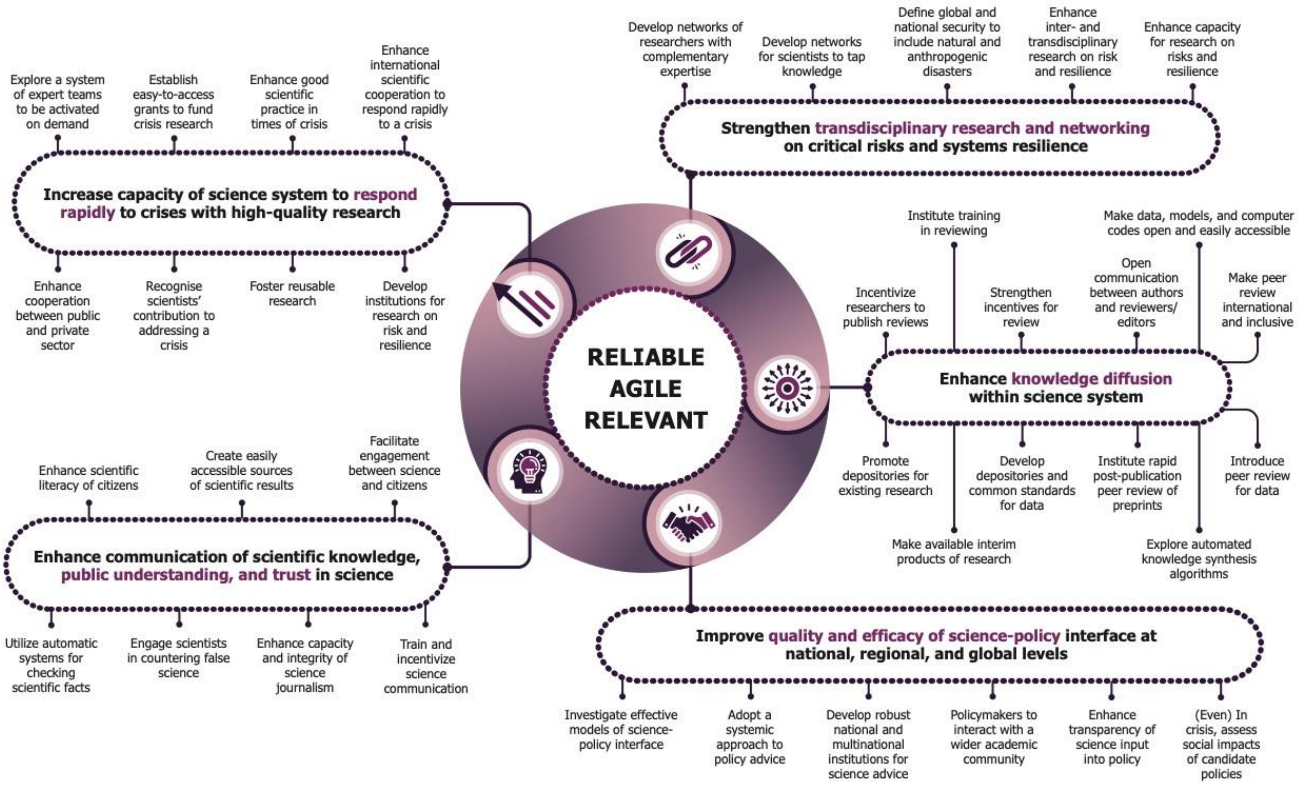

Figure A: Five interrelated transformative changes and specific recommendations within each transformative change.

Introduction

Despite past warnings of an infectious disease (Osterholm and Olshaker, 2020) that could result in a "global catastrophe" (Kaidan, 2020), COVID-19 took the world by surprise. On 31 December 2019 the Wuhan Municipal Health Committee informed the World Health Organization (WHO) of 27 "cases of pneumonia of unknown etiology [unknown cause]" detected in Wuhan City in the Hubei Province of China (Normille, 2020; WHO, Pneumonia, 2020). The source of the disease and how it reached humans was unclear. On 20 January 2020 China's National Health Commission confirmed for the first time that the infection could be transmitted from human to human (BBC News, 2020). That same day the WHO confirmed that it was "now very clear" that human-to-human transmission of the coronavirus had occurred (WHOWPRO, 2020). On 30 January 2020 WHO declared the ongoing outbreak a Public Health Emergency of International Concern (PHEIC), and on 11 March 2020 "made the assessment that COVID-19 can be characterized as a pandemic," adding that "this is the first pandemic caused by a coronavirus" (WHO, D-G, 2020). In response to the outbreak, many countries implemented a number of measures to limit the spread of the virus, including the declaration of a state of emergency, travel restrictions, recommendations to stay at home, bans on holding events, and the suspension of some economic activities. The pandemic, however, persists.

In May 2020, recognizing that the ongoing crisis was both a challenge to the current science system and an opportunity to effect positive changes, the International Institute for Applied Systems Analysis (IIASA) and the International Science Council (ISC) jointly created the IIASA–ISC Consultative Science Platform "Bouncing Forward Sustainably: Pathways to a post-COVID World." Utilizing the convening power and interdisciplinary expertise of the two organizations, the platform was concerned with four themes: Governance for Sustainability, Resilient Food Systems, **Strengthening Science Systems**, and Sustainable Energy.

Strengthening Science Systems brought together participants drawn from key stakeholder groups engaged with science system. Their objective was, in the light of the COVID-19 pandemic experience, to discuss and advance recommendations that would allow the science system to be better prepared to deal with future global shocks.

This report provides: 1) an analysis of how science has responded to COVID-19 and how COVID-19 has affected science systems; 2) a rationale for the need to transform science systems; and 3) a set of recommendations for key stakeholder groups concerned with science systems organized under five broad transformative change areas, as emerged from the discussions in the IIASA–ISC Consultative Science Platform.

The Process

Three consultations were held, each consisting of a three-hour webinar. In total, there were 47 external participants plus members of IIASA–ISC team. To frame the discussion and provide context, a background paper was prepared by the IIASA–ISC team for each consultation. Following each consultation, a report was prepared by the IIASA–ISC team and sent to the participants for their comment and feedback.

The 1st Consultation took place on 19 June 2020. Fourteen scientists were invited to deliberate on the question: which barriers should be reduced and which enablers should be reinforced in order to strengthen the capability of the science system to provide adequate input in crises triggered by extreme events like COVID-19? Based on the ensuing discussion, a summary report of the discussion was prepared, providing a preliminary list of potential policy recommendations.

The 2nd Consultation took place on 20 July 2020. There were 19 participants comprising science funders, science journalists, science publishers, and those concerned with public understanding of science. The objective of this meeting was for the participants to reflect on and critically review the draft recommendations that emerged from the 1st Consultation. While the 2nd Consultation mainly addressed the preliminary recommendations arising from the 1st Consultation, some additional recommendations were advanced.

The 3rd Consultation took place on 7 September 2020. There were 17 participants comprising policy- and decision makers at national and multinational levels, representatives of the private sector, and experts providing scientific advice to policy. The objective of this meeting was for the participants to reflect and critically review the draft recommendations that emerged from the discussions in the first two Consultations. While the 3rd Consultation mainly addressed the draft recommendations arising from the two earlier consultations, some additional recommendations were advanced.

Figure 1 provides a graphical illustration of the process. The background papers and consultation reports are as follows:

- The First Background Paper (Rovenskaya et al., 2020a)
- The 1st Consultation Report (Rovenskaya et al., 2020b)
- The Second Background Paper: Input to the 2nd Consultation (Kaplan et al., 2020a)
- The 2nd Consultation Report (Rovenskaya et al., 2020c)
- The Third Background Paper: Input to the 3rd Consultation (Rovenskaya et al., 2020c)
- The 3rd Consultation Report (Kaplan et al., 2020b).

Figure 1. Major process milestones.

The Science System and the COVID-19 Pandemic

This section of the report provides a brief summary of how science has contributed to addressing the challenges posed by the COVID-19 pandemic, and how the challenges posed by the COVID-19 pandemic have, in turn, impacted science. The pandemic is still very much in play as this report is being finalized. This is therefore not the time to draw definitive conclusions. However, policies with the potential to enhance the science system's capacity to address the challenges posed by future crises are clearly called for.

The role of science and scientists in meeting the challenges posed by the COVID-19 pandemic

Science has moved to center stage in the ongoing COVID-19 crisis. Science is being called upon to provide solutions across a very broad front—not only to the immediate health challenges but also to the many social and economic challenges posed by the pandemic. Science is expected to provide clear insights, reliable solutions, and actionable advice—and to do so in a timely manner. This section provides a view on i) scientists' level of preparedness for the pandemic and their speed of response, and ii) the extent to which science advice has been influential as an input into government policy.

Scientists had anticipated the emergence of such a pathogen. Experts had long been warning of a pandemic. In September 2019 the Global Preparedness Monitoring Board—an independent expert body co-convened by the WHO and the World Bank—called for a global response to "a rapidly spreading pandemic due to a lethal respiratory pathogen" (Henig, 2020). However, policymakers did not act on this advice. According to the editor of *The Lancet,* "The global response to SARS-Cov-2 is the greatest policy failure in a generation. The signals were clear" (Henig, 2020).

Scientists were already undertaking relevant research. The rapidity with which scientists reacted to the virus benefited significantly from research carried out much earlier. Vaccinologists had long been working on early-stage vaccines for the *Coronaviridae* family of viruses which shares large amounts of genetic material with SARS-CoV-2. Vaccine developers thus already had a set of semi-developed vaccines that they were then able to adapt to treat the new coronavirus. The vaccine company Novavax, for example, are using a technology developed for the SARS and MERS outbreaks to develop a vaccine for COVID-19 (Novavax, 2020).

Scientists reacted rapidly to the COVID-19 pandemic. As early as January 2020, medical experts had begun to comment on the new coronavirus outbreak, including warning that its spread was "clearly very concerning," and there were calls "to take the outbreak seriously and monitor the situation carefully" (Microbiology Society, 2020). Influential business figures and experts in many fields began to share opinions, analyses, and advice (Bishop, 2020; Sachs, 2020). Academic research, notably in medical science, reacted to the situation within less than a month. Even before the coronavirus was taken seriously by governments and the public, scientists had determined the genome sequence of SARS-CoV-2 (Cohen, 2020; Holmes, 2020), isolated it from clinical samples (Sunnybrook Research Institute, 2020), and begun the search for a possible vaccine (Straiton, 2020).

The speed with which scientists began the search for a new vaccine was, to a large extent, made possible by Chinese scientists rapidly identifying SARS-CoV-2 as the cause of the disease and then providing the genetic sequence in early January 2020 on the publicly accessible database, GISAID. Around the world, scientists rapidly transformed their laboratories, refocusing their research efforts on the challenges posed by the virus (Baker N., 2020; Hofer et al., 2020). This transformation encountered many obstacles, while preventing others (Henley Business School, 2020).

Already on 20 January 2020 an editorial in *Nature* emphasized that researchers had played a crucial role in publishing and sharing genomic sequences and were to be commended for making sequence data available; it urged them to continue to do so (Editorial, *Nature,* 2020). Moreover, according to *Nature*, by 30 January, at least 54 English-language scientific papers on the coronavirus had already been made available—many via preprint servers—with a few having made their way into peer-reviewed journals (Editorial, *Nature,* 2020). These papers included several studies presenting estimates of the incubation period and scenarios of the virus spread. Other studies focused on the structure or genetic makeup of the virus, which was the information needed to identify drug targets and develop a vaccine.

Science advice systems to deal with the specific challenges of COVID-19 were lacking in the early stages. Despite scientists' warnings, science advice systems to deal with the pandemic were not in place. Faced with the COVID-19 pandemic, many governments initially turned to established science-advice systems and advisers. It took some time before new systems of science advice, specifically geared to addressing the challenges of the COVID-19 pandemic and drawing on the expertise of the appropriate scientists, could be established and were functioning effectively. These delays may account for many scientists' view that governments did not take their advice into account (*The Economist*, 2020).

There are significant institutional differences in the way governments acquire science advice. Variations reflect the differing characteristics of each country's situation—the particularities of the organization and capacities of its science and political systems, as well as the particularities of the challenges the country faces. For example, in the United Kingdom (UK), the Scientific Advisory Group for Emergencies (SAGE) is a standing body that has provided the UK Government with evidence-based scientific advice in emergencies since 2009. SAGE itself relies on external science advice; in the case of COVID-19, this includes the New and Emerging Respiratory Virus Threats Advisory Group (NERVTAG) (NERVTAG, 2015) which consists of medical scientists, virologists, epidemiologists, a sociologist, and a psychologist.

In a number of countries, ad hoc advisory bodies and task forces have been created. For example, in Austria, a task force was set up by the Ministry for Social Affairs, Health Care, and Consumer Protection. Apart from the Ministry staff, this included experts in medical science, virology, epidemiology, computer simulations, and crisis management (Austrian Federal Ministry, 2020). The European Commission launched an Advisory Panel composed of epidemiologists and virologists from different member states to formulate the European Union (EU) guidelines on science-based and coordinated risk management measures (OECD STI Survey, 2020). In South Africa, just prior to initiating a lockdown, when infection was at a very early stage in the country, a non-statutory Ministerial Advisory Committee on COVID-19 was appointed to provide high-level strategic advice to the Minister of Health and Welfare utilizing four committees: Pathologists and Laboratory, Clinicians, Public Health, and Research. Each committee was chaired by a leading scientist in the area (ASSAf, 2020).

Learning from the experience of COVID-19, a number of countries have now established standing bodies to provide scientific advice in cases of public health crises in the future. For example, in the United States (USA) "the National Academies of Sciences, Engineering, and Medicine is convening a standing committee of experts to help inform the federal government on critical science and policy issues related to emerging infectious diseases and other 21st century health threats" (National Academies, 2020). It is too early to make final judgments as to what model worked best and why, but it is unlikely that a one-size-fits-all model can be identified in this regard.

Trust in science has proven critical in policy implementation. A key lesson from COVID-19 is that the same policy can be rendered more or less effective depending on the degree of trust that the public has in science and in the government. The same policy measures—the advice on wearing masks or social isolation, for example—have had very different results depending on the degree of trust in that advice and hence on social compliance with it.

The impact of COVID-19 on science and scientists

The COVID-19 crisis has disrupted the functioning of the science system and highlighted some of its weaknesses. The demands of the crisis have also accelerated a number of trends within science—most notably, the movement to Open Science. This section provides an overview of a number of important impacts of COVID-19 on science.

COVID-19 has affected a wide range of scientific disciplines. The immediate response to COVID-19 naturally came from epidemiology, virology, and other disciplines directly related to public health. Later, other disciplines—for example, psychology, economics, and environmental science—began to provide relevant research to inform policy and society. From a global perspective, focusing research on COVID-19 means that other areas of research are likely to receive reduced attention.

Scientific work has been disrupted. COVID-19 disrupted the science system, as it did all other sectors of society. The need to adjust to teaching in a virtual format put added pressure on university-based researchers, reducing the time available for research. For some researchers, working from home was a good opportunity to focus on writing papers (*Times Higher Education,* 2020) while for other researchers it created additional stress leading to reduced productivity (Viglione, 2020). According to a large-scale survey conducted in May–June 2020, the majority of researchers felt that they were able to adapt to the situation and "continue their professional role throughout" (Rijs and Fenter, 2020).

Work in labs, field work, and expeditions had to be postponed or even canceled (Geib, 2020). As just one example, the World Meteorological Organization (WMO) has expressed concerns about the negative impact of COVID-19 on the quantity and quality of weather observations and forecasts, as well as on atmospheric and climate monitoring (WMO Impacts Observing System, 2020b) due to the reduced number of aircraft flights taking air-based measurements and the decline of surface-based measurements in parts of the world where stations are manual. The resultant reductions in empirical data will decrease the quality and quantity of research in multiple areas that feed on this data.

COVID-19 particularly affects early-career scientists whose future employment is critically dependent on the publications that they are working toward and that are likely to experience delays (Pain, 2020; Subramanya et al., 2020). The closure of childcare and other services has created additional demands on younger scientists in terms of supporting and taking care of their families, thus further reducing the time and energy that they can spend on research. It is widely recognized that the negative impact of COVID-19 on researchers' careers will be very uneven depending on the discipline concerned and also on personal circumstances (Myers et al., 2020; Termini and Traver, 2020).

The need for swift dissemination of research publications has become even more evident. COVID-19 has highlighted the role of preprints in bypassing the often very slow and sometimes biased peer-review procedure to openly and swiftly communicate the most recent research findings relevant to the crisis (Kupferschmidt, 2020). New ways of rapid sharing of research outputs, including interim products, such as research protocols, have been used (Asapbio, 2020). There has been widespread concern regarding the quality of information put into the public domain without having undergone a peer review. This concern has motivated some preprint servers to enhance their manuscript screening policies. Many scientific journals, recognizing the need to respond more rapidly, have introduced fast-tracking of the submissions related to COVID-19 (e.g., Elsevier [Jarvis, 2020]; PLOS [STM, 2018]). However, fast-tracking places considerable pressure on scientists and increases the likelihood of a decline in scientific rigor and quality (Jarvis, 2020).

Research has become more accessible, but science is still currently very far from being fully open. To enhance the dissemination of knowledge that is of immediate relevance, some publishers of peer-reviewed journals have provided free access to publications relevant to COVID-19 (STM, 2019). Portals collecting research related to COVID-19 have been developed to help scientists and other interested parties navigate the rapidly growing amount of research.

Traditional forms of communication and cooperation have been disrupted. Scientists have adopted new forms of engagement. The COVID-19 crisis has seen a marked acceleration in collaboration and cooperation between scientists (Kaiser et al., 2020). Comparative experiences and learning have become essential as countries struggle to define an optimal path in managing the COVID-19 crisis. Events held online have become a new norm, allowing scientists to easily connect with each other across the globe (Baker N., 2020; Lee and Haupt, 2020). Online meetings, however, lack many advantages provided by physical gatherings, such as a face-to-face networking and informal conversations. Furthermore, "zoom fatigue" can endanger the creative thinking process (Sklar, 2020).

The role of private-sector science has become more visible. The private sector responded to COVID-19 by creating new solutions to halt the spread of the virus, innovating and producing new products and services, including ventilators, diagnostic tools, and, most significantly, vaccines (Tognini, 2020). Technology platforms developed in the private sector, most notably in ICT, have been critical to many COVID-19 related initiatives. For example, the COVID-19 High Performance Computing Consortium was created in the USA to offer scientific researchers access to some of the world's most powerful supercomputers from IBM as well as cloud-computing resources from Amazon, Google, and Microsoft

(Shankland, 2020). Using these computational resources allows researchers to forecast the disease spread and to model different vaccines. This exemplifies the important role of the private sector in tackling the coronavirus pandemic.

The WHO has sought the support of technology companies to develop solutions in response to COVID-19, such as population screening, tracking the infection, and designing targeted actions. "We need your commitment… We can only tackle this global threat—and get our economy back on track—by working together," said WHO Director-General Dr. Tedros Adhanom Ghebreyesus, addressing digital technology companies (WHO, Digital Tech, 2020)

Traditional funding sources are at risk. Ad hoc grants are being put in place to fund COVID-19 research. The move to online teaching and the decrease in household incomes due to COVID-19 is expected to lead to a substantial reduction in revenues from tuition fees to universities worldwide (Estermann et al., 2020; Holford and Morgan, 2020). This, in turn, will reduce the research budgets of universities. Other sources of funding, such as those from philanthropic organizations, may also decline (Estermann et al., 2020). On the other hand, funding agencies have responded fairly rapidly to COVID-19 by opening ad hoc calls for research related to the ongoing pandemic (Osuchowksi et al., 2020). For example, in May 2020 the EU convened the Coronavirus Global Response International Pledging Event in which country leaders committed nearly 7.4 billion USD to research on the COVID-19 vaccines and therapies, as well as to the distribution of the vaccine to poor countries once it becomes available. The paramount importance of multilateral cooperation to tackle the COVID-19 challenge was continuously emphasized (Baker D., 2020; Wintour, 2020; Worley, 2020).

COVID-19 has brought science to the forefront of public attention. While universal access to science is recognized in the Universal Declaration of Human Rights (Article 27) (UNDHR, 1948), in the normal course of events scientific progress provokes only limited public interest. During the COVID-19 crisis, with scientific evidence and advice playing a key role in determining everyday life—from going to work, to sending children to school, and to detecting the first signs of disease—public interest and attention to science and scientists is hugely elevated.

Science rarely speaks with a single voice (Kaiser et al., 2020). Indeed, debate and disputation are central to the scientific enterprise. Debate and contestation are particularly intense when, as in the COVID-19 pandemic, and more especially in its early stages, knowledge and data are very limited. During the COVID-19 crisis, the public has been exposed to scientific debate and disagreement, which in some instances may have led to an undermining of trust. These divisions and contestations within science present a further complex problem for government: which scientists and what scientific advice should receive their attention?

Moreover, the public has also become more aware of cases of breaches of scientific conduct. The recent case of the retraction of a paper related to possible COVID-19 treatment due to concerns about the reliability of input data (Horton, 2020) is one example of a situation that can lead to a serious erosion of trust in science.

Transparency is an efficient antidote against losing trust. The issue of trust in science and its possible erosion has long been discussed. These discussions have significantly intensified with the advent of COVID-19 (Horton, 2020). COVID-19 has clearly demonstrated that governments which have made explicit the scientific data, the models being used, and the reasoning behind their policy decisions have earned the trust of the community. By contrast, where governments have imposed decisions from on high, particularly in open and democratic societies, compliance has been limited. Transparency and openness have been essential to the development of trust. Through citizen science, lay people have become involved in research projects related to COVID-19. (Norris, 2020; Steigleder, 2020). Citizen engagement in science helps to build trust in science (Šucha and Sienkiewicz, 2020).

Science has become far more influential in policy advice. COVID-19 has resulted in science being increasingly drawn into public policy. Many governments have sought the advice of experts and scientists to develop strategies to combat the effects of the COVID-19 pandemic (OECD STI Survey, 2020). Governments have primarily drawn on the country's own experts but also more widely on external areas of expertise, including international agencies.

Science advice is increasingly drawn from different disciplines. Initially, governments sought advice on combating the health emergency resulting from COVID-19; but increasingly the advice of scientists has also been sought in relation to policies to address the adverse social and economic consequences resulting from the COVID-19 pandemic. Among the most complex problems faced by governments are the trade-offs between various policies, particularly as policies that slow down the spread of the virus entail significant negative economic and social costs and consequences.

Transforming the Science System

The previous section outlined how the science system has impacted the many challenges posed by COVID-19 and how COVID-19, in turn, has resulted in a number of changes to the science system. Many experts are of the opinion that a great deal has been accomplished within a short period of time (Jhingree, 2000; Johnson, 2020; Le Guillou, 2020) and in particular that unprecedented data sharing has resulted in faster-than-ever research on a disease outbreak: "Never before … have so many experts in so many countries focused simultaneously on a single topic and with such urgency" (Weichselgartner and Kasperson, 2010). Perceptions as to how science has responded to the crisis may vary. There is, however, a broad consensus on the considerable room for improvement needed if the science system is to serve the public interest in the context of rapidly evolving exogenous shocks. Drawing on the experience of the interrelationship between the COVID-19 pandemic and the science system, this section relates to two questions.

The first question is concerned with the objective. In broad terms, what improvements must be made if the science system is to substantively enhance its capacity to address the challenges posed by future global crises?

The second question is concerned with the barriers. What are the principal barriers constraining the science system's capacity to address the challenges posed by future crises?

Objective

Analysis of the COVID-19 crisis reveals that if the science system is to be in a position to react more efficiently and more effectively to future global exogenous threats, three axes of improvement are required.

- First, the ability of the science system to react swiftly to newly emerging and rapidly unfolding issues at national and international levels, as appropriate, must be significantly enhanced: *increased agility*.
- Secondly, the science system will have to improve the quality of its output: *greater reliability*.
- Third, the science system will have to be more effectively linked to policy and to the public: *increased relevance*.

The objective is to ensure that the science system advances along all three axes simultaneously. While there are well-recognized trade-offs between these axes, the objective is not to make those trade-offs, for example, increased agility should not be achieved at the expense of a reduction in quality or reliability. In other words, the objective is not to move to a new position on an existing frontier, but rather to move the entire science system to a new frontier. Here, trade-offs, of course, will exist, but the science system will exhibit substantive advances along all three axes.

The advance of the science system to a new frontier confronts many barriers that are currently constraining this movement. A number of recommendations aimed at overcoming or mitigating these barriers will now be put forward. Before elaborating the recommendations, however, this report will outline the main barriers currently constraining the science system from enhancing its capacity to react more effectively and efficiently to future global crises.

Barriers

COVID-19 has highlighted a number of constraints and barriers needing to be overcome so that the science system can move to a higher frontier in terms of agility, reliability, and relevance. Many of these constraints and barriers are related to the following five broad areas.

- **Research and research networks on risk and resilience**

Research on future risks was highly ranked by participants in the 1st and 2nd Consultations as a means of strengthening the capability of the science system, and also its capacity, to provide effective policy inputs in crises triggered by extreme events like COVID-19 (see Figure 2). There is a rich and ever-growing body of research on various risks. While enormous progress has been made in understanding, preventing, and dealing with risk, current risk and resilience research shows certain limitations (Aitsi-Selmi et al., 2016): risk analyses tend to focus on the physical and economic dimensions, but social vulnerability is generally poorly researched. Insufficient attention is given to the analysis of compound hazards or of factors affecting exposure and vulnerability. These factors depend on the context, the stage of the disaster, and the national setting. The involvement of stakeholders responsible for policy planning and implementation in research design and research dissemination continues to be low (Weichselgartner and Kasperson, 2010). These and other factors inhibit science-informed decisions relating to risk mitigation and adaptation. International scientific collaboration can facilitate progress but is limited in the prevailing geopolitical climate.

Much of the research is based in and focused on the Global North. Scientists located in the Global North have limited access to Global South–related risk data and knowledge, while the Global South has very limited research capacity. Consequently, there are significant gaps regarding the understanding of the risks and the resilience of societies of the Global South. As has been so clearly demonstrated by COVID-19, in a globally interconnected world, the vulnerability of the Global South puts the entire world at risk. International collaboration can help to facilitate more research on risk and resilience focusing on the Global South and relevant interconnections.

International scientific collaboration is, however, facing a number of threats. Conferences, research visits, and the international labor market of researchers have been a key factor in fostering scientific exchange and mobility, and this has improved research quality. New visa regimes, restrictions on travels etc., will change the ways in which we collaborate. Science presently relies on networks created before COVID-19, but current restrictions, especially if continued, will have a negative impact on networks and will particularly affect young scientists. This, in turn, will undermine the quality of future research. Of particular concern is a likely severe disruption to research networks centered on major research universities in the industrialized countries. Students from all over the world undertake postgraduate studies and research at these institutions and establish their global networks there. There is likely to be a significant decline in the number of foreign students entering these universities. The decline in students will, in turn, negatively impact on revenue streams, further limiting research and the flow of foreign students. New networks and new mechanisms to support them are required. An expanded role for universities in the South requires further investigation.

Another very serious barrier to international collaboration is the current tendency toward scientific rivalry, while the nationalization of science in some countries runs counter to international cooperation in science.

- **Responsiveness of the institutions of science and scientists to new challenges**

The response of scientists to a new crisis is constrained by concerns regarding their job security and career advancement. Putting aside current research to focus on a new topic may lead to delays in publishing papers and missed funding opportunities. This is especially detrimental for early-career scientists. The lack of a system of recognizing and rewarding the contributions made by researchers to addressing an urgent crisis significantly inhibits scientists from undertaking such research.

COVID-19 appears to aggravate existing inequalities in science. Female scientists and especially scientists with young children are experiencing a substantial decline in the time they can devote to research (Myers et al., 2020).

Financial incentives are needed to reorient scientists toward focusing on crisis-related issues. However, currently such financial incentives are distinctly limited. National funding agencies typically receive money from the government to support research according to accepted national priorities. The funding agencies have limited freedom to establish new priorities and to redirect funding to those new priorities within a short period of time. In practice, any redirection of funding usually happens through adjustments within existing calls. However, adjustments to existing calls can release only limited resources. Establishing new research priorities requires approval by the government and is thus time-consuming.

In the early stage of a crisis, data and expert knowledge on the fundamentals of the phenomenon are naturally very limited. As scientists' starting point is the frontier of existing knowledge, the ability to effectively utilize existing knowledge is critical. In response to COVID-19, much of the early research made extensive use of previous research including research on SARS (Wilder-Smith et al., 2020) and even the Spanish flu outbreak in Europe in 1918–1920 (Franchini et al., 2020). The science system and the planning and evaluation of research currently pay little attention to the importance of generating knowledge that could be applicable to future crises.

- **Diffusion of scientific knowledge**

As many as 3 million peer-reviewed research articles are published globally every year (STM Report, 2019). Peer review is essential to communicating scholarly research (Mulligan et al., 2012). Weaknesses in the current publication peer-review system were recognized and extensively discussed prior to COVID-19 (Mulligan et al., 2012) including the length of time taken, bias, susceptibility to abuse (Gasparyan et al., 2015) and concern regarding to the degree to which peer review ensures quality. These weaknesses are particularly critical in respect of peer review of interdisciplinary research, where identifying suitable reviewers is a challenge. Furthermore, the prevailing practice of publishing only final research outputs slows the dissemination of new knowledge. Journal subscription fees impose high paywalls, inhibiting access by scientists and citizens. High article publishing charges (APCs) are applied to open-access publications, preventing researchers without access to appropriate funds from publishing. The proliferation of preprints with the advent of COVID-19 greatly accelerated the dissemination of knowledge. However, as there was very limited quality control, the positive impact was reduced. Participants in the 1st and 2nd Consultations ranked *Access to research data, results and publications* as the most important factor in strengthening the capability of the science system and its capacity to provide effective input to policy in crises triggered by extreme events like COVID-19 (see Figure 2).

- **Communication, public understanding, and trust in science**

The issue of trust in science and its possible erosion has been long discussed, and these discussions intensified significantly with the advent of COVID-19. COVID-19 has seen an explosive growth of false and fake news (WHO, Munich Conference, 2020). The expansion of social media and platforms accelerated this phenomenon (Zhou and Zafarani, 2020). False news on Twitter, for example, is typically retweeted by many more users and spread far more rapidly than truthful news (Vosoughi et al., 2018). The public is being exposed to massive flows and a wide variety of forms of misinformation Posetti and Bontcheva, 2020) and pseudoscience (Caulfield, 2020) around COVID-19 which strongly challenges trust in science.

One reason for lack of trust is the lack of understanding by the public as to how science functions and what science can and cannot do. Few scientists regard communication of their research as part of their work. Moreover, the performance evaluation system places very little emphasis on communication of scientific findings and results. Science is often communicated by science journalists, but there is no effective regulation of journalists to ensure that what they communicate is sound and evidence-based. Participants in the 1st and 2nd Consultations ranked *Transparency of the science system, Understanding of science by the public,* and *Communication of scientific results to the public* highly as a means of strengthening the capability of the science system and its capacity to provide effective input into policy in crises triggered by extreme events like COVID-19 (see Figure 2).

- **Science–policy interface**

Participants in the 1st and 2nd Consultations ranked the *Role of scientists in advising governments and transparency of science-to-policy processes* highly as a means of strengthening the capability of the science system and its capacity to provide effective input into policy in crises triggered by extreme events like COVID-19 (see Figure 2). Science advice to policy faces a number of obstacles. In many countries, scientific capacity is distinctly limited, and many countries do not have standing scientific bodies that provide advice to policy dealing with risk. Scientific advice is often required at short notice, while gathering and analyzing evidence is a lengthy process. In some countries, scientific inputs into one part of government result in policy measures being adopted without consultation with other parts of government (WHO, Munich, 2020). Furthermore, the lack of transparency in the functioning of advisory bodies is a key factor undermining trust in their work (Carrell et al., 2020).

Participants in the 1st and 2nd Consultations ranked *Systems thinking in policy* highly as a means of strengthening the capability of the science system and its capacity to provide effective input into policy in crises triggered by extreme events like COVID-19 (see Figure 2). However, advisory boards and task forces involved in the design of public policies to deal with COVID-19 often engage only a very limited range of expertise; for example, many lack experts in economics and the behavioral sciences. This absence limits the capacity of these boards to provide nuanced assessments of the alternative policy measures and to anticipate possible multidimensional unintended consequences. As one example, an editorial in the *South African Medical Journal* noted that, "The absence of a truly multidisciplinary input involving the humanities, social sciences and relevant civil society and private sector actors, including actuaries … robs South African policymakers of valuable insights that could prove invaluable in the country's fight against the pandemic" (*SAMJ,* Editorial, 2020). While the importance of practicing a systems-based approach to deal with a complex crisis like COVID-19 has indeed been recognized, its practical application is far more difficult.

Figure 3 depicts a systems view on the science system summarizing the factors and interrelationships discussed above.

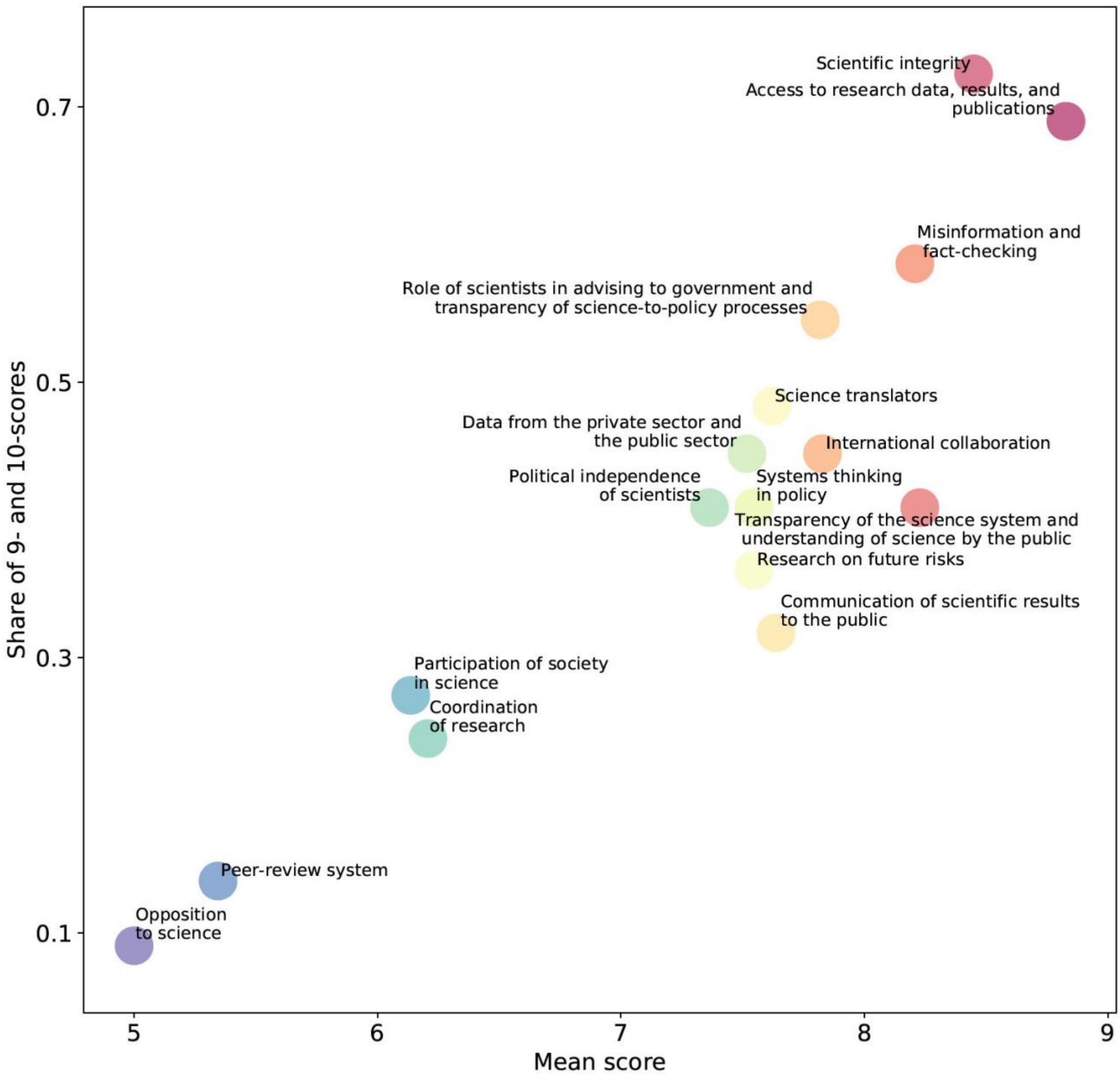

Figure 2. Survey results. Respondents were asked the question: On a scale of 1–10 where 1 is the least important and 10 is the most important, which elements should be the most important focus for policymakers to strengthen the capability of the science system and its capacity to provide effective input into policy in crises triggered by extreme events like COVID-19?

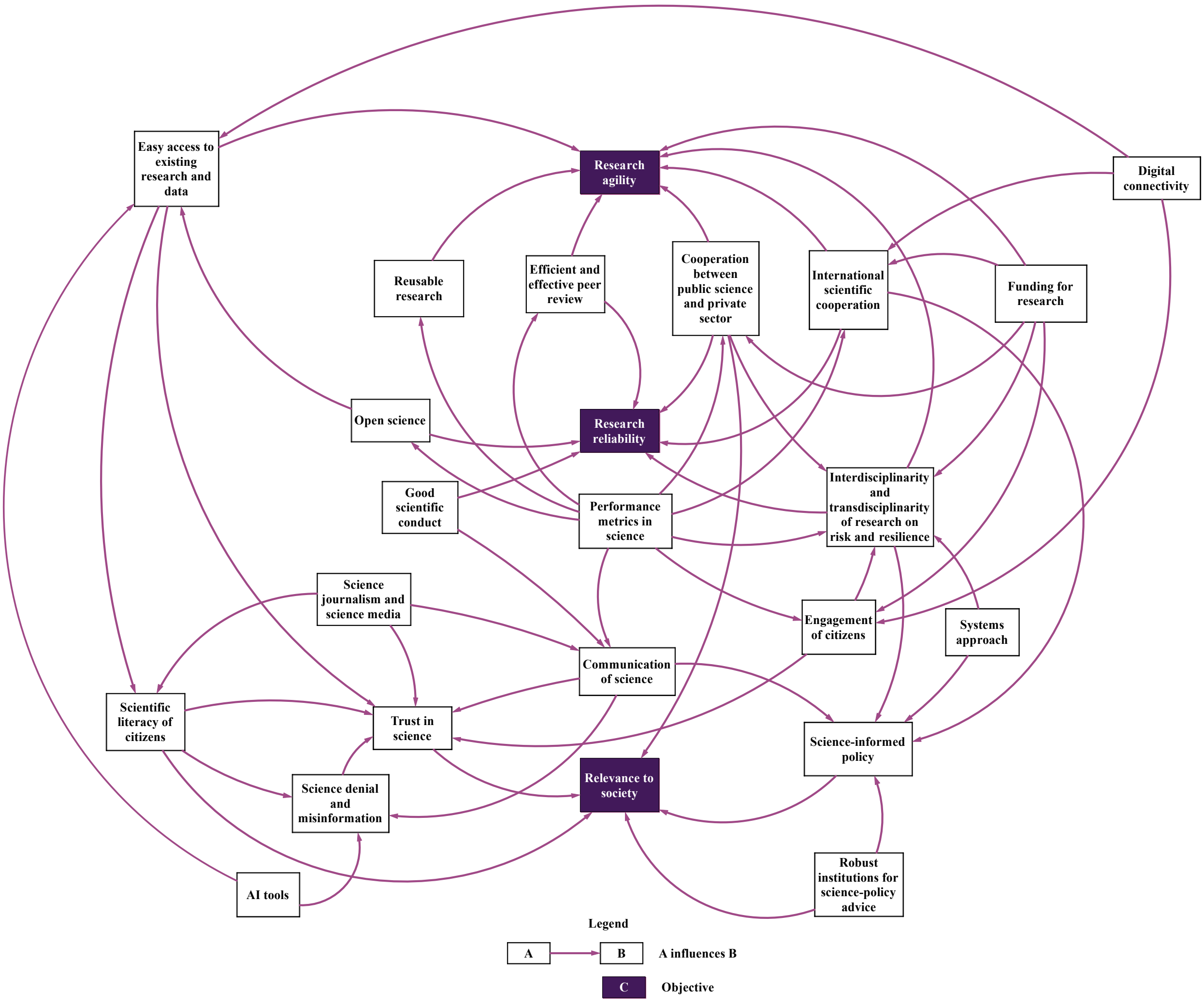

Figure 3. Systems view of the science system. Boxes depict major components and arrows depict major influences.

Moving the Science System to a New Frontier:

Recommendations

As outlined earlier, for the science system to significantly enhance its capacity to respond to future global crises, three axes of improvement were identified: the science system will need to be simultaneously more agile, more reliable, and more relevant, both for policymakers and the citizenry. However, there are many barriers to this objective. The principal barriers have been summarized in a previous section of this report. The present section provides recommendations designed to overcome or mitigate the barriers identified and to propose directions forward.

Simultaneous improvement along all three axes necessarily entails many changes to the existing science system. Accordingly, a large number of recommendations are put forward. These recommendations are grouped under five interrelated major transformative changes (See Figure 4).

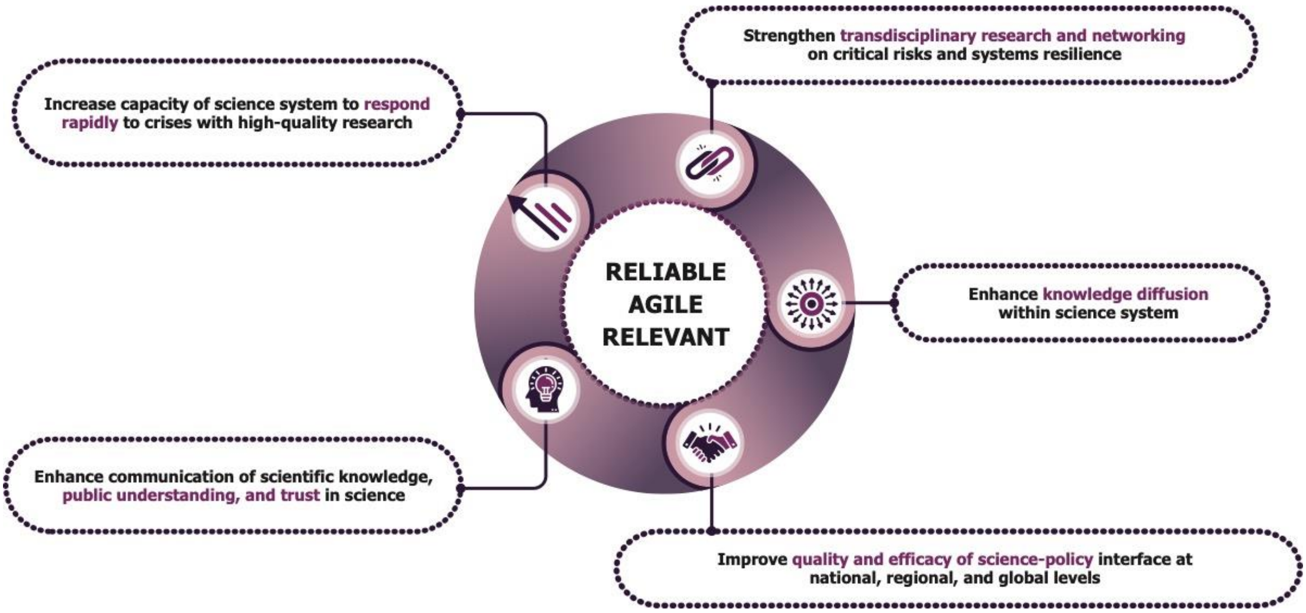

Figure 4. Five interrelated transformative changes.

Strengthen transdisciplinary research and networking on critical risks and systems resilience

Scientific knowledge is essential for understanding, anticipating, and addressing risks. As modern risks are multidimensional, scientific knowledge to address crises will draw from and involve the intersection of many disciplines. Action needs to be undertaken to enhance scientific capacity where this is poorly developed. Networking and global collaboration, always important for science, are especially important in times of crisis when science needs to be agile. Where scientific capacity is limited, networking and global collaboration can play a key role in allowing access to the requisite scientific knowledge. The following five recommendations address the positioning, content, and capacity of risk research. Figure 5 provides an overview.

- **Define global and national security to include natural and anthropogenic disasters.**

The Sendai Framework for Disaster Risk Reduction 2015–2030, adopted at the Third UN World Conference, defines disaster risk in the broadest terms: "Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment" (UNDRR Sendai Framework, 2015). The Sendai Framework requires that governments, at every level, adopt policies and practices for risk reduction. "Each State has the primary responsibility to prevent and reduce disaster risk, including through international, regional, subregional, transboundary and bilateral cooperation" (UNDRR Sendai Framework, 2015). This recommendation conforms to the Sendai Framework.

- **Enhance capacity for research on risks and resilience.**

Local scientific capacity is a critical component for any country to develop effective strategies to address risk. While risks may be global, the manner in which they play themselves out and particularly the way in which different societies respond, show considerable variation. Local context is all important. Moreover, the presence of local scientific capacities that are dedicated to addressing local needs are critical to creating local trust in science and the advice that science provides to policy. All countries should accordingly develop the capacity to produce, access, and effectively use scientific information in relation to the relevant risks. However, as is evident, and as the Sendai Framework recognizes, most developing countries have very limited scientific capacity. Many global risks originate in developing countries. In a globally interconnected world, the inability of developing countries to deal with crises exposes all countries to risk. It is therefore in the interests of all that developing countries are provided with significant external support to further develop their scientific capacities—financial support, technology support, and technology transfer (Amaratunga et al., 2018).

- **Develop networks for scientists to tap knowledge.**

International scientific cooperation is important for all countries and for the scientific endeavor in general. However, the development of networks and mechanisms to tap into knowledge created elsewhere assumes far greater importance for those countries whose capacity is limited. The COVID-

19 crisis has demonstrated many examples of countries with very limited scientific capacities that were able to draw on the experiences of other countries to develop effective and timely policy responses. The Democratic Republic of the Congo, for example, has relied strongly on foreign and international organizations at all stages of the COVID-19 crisis (Kaiser et al., 2020).

Reliable and affordable digital connectivity is today a necessary prerequisite for effective networking and collaboration—both within and between countries. But, in some countries, digital connectivity remains limited and/or costly. Moreover, those countries are generally ones whose own research capacities are limited and who would therefore most benefit from scientific collaboration. Supporting such countries to acquire effective internet capacity is an indispensable step toward enhancing their scientific capacity.

- **Enhance inter- and transdisciplinary research on risk and resilience.**

As the COVID-19 pandemic has so clearly demonstrated, crises are always multidimensional. COVID-19 has clearly been far more than a medical problem; it has had multiple implications for society, for the economy, and for politics. Consequently, policies to address COVID-19 entail the engagement of many different scientific disciplines. Research on risk should be interdisciplinary, encompassing a range of disciplines including the social and behavioral sciences working together with disciplines that have primary relevance to the crisis at hand (medical in the case of COVID-19). This will enable systemic understanding of the crisis and appropriate systemic solutions. This recommendation accords with the Sendai Framework: "Policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be leveraged for the purpose of pre-disaster risk assessment, for prevention and mitigation and for the development and implementation of appropriate preparedness and effective response to disasters" (UNDRR Sendai Framework, 2015).

Engaging with the citizenry and other relevant stakeholders is necessary for gaining knowledge of the nature of social and economic vulnerability, as well as the realities of their decision making. Both are critical factors for ensuring the success of science-informed strategies to deal with crises. This underlines the importance of transdisciplinary research in which "not only are the boundaries between disciplines crossed [interdisciplinary research], but also … those [boundaries] between the academy and other social and political spheres, such that a wide range of actors are involved in the design, development and delivery of research" (Bracken et al., 2014). Transdisciplinary research should be significantly advanced to close the gap between knowledge and action (Klenka and Meehan, 2017) which is necessary to enhance social resilience to the effects of crises.

Citizen science is another very promising approach to strengthening research of risk. "Citizen science for disaster risk reduction (DRR) holds huge promise and has demonstrated success in advancing scientific knowledge, providing early warning of hazards, and contributed to the assessment and management of impacts" (Hicks et al. 2019).

Applications of citizen science to critical risks should be further developed.

- **Develop networks of researchers with complementary expertise.**

Apart from their role in providing a source of knowledge and support to countries where capacity is limited, international research networks and scientific collaborations are central to accelerating scientific progress toward producing effective strategies for disaster risk reduction. International collaboration allows researchers to access the knowledge and experiences of crisis and of the response to crisis in other countries and to make use of that experience. International collaborations also result in more coherent international approaches on disaster risk reduction and contribute to strengthening social resilience. There are many existing Science and Technology networks which address potential crises and their resolution. Examples of global partnerships include the Global Volcano Model Network, the Global Flood Partnership, the Global Alliance of Disaster Research Institutes, the International Network for Government Science Advice, and the Young Hydrologic Society.

COVID-19 has clearly demonstrated the value of international collaboration. International collaboration has been emphasized, for example, in the joint statement of 15 national academies highlighting the critical need for international cooperation to tackle COVID-19 pandemic (National Academy of Medicine, 2020). On the other hand, there has been a counter trend toward the nationalization of science systems by some countries. The demonstration of the value of international cooperation provided by COVID-19 should be used by scientists, academies, international science organizations, and others to press for a greater degree of international cooperation (Kellerhoff, 2020), and science should be understood as a global public good.

One effective way of supporting and facilitating international collaboration is through joint funding calls, whereby each national funding body funds researchers from its country proportionally to their contribution to the project. Such funding mechanisms could establish the foundation for long-lasting collaboration between scientists well beyond the time of the call. Other funding mechanisms that promote cross-border collaboration and networking should be developed.

It would also be helpful to assess how such networks function and how they can be rendered more effective, particularly at times of crisis where the need for effective networks is greatest.

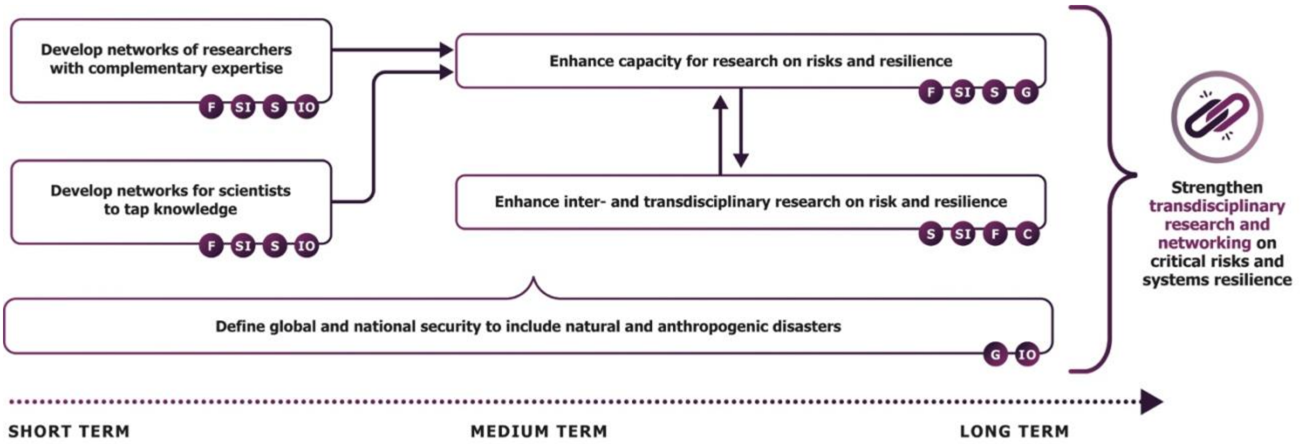

Figure 5. Recommendations (presented in boxes) supporting the transformative change on Strengthen transdisciplinary research and networking on critical risks and systems resilience. Arrows indicate a contribution of recommendation A to effecting recommendation B (only major links are depicted). Abbreviations in bold next to each recommendation indicate major actors responsible for the implementation of this recommendation (**B**=Business/private sector, **C**=Citizens, **F**=Funders, **G**=Governments, **IO**=International organizations, **SP**=Scientific publishers, **SJM**=Science journalists and media, **SI**=Scientific institutions (publicly funded), **S**=Scientists). The horizontal axis provides an indicative time line (short term=start and make progress soon, medium/long term=may start soon but will take time to realize).

Increase capacity of science to respond rapidly to crises with quality research

Crises pose challenges which are both severe and immediate. Delays are costly. The science system is required to react swiftly to generate research that can inform understanding of the threats and the appropriate policy responses. A raft of measures, encompassing the entire research enterprise, is needed to increase the agility of the science system. These measures encompass research institutions; research teams; research funding; research evaluation and incentives; research models and data; standards of scientific practice; international scientific cooperation and increased engagement of the private sector and enhanced cooperation between public and private sector science. The following eight recommendations address these themes. Figure 6 provides an overview.

- **Develop institutions for research on risk and resilience.**

Scientific capacity must be housed in institutions. COVID-19 has demonstrated how difficult it is for poorly endowed research institutions to respond with agility to sudden threats. Strong research institutions are an essential prerequisite for a rapid and quality response. By contrast, in a number of countries, the funding of institutions focused on epidemiology and public health risks and response to disasters was significantly reduced prior to the COVID-19 crisis (Scheck and Hing, 2020). Research institutions cannot be created overnight in response to a crisis. They can only be developed over time, and development requires secure funding. It is vital that adequate, reliable, and ongoing public funding is provided to institutions that undertake research on exogenous risks. Institutions need ready access to additional funding if a crisis occurs; this will allow them to rapidly produce the knowledge that is urgently required and to develop effective policies to address the crisis.

- **Explore a system of expert teams to be activated on demand.**

For the spectrum of likely risks, governments should consider identifying the individuals and institutions best positioned to provide the requisite research so that they can be linked together and rapidly mobilized in the event of a crisis. As crises are inevitably multidimensional, "emergency teams" should possess relevant and complementary expertise in different disciplines needed to deal with particular kinds of exogenous shocks. These "emergency teams" should exist in a stand-by mode, ready to be activated as and when required. Funding for the work of such emergency teams should be readily available to avoid the delays associated with the usual funding procedures.

- **Establish easy-to-access grants to fund crisis research.**

At the onset of a crisis, resources must be readily available to enable scientists to shift their research to the challenges posed by the emerging crisis. The usual application and award processes for funding are far too cumbersome and time-consuming. Easy-to-access grants that could be rapidly awarded are essential (European Commission, 2020). However, national and international agencies distributing public funding for science have limited flexibility to redirect resources to research on issues arising from the crisis. Moreover, any deviation from the business-as-usual allocation of research funding requires a judgment call to be made as to whether such a deviation is indeed justified. In the spirit of democracy, this should be determined through a dialogue and consensus-seeking decision making among scientists, funders, and policymakers. Communication channels between funding agencies, scientists, and policymakers should be established that are ready to be activated when the crisis hits.

Earmarked funding for research into issues emerging in crisis situations could be set aside every year. However, the trade-off entailed by such a solution would need to be carefully evaluated, as it would result in ongoing research receiving less funding. This is a particularly difficult trade-off for countries where resources for research are very limited.

- **Recognize scientists’ contribution to addressing a crisis.**

At times of crisis, many researchers are required to redirect their research to address new challenges. Putting aside ongoing research creates risks for researchers, especially if they are reliant on third-party funding. As currently constituted, performance metrics evaluations discourage scientists from redirecting their research and presenting their results rapidly, for example, via preprints. Accordingly, performance evaluation systems should be adjusted to fully recognize the contribution made by scientists to addressing issues posed by crises, even if this research does not result in publication in a peer-reviewed journal or other traditionally recognized outputs. Special attention needs to be paid to young researchers who are often dependent on short fixed-term insecure contracts and are, at the same time, under pressure to demonstrate "high productivity" (Eaton, 2020). Senior well-established scientists have a responsibility to lead by example in redirecting research to address the crisis. At the same time, senior scientists should encourage and empower young scientists to similarly undertake research relevant to the crisis.

- **Foster reusable research.**

Existing, reusable, and general-purpose models are important to enhancing the agility of the science system to provide rapid research inputs, particularly at early stages of the crisis. As one example, the development of comprehensive models forecasting the spread of COVID-19 that would include complex pathogen- and society-based variables requires considerable effort and time (months to years). However, existing models developed for previous influenza pandemics or SARS or MERS outbreaks could be immediately utilized. Currently, the planning and evaluation of research pays little attention to the importance of generating knowledge that could be reused in future crises. Prioritizing such research would help enhance agility of the science systems.

- **Enhance international scientific cooperation to respond rapidly to a crisis.**

Scientific networks and collaboration, always central to the scientific enterprise, are particularly critical in times of crisis. Enhanced cooperation simultaneously allows for greater agility on the part of science to respond to crises, as knowledge and results are shared rather than duplicated; it also allows for enhanced quality, as additional and different perspectives and skills are brought into play. The COVID-19 pandemic has seen a marked increase in collaboration and networking among scientists. However, there have been limits. As noted earlier, the basis on which many international scientific networks, and especially those that foster linkages between researchers in the developed and the developing countries, has come under significant strain as a consequence of COVID-19. New networks and new mechanisms to support them are urgently required. An expanded role for universities in the South in developing postgraduate studies and research requires further investigation.

The recommendations of this report concerning funding and the need to counteract "nationalization" of science to enhance international collaboration in general are especially relevant when a rapid response to a crisis is needed.

- **Enhance good scientific practice in times of crisis.**

There is widespread concern that the rush to conduct research and publish the results related to COVID-19 may have resulted in the quality of some of this research being lower than the usual standard. Good practices regarding how to conduct quality research in response to a crisis should be analyzed and shared widely. Existing codes of scientific conduct should be amended with explicit statements detailing how cases of scientific misconduct that are likely to occur in times of exogenous crises would be constituted. Of particular importance is a code of ethical conduct for researchers working in disaster zones. At the international level, the World Health Organization provides some guidance for research on public health emergencies (WHO, Ethical, 2020) and the International Science Council (ISC) and International Network for Government Science Advisors (INGSA) are currently in discussion to develop broad Guidelines for Conduct of Scientists in Emergencies. These activities should be broadly supported.

- **Enhance cooperation between public and private sector.**

The private sector forms a large part of the research ecosystem. With few exceptions, the private sector makes the biggest contribution to national research budgets. Even in respect of basic scientific research, in many countries, the private sector is more significant than the public sector. Moreover, the share of the private sector is tending to increase (Tulsi, 2018).

Reflecting on the experiences from the COVID-19 pandemic, the International Chamber of Commerce recently concluded that, "The COVID-19 pandemic has spotlighted the crucial need for international scientific collaboration in both the public and private sectors…. International cross-border scientific collaboration including between public and private researchers should be supported, and policies and regulations that could hinder this international collaboration and exchange avoided" (International Chamber of Commerce, 2020).

The private sector possesses data that are critical to developing effective responses to crises. Relevant in the COVID-19 pandemic are behavioral data, and data on mobility dynamics and purchasing patterns, among many others. Some companies have made valuable high-level aggregative data available: for example, Google has shared so-called community mobility reports and Yandex, Russia's biggest IT company, has made data available that shows how people's mobility has changed in response to the COVID-19 pandemic (Russia Beyond, 2020). However, these are exceptions. Much of the data in the private sector remains inaccessible.

While there are effective collaborations between publicly funded science and science in the private sector in many fields, much more collaboration is required. Businesses respond very largely to financial incentives. Funding for public–private collaborations to address the challenges resulting from crises is therefore central. The greatest need for cooperation is often in high risk areas. Here, public funding can be used to match private funding and thereby incentivize companies to enter high risk areas. Tax concessions can also serve to incentivize companies to address social needs arising from a crisis.

When a major global crisis such as COVID-19 emerges, public and private sectors need to be brought together to address pressing global challenges, while temporarily setting aside sectional interests. The proclamation of global crisis by the United Nations, for example, could signal the need for a common effort across the public–private interface, with attendant financial protocols to spread risks, avoid jeopardy, and ensure appropriate financial returns. This proclamation could be combined with the setting of clear performance targets in relation to combating future crises. The Paris Agreement on Climate Change, for example, has resulted in many businesses aligning their strategies with the achievement of these targets.

More long-term strategies could entail "changing the mind set" in the business sector such that there is far greater recognition and acceptance of its potential social role in addressing future crises. This could be through education and/or regulatory changes that require firms to account for their social contributions. Collaboration can also be facilitated by encouraging mobility between public- and private-sector science. The presence of representatives from the business sector on the boards of universities and public science institutions could promote linkages. Other organizations—university technology transfer offices, for example—also build these linkages. So-called relational professionals that are able to communicate sensitively to both communities may be of value.

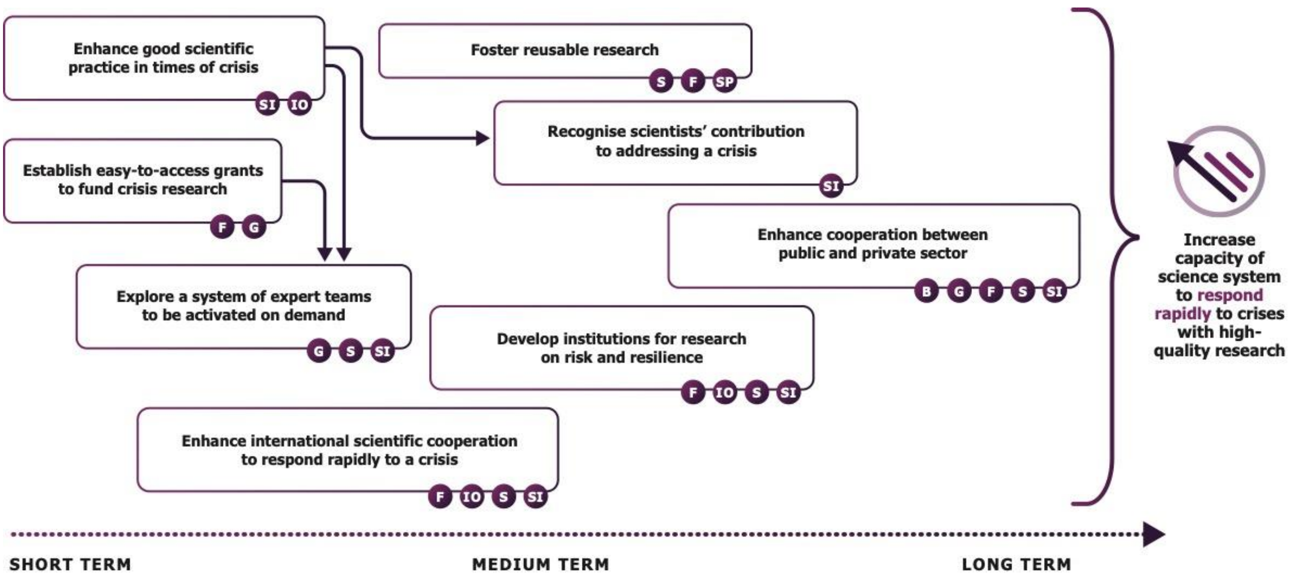

Figure 6. Recommendations (presented in boxes) supporting the transformative change on Increase capacity of science system to respond rapidly to crises with high-quality research. Arrows indicate a contribution of recommendation A to effecting recommendation B (only major links are depicted). Abbreviations in bold next to each recommendation indicate major actors responsible for the implementation of this recommendation (**B**=Business/private sector, **C**=Citizens, **F**=Funders, **G**=Governments, **IO**=International organizations, **SP**=Scientific publishers, **SJM**=Science journalists and media, **SI**=Scientific institutions (publicly funded), **S**=Scientists). The horizontal axis provides an indicative time line (short term=start and make progress soon, medium/long term=may start soon but will take time to realize).

Enhance knowledge diffusion within science system

The swift dissemination of high-quality research is a prerequisite for both rapid progress in science and effective science advice to policy and society, particularly in crisis situations. The recommendations regarding how to enhance the diffusion of scientific knowledge within the science system is in two parts. Part 1 proposes several improvements for the system of peer review of publications. Part 2 addresses issues of access to and navigation of existing scientific knowledge.

Part 1: Review

The current peer-review system as a research quality assurance and legitimacy mechanism has been subject to considerable questioning prior to COVID-19 (Ioannidis, 2019; Mulligan et al., 2012). Peer review of interdisciplinary research presents particular difficulties (Editorial, *Nature,* 2018). COVID-19 underlined the imperative of making the peer-review system agile, international, rigorous, and inclusive if science is to meet the challenges of future crises. International organizations of science, including ISC and UNESCO, could take a lead in devising a more effective system of peer review through a dialogue with international disciplinary bodies, national academies, publishers, and national research councils. Figure 7-1 provides an overview of seven recommendations.

- **Institute rapid post-publication peer review of preprints.**

The COVID-19 crisis saw a rapid proliferation in preprints. Preprints are particularly valuable at times of crisis, speedily placing relevant research in the hands of those addressing the crisis and of concerned citizens. However, preprints may be flawed or misconceived (Kwon, 2020). Currently, there is no widespread agreement as to how to manage the review process for preprints; preprint servers typically conduct only a basic screening process. In response to the surge of preprints, platforms that are involved with health-related research such as bioRxiv (Kwon, 2020) and medRxiv (Else, 2019) have enhanced their screening procedures; for example, they do not accept papers that can cause harm or may fuel conspiracy theories (Kwon, 2020).

There is an urgent need for a clear system of preprint review. Reviews should be post-publication, rapid, and light, allowing readers to have an overall assessment of the quality of the preprint. Post-publication reviews do not affect the decision to make the preprint available and hence will not slow down the publication process. Reviews do not have to be comprehensive. They can provide enough information for readers to take a view on the merit of the preprint. Some platforms (e.g., Publons: Publons, 2018) already utilize such a system of post-publication review but these are not yet widespread.

- **Institute training in reviewing.**

Peer review has proven to be an effective mechanism for quality assurance of research; most scientists seem to be reasonably satisfied with the peer-review system (Mulligan et al., 2012). Scientists should continue to review each other's work. However, scientists frequently misunderstand their role as a reviewer. For example, reviewers often recommend the authors to revise their paper in conformity with how they, the reviewers, "would do" the study rather than to review what has been done (Faggion, 2016). If peer review is not double-blind, it may suffer from affiliation, gender, ideological, or other biases (Mulligan et al., 2012). In the survey cited above, about two-thirds of respondents considered that formal training of reviewers would improve the quality of review (Mulligan et al., 2012) There are a few training programs that develop the capacity to review, but this practice is not widespread. The development of the capacity to provide an effective quality review should be made integral to the training of scientists. Standards of review quality should be developed and enforced (Tennant and Ross-Hellauer, 2020).

Science is becoming more interdisciplinary (Pautasso and Pautasso, 2010). Sound peer review is especially critical to ensure the quality of interdisciplinary research. As interdisciplinary research combines knowledge from various disciplines in a novel way, it needs to be reviewed to evaluate disciplinary rigor and the novelty and value of the interdisciplinary approach. Training and good standards of interdisciplinary research review should be promoted.

- **Strengthen incentives for review.**

Currently, apart from their own interest in the research, there is little incentive for scientists to undertake reviews. As a result, journals have difficulty in locating willing reviewers and ensuring a swift review process. The time taken to locate reviewers is a major cause of the lengthy time to publication. According to a large-scale survey conducted in 2018, "75% of journal editors say the hardest part of their job is finding willing reviewers" (Vesper, 2018). Artificial Intelligence (AI) can be a useful mechanism for identifying appropriate reviewers and should be used more fully.

Quality review takes considerable time but is poorly rewarded (Kennedy, 2017). Some publishers offer reviewers access to their journals; other rewards include training courses and public expression of gratitude (Seeber and Zaharie, 2018). There are examples of direct payments to reviewers, but this is rare (Gasparyan et al., 2015). A survey conducted in 2007 revealed that reviewers have mixed perceptions of the effectiveness of the financial incentives. Of 13 potential material and non-material incentives, "free access or subscription to this journal," "annual acknowledgment on the journal's web-site," and "more feedback from the editor about the outcome of the submission" were ranked most highly, followed by "appointment of best reviewers to the journal's editorial board" and "consultancy-equivalent fee for the time spent" (Tite and Schroter, 2007). In 2013 Elsevier piloted the awarding of certificates of excellence for reviewers (Gasparyan et al., 2015). This could be a welcome additional incentive.

If the quality of reviews is to be enhanced, there is a clear need to further develop the incentive system and apply it widely to encourage and reward reviewers. Apart from material incentives, journals should give much more acknowledgment and recognition to reviewers. Reviews should be accorded greater significance in the career assessment of scientists. One option may be open authorship of reviews. Furthermore, reviews should be recognized as a form of publication.

- **Open communication between authors and reviewers/editors.**

Currently, authors have very little opportunity to dispute the outcomes of a review and the decision of the editor regarding their publication. A regular routine designed to resolve such disputes should be considered. This will reduce the risk of important research being overlooked or its dissemination delayed (Faggion, 2016).

- **Incentivize researchers to publish reviews.**

Writing a review article surveying a wide field of research is a particularly difficult task. Review articles are relatively rare, yet they can be a very efficient way of familiarizing scientists and a broader public with the state of research in a given field. A review of the research landscape may be particularly valuable in a rapidly developing crisis. Such articles reviewing extant research should be encouraged by journals and funders, more particularly at times of crisis.

- **Make peer review international and inclusive.**

There is considerable regional disparity among researchers regarding reviews. Researchers in leading locations of science research, such as the United States, the United Kingdom, and Japan, typically write nearly two peer reviews per own-authored article submitted, compared with about 0.6 peer reviews per article submitted by those in emerging countries such as China, Brazil, India, and Poland (Vesper 2018). The challenge to the international science community is to create processes of dissemination and review that are global and responsive to diverse national capacities and needs. An international system with a database of potential reviewers that could be rapidly mobilized should be put in place. An example of a possible precursor of such a database emerged during COVID-19, Outbreak Science Rapid PREreview, provided a platform where researchers were able to request or provide swift reviews of outbreak-related preprints (Kwon, 2020).

- **Introduce peer review for data.**

The COVID-19 experience not only underlines the necessity of strong peer-review systems for scientific articles but also for the data on which many claims of scientific truth depend. The critical importance of ensuring that data are provided and can be reviewed was revealed when a recent article in *The Lancet* had to be retracted due to critical inconsistencies being found post-publication in the data underpinning it (Boseley and Davey, 2020). Effective peer review is predicated on access not only to the data, but also to the models and computer codes that provide evidence for scientific claims. Better and more agile peer-review systems are necessary not only for scientific articles but also for data.

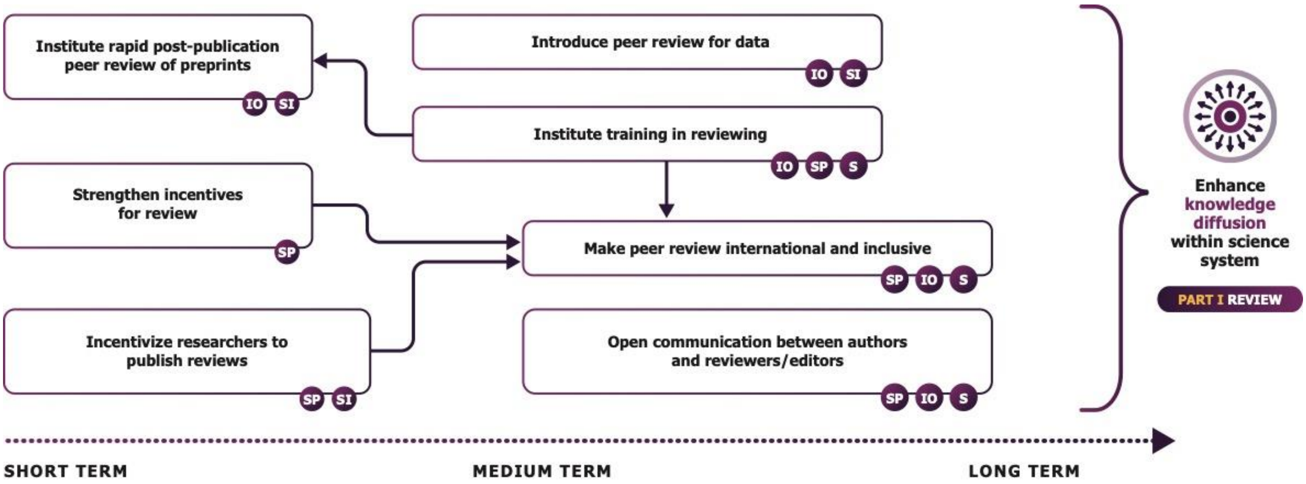

Figure 7-1. Recommendations (presented in boxes) supporting the transformative change on Enhance knowledge diffusion within science system. Part 1: Review. Arrows indicate a contribution of recommendation A to effecting recommendation B (only major links are depicted). Abbreviations in bold next to each recommendation indicate major actors responsible for the implementation of this recommendation (**B**=Business/private sector, **C**=Citizens, **F**=Funders, **G**=Governments, **IO**=International organizations, **SP**=Scientific publishers, **SJM**=Science journalists and media, **SI**=Scientific institutions (publicly funded), **S**=Scientists). The horizontal axis provides an indicative time line (short term=start and make progress soon, medium/long term=may start soon but will take time to realize).

Part 2: Access and Navigation

Open science is critical to ensuring that scientific knowledge is shared globally (OANA, 2018–2020). This sharing of knowledge is, in turn, a prerequisite for successfully combating a global crisis. Open access to the record of science data as well as the transparency of the research process itself are the two cornerstones of Open Science (Global Open Access Portal, n.d.). Open Science enables reproducibility, which in turn allows for greater validation of results and increases research rigor; it reduces duplication permitting more effective use of resources and facilitates more inclusive participation in research (NASEM, 2018). The challenge is to identify a viable business model for Open

Science and to facilitate a cultural shift through aligned incentives. The following recommendations cover four areas of improvement: see Figure 7-2 for the overview.

- **Develop depositories and common standards for data.**

Journals should be responsible for ensuring that relevant data and models are easily accessible; this should be a condition of publication. It should be the responsibility of funders to impose this as a condition for funding. Data should be deposited in open and well managed repositories. Many such data depositories already exist, for example, the World Data System (WDS) operating under the ISC (World Data Systems, 2020) which links the data repositories of its members in a virtual network and certifies them as meeting criteria on scientific relevance, governance, data management, etc. The utilization of such data repositories should be promoted. Common data standards will further improve the efficiency and speed of research and should thus be developed and promoted.

- **Promote depositories for existing research.**

The digital revolution is a critical enabler of the movement to open science, providing digital means to make research accessible via online depositories. Each research institution should introduce and maintain a depository that gives as complete as possible access to the scientific output produced by the institution. Beyond open access, platforms aggregating research on a particular topic should be developed, such as, for example, the global research database on COVID-19 operated by WHO (WHO, COVID-19, 2020). Conditions should be created whereby such platforms could rapidly emerge with the onset of a crisis. These depositories and platforms could include publications in different languages. Automatic language translation could be used to make research in different languages widely accessible.

- **Make data, models, and computer codes open and easily accessible.**

Modern research increasingly relies on large volumes of diverse data that often cannot be contained within a conventional scientific paper. However, the sharing of data is fundamental to ensuring the integrity of the research. Access to the data is required to test for reproducibility and for the enhancement of Open Science. A suitable framework for accessibility to data is a FAIR format (Findable-Accessible-Interoperable-Reusable) (Wilkinson et al., 2016). In addition to data, models and computer codes that provide evidence for scientific claims must be concurrently accessible for scrutiny and reproducibility. Computer code utilized in manipulating data or in models should be openly available. In some cases, the characteristics of the machine that undertook the computation will also be required. Open-source software should be used as much as possible.

- **Make available interim products of research.**

At present, scientists are almost entirely focused on the publishing end of their work: the final paper. Until that paper is published, the authors receive no reward. This incentive system thus locks up all knowledge until final publication. This situation should be fundamentally changed. For example, deposition of data in a publicly accessible depository prior to publication would allow access on the part of other researchers and significantly speed up the scientific process.

Apart from data, other well-grounded products of the research process that predate publication of the article such as substantive ideas/hypotheses, research protocols, negative results etc., should be made available (NAP, 2018) and be eligible for funding. Suitable formats for the sharing of these other products should be identified. Attributing authorship of the different components of the research process through such a system would allow for greater levels of accountability. The key is to develop a system that allows for the widest and most rapid diffusion of knowledge while simultaneously rewarding new scientific discovery. These ideas have been suggested by some experts (Freeman, 2020). A broader discussion and detailed elaboration as to how such a system could be implemented is required.

- **Explore automated knowledge synthesis algorithms.**

Rapidly developing natural language processing and big data analytics will enable automated knowledge synthesis which can revolutionize the scientific process. Some initiatives have begun to emerge that utilize these advances (Freeman, 2020; Ungs, 2020). The effectiveness of natural language processing and big data analytics should be further explored.

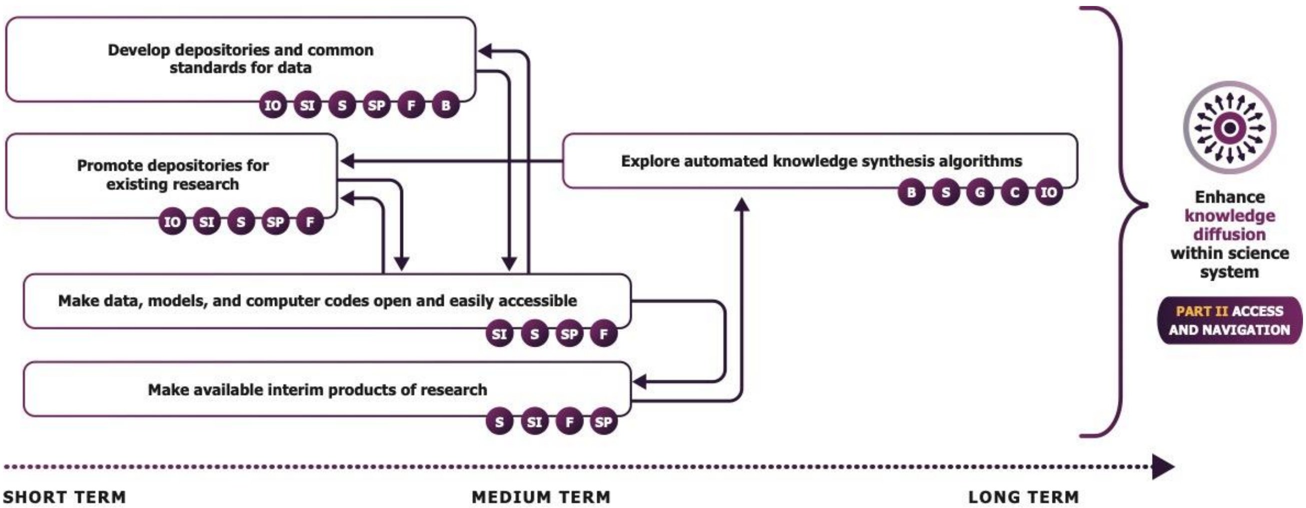

Figure 7-2. Recommendations (presented in boxes) supporting the transformative change on Enhance knowledge diffusion within science system. Part 2: Access and Navigation. Arrows indicate a contribution of recommendation A to effecting recommendation B (only major links are depicted). Abbreviations in bold next to each recommendation indicate major actors responsible for the implementation of this recommendation (**B**=Business/private sector, **C**=Citizens, **F**=Funders, **G**=Governments, **IO**=International organizations, **SP**=Scientific publishers, **SJM**=Science journalists and media,

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Enhance communication of scientific knowledge, public understanding, and trust in science

Trust in science and in the recommendations emanating from scientists are key to the effectiveness of science-based policies. Clear communication, transparency, and broad public understanding of how science works are three foundations on which to enhance trust in science. The recommendations below are addressed to these issues. Figure 8 provides an overview.

- **Create easily accessible sources of scientific results.**

The general public often has difficulty in understanding scientific language and disputes. Specially developed sources of reliable scientific information provided in accessible language should be made available to allow the general public to inform themselves on the latest advances in science with societal relevance. Funding incentives should be put in place to encourage scientists to engage in knowledge synthesis and translation work. Machine reading can substantially improve knowledge synthesis and can aid in locating and interpreting information that supports scientific assessments. Similarly, machines can help disseminate new findings effectively by applying individual-targeting algorithms. Governance protocols for these emerging machines should be developed.

- **Train and incentivize science communication.**

Scientists currently do not see it as their role to engage in a conversation with society. Scientists see themselves as researchers producing science, not communicating science. A complete mindset change among scientists, science institutions, and funders is required to include communication of science as a core requirement. Efforts of scientists to communicate science to the public and to engage with citizens should be rewarded. New metrics to assess the performance of scientists and scientific institutions are needed in this regard. Scientists should be trained and incentivized in the communication of science. Visual and interactive tools and other means to communicate science to a far broader audience should be widely utilized. As just one example, The Jamming the Curve competition initiative in the USA will develop engaging games to boost public understanding of COVID-19 (NAS, 2020).

Despite concerns expressed by scientists and others, evidence suggests that communicating epistemic uncertainty does not undermine audiences' trust in the facts and communicators (van der Blesa et al., 2019–2020). On the contrary, communications should include clear and open acknowledgment of the limitations and uncertainties related to scientific findings (Hunter, 2016). The degree of consensus among scientists should be made explicit.

Institutions that convey scientific information to the public should be aware that the authority and credibility that their organization has with the public will impact on the public's perception and how reliable they find the information being conveyed to them. Some evidence exists that press releases emanating from institutions communicating research may exaggerate results and advice compared to the original publications (Sumner et al., 2014). These institutions should ensure that communications with the public on the part of persons connected with the institution are accurate and sound (Vallejo and Ong, 2020).

- **Engage scientists in countering false science.**

Science denial and misinformation have been increasing rapidly during the pandemic. For example, claims have been widely disseminated that science has created or exaggerated the COVID-19 crisis and is responsible for the economic recession that has resulted from lockdown policies (Young, 2020). Public skepticism and distrust of science has been encouraged and facilitated by powerful political forces (Friedman and Plumer, 2020; *Lancet* COVID-19 Commission, 2020; Scofield, 2020). It is critical that science denial and misinformation be countered. Scientists themselves should play a more active role in combating misinformation in their fields. Faced with a deluge of false claims about science and the manipulation of science for political and ideological ends, it is incumbent on scientists to be far more active in refuting such claims and to more rigorously defend the importance and integrity of science. Individual scientists, but more particularly, science organizations—national and global— must engage in urgent discussions on how best to act in this regard.

- **Enhance capacity and integrity of science journalism.**

How science is communicated is critical to building trust in science. The media may exaggerate scientific findings, which then do not meet expectations, and so further erode trust in science. Often, the views of celebrities—and not scientists—are given prominence and are widely disseminated. The media should ensure that the "experts" that they engage to provide scientific advice are, in fact, substantial and reputable scientists.

The science communication challenge is complicated by the public looking to science for clear and unambiguous research results and advice for policy. However, scientists are in constant debate. This is especially so when, as with the COVID-19 pandemic, there are many unknowns and data are limited. Time is needed before anything approximating a scientific consensus emerges. In the interim, scientists may offer very different advice. A graphic illustration of diverging scientific views are what has been termed "Dueling petitions about what to do about COVID-19" represented by the Great

Barrington Declaration and the John Snow Memorandum, each of which is supported by eminent scientists (Prasad, 2020). Particularly where scientists offer differing results and policy advice, as is very likely in times of crisis, science journalists as "science translators" play a key role.

Science journalism is an important attribute of democracy and it is of utmost importance for the building of public trust in science. Because responsible and effective science journalists have a critical role to play in enhancing understanding and legitimacy of science, there is a case for public funding to enhance the capacity of science journalism and science media, for example, through training programs. This is especially critical in countries where science journalism and science media are not well developed.

Integrity in science journalism is especially important in times of crisis. There is some evidence that public trust in journalism in general may be declining in some countries (Ingram, 2018; Beckett, 2020; Tobitt, 2020) Science journalists and science media have a responsibility to society to ensure that the public receives only sound and verifiable scientific information. Closer cooperation between scientists and journalists would enhance the quality of science communication. Such cooperation can be facilitated by an intermediary agency. There are examples of such intermediary agencies (Science Media Center, n.d.). Greater transparency on the part of science, aided by science journalism, would enable the public to better understand how scientists obtain their results.

- **Utilize automatic systems for checking scientific facts.**

COVID-19 has seen a proliferation of scientific misinformation and false claims. Machine learning including natural language processing that provides algorithms for deception detection can be used for filtering out misinformation and fact-checking. A number of tools are already available, for example, *Fakespot* (Fakespot, n.d.), which assesses the validity of online reviews based on the URL, and *NewsGuard* (Guardtech, n.d.), which integrates opinions from a large pool of journalists and informs users about the reliability of new websites and organizations (Komendatova et al. in press).

- **Facilitate engagement between science and citizens.**

Citizen engagement in science is a democratic imperative in a world increasingly conditioned by science. There is a need to create incentives for the scientific community to engage in processes of deliberative societal dialogue about the creation and use of new knowledge. In designing this dialogue, the dual nature of science should be recognized: science is capable of producing utilitarian value over the short term where its link with technology is key. Science is also a public good whose intrinsic value is to expand knowledge about the universe that can lead to unanticipated breakthroughs and major societal and economic paradigm changes (Nowotny, 2014).

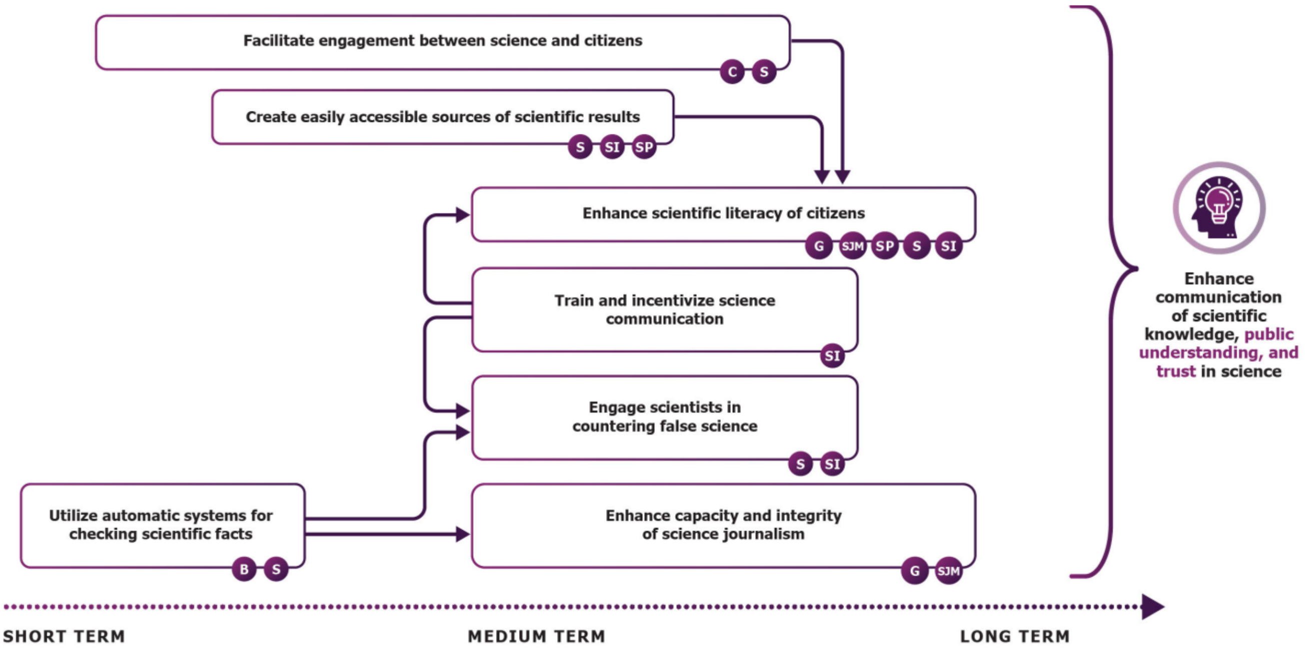
Citizen science is an important contribution to a more socially engaged science. The main limitation of citizen science is the problem of scale. The impact of citizens' engagement in science is generally confined to people who are directly involved in the exercise (Stilgoe et al., 2014). Digitalization is a promising tool for the scaling up of citizen science. For example, a Belgian platform called *Everyone Scientist* (Everyone Scientist, n.d.) claims to be "the place where everyone can do science, regardless of your background." Approaches for scaling up should be further explored including crowd sourcing of data and ideas. For example, The Royal Society of the UK recruited 1,800 "volunteer researchers" from academia, business, and other sectors of the society who will feed their experience into modeling work on COVID-19 (Tatalović, 2020).

In addition to scientific merit, journals should score engagement with society on the part of authors as a positive factor in accepting papers for publication. It should be recognized that public engagement is costly and can be politically risky (Kleinman et al., 2011). Serious attention should be given to finding cost- and effort-efficient ways of growing citizens' engagement in science.

- **Enhance scientific literacy of citizens.**

Scientifically informed policies need public acceptance if they are to be successfully implemented. Public trust in science, albeit with significant variations across countries, generally remains high (EuroScientist, 2015; OECD Science Survey, 2020). However, there is an observable lack of public understanding of how science functions and what science can and cannot do. This lack of public understanding is most evident in developing countries, but is also widespread in the developed world. The diversity of views and contestation are integral to the scientific endeavor. However, it is often difficult for individuals outside the science community to distinguish a healthy scientific debate from an ill-founded contestation (Field and Powell, 2001).

To support trust in science, the public should be educated to understand that science does not speak with one voice, that it often takes time for anything approximating a scientific consensus to emerge, and that there is no one way in which science undertakes research or derives answers. It is essential to enhance the scientific literacy of citizens, which includes imparting not only scientific facts, concepts, and methods, but also the processes by which science operates. The centrality of debate and contestation for science should be taught very early, as an integral component of science instruction in school. Those involved in the popularization of science should pay more attention to conveying this message to the general public.



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Improve quality and efficacy of science–policy interface at national, regional, and global levels

As underlined by the then Secretary-General of the United Nations H.E. Ban Ki-moon, "decision-making processes have to be informed by scientific evidence and knowledge, and [that] international and transdisciplinary scientific collaboration is a prerequisite to reach global sustainability" (Science Advisory Board, 2013). As science advice has moved to center stage as an input into policy in the COVID-19 pandemic, this has challenged national science–policy systems. Countries have adopted very different institutional responses (Cowen, 2020) and systems are still evolving. It is too early to draw hard conclusions with respect to the relative merits of different systems and responses. However, some lessons have been learned that provide broad guidelines as to how science can become a more effective input into policy, as summarized in six recommendations below; Figure 9 provides an overview.

- **Develop robust national and multinational institutions for science advice.**

The COVID-19 pandemic has demonstrated the critical importance, but also the limitations, in the current science–policy system. Countries differ widely in how they institutionalize the science-policy interface (International Science Council, 2020). There is no unique best institutional model. In some countries, scientists are embedded directly in the government, while other countries require scientists who are providing advice to be located outside of government structures.

Developing countries tend to have major weaknesses at the science–policy interface. However, experience with tackling COVID-19 pandemic shows that it can be a real challenge to ensure that policies are informed by science, and this is not only the case for developing countries. According to UNDESA, for example, even in countries where the science–policy interface is strongly institutionalized, the COVID-19 pandemic has made it apparent that there is clear room for improvement (Roehrl et al., 2020).

Improvement requires science–policy interaction to be institutionalized and for such institutions to be robust (Vallejo and Ong, 2020). Institutions need to be long-lasting; thus, provision must be made for stable and predictable sources of funding.

The breadth and depth of international scientific cooperation among institutions engaged in science-policy advice should be enhanced. This cooperation will further advance scientific excellence as well as significantly enhance the quality of science inputs to policy. International collaboration allows for sharing of evidence and the emergence of a scientific consensus. This consensus can then be communicated to policymakers. Scientific consensus, based on international global scientific collaboration, is especially critical for forecasting future global challenges and threats, and allows policymakers to take preemptive action.

In recent years, the United Nations has considerably enhanced the use of science advice in its decision-making processes and introduced institutional adjustments to "balance scientific integrity and interaction between policy and science" (National Research Council, 2002). Some UN bodies have already introduced chief scientist positions, for example, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). The Scientific Advisory Board of the United Nations Secretary-General was created in 2013 (the Secretariat is hosted by UNESCO). Science advice mechanisms should also be further developed at the multilateral level.

- **(Even) In crisis, assess social impacts of candidate policies.**

More attention should be paid to the political, social, and economic contexts and to the decision-making realities in different countries. Insights and practices drawn from one context may have very different and unanticipated outcomes when applied to another context. It is therefore important to assess the social impacts of policies and the likely responses of society prior to policy decisions being made.

There are a number of different methods and routines whereby the social impacts of different policy options can be formally assessed. Social Impact Analysis (SIA) for example is widely utilized either ex ante or ex post the implementation of policy. However, such methods take time and in situations of crisis, government are required to act or react very rapidly. Nevertheless, some clear and deliberate ex ante assessment of the social impact of any intended policy is essential. Alternative methods of determining the social impact of policies in situations where governments are required to act rapidly are required. Assessments based on expert judgments drawn from as broad a spectrum of specialists as possible should be utilized. The perspectives of social scientists who are engaged in risk research and who have a sound understanding of soft systems—social systems and institutions—will be particularly valuable.

- **Policymakers to interact with a wider academic community.**

As many aspects of the COVID-19 crisis have so clearly demonstrated, science does not speak with one voice. Particularly where scientific advice is strongly contested and scientists provide very different policy advice and support for such advice, policymakers would benefit from access to "third parties" to discuss and evaluate the advice being advanced. Academics and academic institutions that lie outside the formal science advisory system can play a useful role here. Scientific organizations such as the national academies of science, should be engaged much more systematically in reviewing existing policies and programs and in preparing new initiatives. International organizations of science and other international bodies that dispense advice can also be useful for scientifically informed policy making (UNESCO 2016).

- **Adopt a systemic approach to policy advice.**

COVID-19 is a multi-faceted crisis and dealing with it requires a holistic systemic approach. Systems thinking can help policymakers to gain a fuller sense of the spread of infection, as well as a better understanding of "the multiple implications of decisions and (in)actions in face of such a complex situation involving many interconnected factors" (Bradley et al., 2020). Future crises are likely to be similar in this respect. However, the advantages of a systems-based approach are often insufficiently recognized.

Science advice should engage a number of scientists and a range of scientific disciplines. This will significantly improve the breadth and quality of advice. Instead of a "linear," unidirectional model of science informing policy, a dialogue between scientists and policymakers as two partners based on codesign and coproduction principles should be promoted. For their part, scientists engaged in providing science advice to governments should recognize and acknowledge that their advice, while important, covers only the area of their discipline and expertise, whereas policymakers are confronted with a plethora of science-based and non-science-based considerations. Scientists should also consider that their knowledge is always interpreted in a political context. In the final analysis, responsibility for integrating different aspects of advice, giving consideration to the trade-offs involved and making informed policy decisions, rests with policymakers.

- **Enhance transparency of science input into policy.**

As far as possible, the advice of scientists to policymakers should be made open and transparent (Douglas, 2020). Openness and transparency, and the freedom to discuss and debate scientific advice, is critical to public trust and legitimacy. Trust and legitimacy, in turn, will make policies far more effective.

Increased transparency of science-advice mechanisms—especially after the COVID-19 crisis which propelled scientists and science advice to the very center of policy—will allow science advisory bodies to be more effective. This includes being transparent to the general public and to relevant stakeholders, including the expert community. Expert judgment and the evidential basis of given recommendations should be made transparent. Scientists need to provide greater clarity regarding the assumptions that they make in analyses. It is also very important for scientists to be straightforward and direct in terms of the limitations of their knowledge and the degree of confidence that they have in the policies they propose.

Scientific advice to policymakers should be formulated and communicated in a form best suited for policymakers. Science advisers need to recognize the capacities of policymakers to comprehend and engage with the science advice advanced and formulate their advice accordingly. Multiple perspectives and opinions coming from the scientific community can be confusing for policymakers. Science "translators" could be helpful in bridging the gap between scientists and policymakers.

For their part, governments need to be transparent in their thinking and deliberations concerning the different policy options and to communicate this effectively to the citizenry and relevant stakeholders.

In some instances, the capacity of government to assimilate and absorb scientific advice is a major constraint. Enhancing the scientific literacy of government officials and their understanding of how science functions is thus very important for improving the effective utilization of science advice in policy.

Governments should refrain from any attempt influence the scientific advice that they receive. Sir Robert May, the then Chief Scientific Adviser to the UK Government and Head of the Office of Science and Technology (OST), published Guidelines on The Use of Scientific Advice in Policy Making in 1997, which have been updated several times (Chief Scientific Advisor UK, 2009). This document sets out key principles for government structures to apply in the use and presentation of scientific advice (UK Parliament, 2001) and could serve as one example of good practice.

- **Investigate effective models of science–policy interface.**

At varying times, many countries have formed advisory boards and task forces of relevant experts to gather scientific advice on dealing with COVID-19 (OECD Survey on STI, 2020). However, the activity and membership of such bodies is sometimes not sufficiently transparent (Carrell et al., 2020). There are different models of how best to make the views of the scientific community available to policymakers. One variant is to have a chief scientist whose task is to gather together various science inputs and communicate them to the policymakers. In another model the diverse voices of the scientific community reach policymakers directly through various platforms. As the COVID-19 pandemic has evolved, so too have science–policy advice institutions and practices. While some general requirements for effective policy advice are evident, such as the need for transparency and for advice that is broadly based in terms of scientific disciplines, there is clearly no one institutional form that is most appropriate for all countries. Governments, while learning from the experience of other countries about the effectiveness of different systems in practice, should establish scientific advisory processes that take cognizance of their own needs and resources.

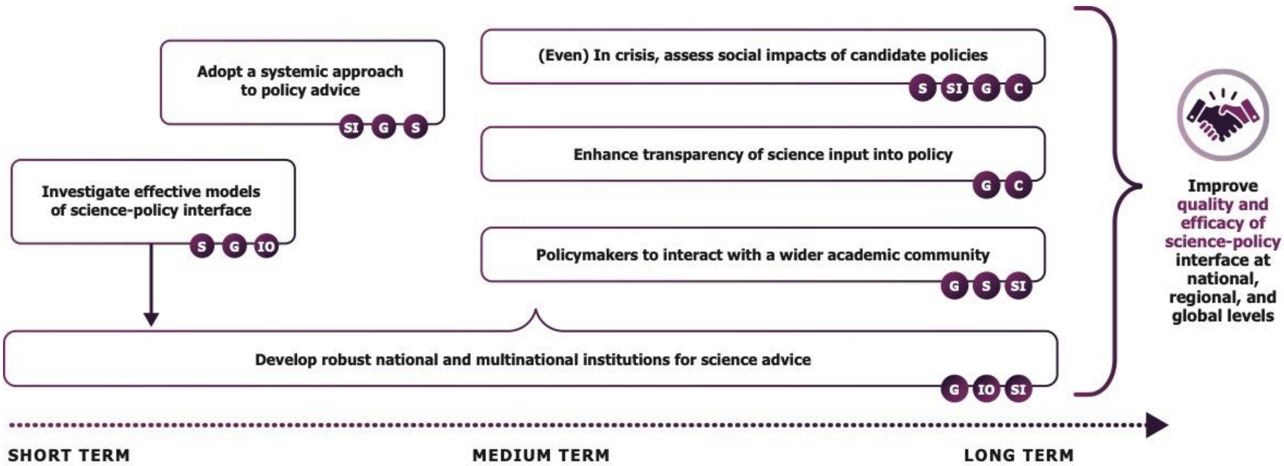

Figure 9. Recommendations (presented in boxes) supporting the transformative change on Improve quality and efficacy of science–policy interface at national, regional, and global levels. Arrows indicate a contribution of recommendation A to effecting recommendation B (only major links are depicted). Abbreviations in bold next to each recommendation indicate major actors responsible for the implementation of this recommendation (**B**=Business/private sector, **C**=Citizens, **F**=Funders, **G**=Governments, **IO**=International organizations, **SP**=Scientific publishers, **SJM**=Science journalists and media, **SI**=Scientific institutions (publicly funded), **S**=Scientists). The horizontal axis provides an indicative time line (short term=start and make progress soon, medium/long term=may start soon but will take time to realize).

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Chair: **Lidia Brito**, Director, UNESCO Regional Bureau for Sciences in Latin America and the Caribbean

- **Zakri Abdul Hamid**, Pro Chancellor, Multimedia University, Malaysia
- **Kathie Bailey**, Director, Board on International Scientific Organizations (BISO), National Academies of Sciences, Engineering, and Medicine (NASEM), USA
- **Anne Bardsley**, Deputy Director – Koi Tū: The Centre for Informed Futures; Advisor – International Network for Government Science Advice (INGSA), The University of Auckland, New Zealand
- **Geoffrey Boulton**, Regius Professor of Geology Emeritus, University of Edinburgh, UK
- **Carlos Henrique de Brito Cruz**, Professor at the Gleb Wataghin Physics Institute at the State University of Campinas (UNICAMP), Brazil
- **Craig Calhoun**, Professor of Social Sciences, Arizona State University, USA
- **Anne Cambon-Thomsen**, Co-chair of the Research Data Alliance (RDA) COVID-19 Working Group, France
- **Dante Cid**, Vice-President of Academic Relations - Latin America, Elsevier
- **Alessandra Colecchia**, Head, Science and Technology Policy Division, Organisation for Economic Co-operation and Development (OECD)
- **Olga Contreras**, Deputy Director of Innovation, Technology Transfer and Entrepreneurship, National Secretariat for Science and Technology, Guatemala
- **Andreas Diensthuber**, Founder and Managing Director, Solgenium OG, Austria
- **Eran Feitelson**, Head of Advanced School for Environmental Studies, The Hebrew University of Jerusalem, Israel
- **Mark Ferguson**, Chief Scientific Adviser to the Government of Ireland and Director General, Science Foundation Ireland (SFI), Ireland
- **Alexandra Freeman**, Executive Director, Winton Centre for Risk & Evidence Communication, University of Cambridge, UK
- **Jim Hall**, Director of Research in the School of Geography and the Environment, University of Oxford, UK
- **Tarja Halonen**, 11th President of Finland; Member, Council of Women World Leaders
- **Mohamed Hassan**, President, The World Academy of Sciences (TWAS), Italy
- **Barbara Kalumenos**, Director of Public Affairs, International Association for Scientific, Technical and Medical Publishers (STM), UK
- **Hiroshi Kuniyoshi**, Deputy to the Director General, United Nations Industrial Development Organization (UNIDO)
- **Martin Lees**, Chair, OECD-IIASA Task Force on Systems Thinking, Anticipation, and Resilience, France
- **Amy Luers**, Global Director, Sustainability in the Digital Age, Future Earth
- **Antonella Mei-Pochtler**, Special Advisor to the Federal Chancellor of Austria; Head, Think Austria – Strategy Unit of the Federal Chancellor, Austria
- **Johann Mouton**, Director, Centre for Research on Evaluation, Science and Technology, Stellenbosch University, South Africa
- **Shantanu Mukherjee**, Chief, Policy and Analysis Branch of the Division for Sustainable Development, United Nations Department of Economic and Social Affairs (UN DESA)
- **Helga Nowotny**, Professor of Social Studies of Science Emeritus, ETH Zurich, Switzerland
- **Connie Nshemereirwe**, Immediate Past Co-Chair, Global Young Academy, Uganda

- **Ana Persic**, Chief of Section a.i., Science Policy and Partnerships, United Nations Educational, Scientific and Cultural Organization (UNESCO)
- **Ingrid Petersson**, Director General, Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), Sweden
- **Dorsamy (Gansen) Pillay**, Deputy Chief Executive Officer, Research and Innovation Support and Advancement (RISA), National Research Foundation (NRF), South Africa
- **Montira Pongsiri**, Associate on Health, Stockholm Environment Institute Asia Centre in Bangkok, Thailand
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- **Thomas Reuter**, Board and Executive member, World Academy of Arts and Science (WAAS), and Professorial Fellow, Asia Institute of the University of Melbourne, Australia
- **Andrew Revkin**, Founding Director, Initiative on Communication & Sustainability, The Earth Institute, Columbia University, USA
- **Vladimir Ryabinin**, Assistant Director General, United Nations Educational, Scientific and Cultural Organization (UNESCO)
- **Magdalena Skipper**, Editor in Chief, Nature, UK
- **Mandi Smallhorne**, Vice President of the World Federation of Science Journalists (WFSJ), South Africa
- **Carthage Smith**, Head of Global Science Forum, Organisation for Economic Co-operation and Development (OECD)
- **Pradeep Srivastava**, Executive Director, Technology Information, Forecasting and Assessment Council (TIFAC), India
- **Geza Toth**, Global Lead, Carbon and Forest Program, Barry Callebaut Sourcing AG, Switzerland
- **Maria Uhle**, Program Director for International Activities, National Science Foundation (NSF), USA
- **Veerle Vandeweerd**, Founder and Executive Director, Platform for Transformative Technologies; Founder and former policy director of the Global Sustainable Technologies and Innovation Conference Series, USA
- **Murray de Villiers**, Senior Manager, EMEA Academic Program, SAS, South Africa
- **Timo Vuori**, Secretary General, Chief Executive of the International Chamber of Commerce of Finland, Finland
- **Peter Weingart**, Professor Emeritus in Sociology of Science, University of Bielefeld, Germany
- **James Wilsdon**, Director, Research on Research Institute (RoRI), University of Sheffield, UK
- **Doug Wilson**, Director, Government Office for Science COVID-19 Response, United Kingdom
- **Xin Xu**, ESRC Postdoctoral Research Fellow at the Centre for Global Higher Education, Department of Education, UK

IIASA–ISC Strengthening Science Systems Team leadership

- **David Kaplan**, Senior Research Specialist, ISC
  Team Co-Leader
- **Elena Rovenskaya**, Program Director, Advanced Systems Analysis Program, and Acting Program Director, Evolution and Ecology Program, IIASA
  Team Co-Leader
- **Sergey Sizov**, Science Diplomacy Officer, IIASA
  Team Alternate Leader

IIASA–ISC Consultative Science Platform leadership and Team members

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ABOUT THE IIASA-ISC CONSULTATIVE SCIENCE PLATFORM:

Transformations within reach: Pathways to a sustainable and resilient world

Starting in May 2020, a partnership between the International Institute for Applied Systems Analysis (IIASA) and the International Science Council (ISC) has drawn on the combined strengths and expertise of the two organizations to define and design sustainability pathways that will enable building-back a more sustainable post COVID-19 world. The platform has engaged a unique set of transdisciplinary global thought leaders on four themes:

- Governance for sustainability
- Strengthening science systems
- Resilient food systems
- Sustainable energy

The series of publications, Transformations within reach: Pathways to a sustainable and resilient world, presents the results and recommendations of the platform on the design of sustainable pathways and policy choices during the COVID-19 recovery period.

The platform is informed and supported by an advisory board under the patronage of the former Secretary-General of the United Nations H.E. Ban Ki-moon.

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IIASA is an independent, international research institute with National Member Organizations in Africa, the Americas, Asia, and Europe. Through its research programs and initiatives, the Institute conducts policy-oriented research into issues that are too large or complex to be solved by a single country or academic discipline. This includes pressing concerns that affect the future of all of humanity, such as climate change, energy security, population aging, and sustainable development. The results of IIASA research and the expertise of its researchers are made available to policymakers in countries around the world to help them produce effective, science-based policies that will enable them to face challenges such as these.

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International Science Council

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The vision of the ISC is to advance science as a global public good. Scientific knowledge, data and expertise must be universally accessible and their benefits universally shared. The practice of science must be inclusive and equitable, as should opportunities for scientific education and capacity development. ISC is a non-governmental organization with a unique global membership that brings together 40 international scientific Unions and Associations and over 140 national and regional scientific organizations including Academies and Research Councils.

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