



# Navigating the winds of change: strategic foresight and the power of weak signals

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## Abstract

In an era of increased complexity, interdependence, uncertainty and rapidly advancing technology, the ability to identify and swiftly adapt to current and future trends is key to progressing sustainability. Intersecting drivers and stressors are converging to destabilize socioecological systems and reshape national, regional and global outlooks. The intersecting and converging crises of the 21st century have exposed the limits of planning that relies too heavily on linear extrapolations from well-known global/mega-trends. This study explores whether a limited number of emerging trends that only manifest as weak signals today serve as central conduits (super-nodes) for amplifying and accelerating systemic disruption. Using an exploratory mixed-methods design, a global Delphi survey ( $N=790$ , 132 countries) generated 1200 horizon-scan items, inductively coded into 29 clusters. Scenario stress-testing distilled the findings into 280 candidate weak signals—ranked by likelihood, impact, and timing—from which 20 were shortlisted and mapped onto a  $20 \times 20$  influence matrix through structured expert debate. Weighted degree centralities and a 10,000-run bootstrap test identified statistically significant hubs. Results suggest that anticipatory governance can be strengthened by prioritizing high-centrality signals and institutionalizing ongoing weak-signal scanning alongside transparent, multi-source decision-making to avoid cascading risks across planetary-health, economic, and technological systems. At the midpoint of a decade dominated by disruption—climate change, pandemic, geopolitical upheaval, widening inequality, war, misinformation and the rapid rise of Artificial Intelligence—we posit that strategic foresight and informed anticipation is a critical imperative in the pursuit of a global common good and a resilient future.

**Keywords** Weak signals · Anticipatory governance · Systemic resilience · Disruption · Foresight

## Introduction

As the third decade of the twenty-first century unfolds, the world is confronting not a single crisis but a tangled web of interlocking ones—a *polycrisis*. Climate-related disasters, zoonotic pandemics, geopolitical instability, and the rapid commercialisation of artificial intelligence are converging in ways that amplify, rather than merely add to, their individual impacts (UNEP 2024). This compounding uncertainty often outpaces conventional planning approaches,

which remain focused on observable trends and assumed continuities (Cuhls et al. 2024; Mohammadi 2023).

Such approaches tend to privilege entrenched trajectories or global megatrends, increasing the risk that decision-makers are blindsided by the unexpected. Strategic foresight, by contrast, expands the lens to include potential discontinuities—especially those signalled by so-called *weak signals* of change. These are early indicators or symptoms of emerging developments that, while not yet widely recognized or empirically substantiated, may carry high

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disruptive potential. Their implications—positive or negative—can significantly impact both human and socio-ecological resilience.

Weak signals are often embedded in fragmented information and are typically overlooked in mainstream analyses, meaning they are rarely recognized as priorities. However, they deserve closer attention precisely because of their capacity to evolve into significant disruptions. Analysing weak signals helps policymakers ask, “*what if?*”—probing how emerging threats could reconfigure current strategies, programmes, or systems. Anticipating their escalation, while also considering broader trends and megatrends, can illuminate unexpected dynamics and enhance preparedness in complex, uncertain environments (Sakellariou and Vecchiato 2022).

Most strategic planning still relies on what Börjeson et al. (2006) term “continuity scenarios”—linear projections from dominant trends. These often miss subtle shifts that precede major systemic changes. Ansoff (1975) introduced the term *weak signals* to draw attention to such early warnings. Hiltunen (2008) refines the concept of weak signals by emphasizing their novelty, ambiguity, and interpretive distance, while Linstone and Turoff (2011) underscore the role of iterative expert dialogue in their identification.

Despite this conceptual richness, empirical research on weak signals remains limited. It is often siloed within single sectors—such as technology or public health—failing to account for the cross-domain interactions central to complex systems thinking (Helbing 2013). Signals are also commonly treated in isolation, although their true significance often lies in how they combine, reinforce, or neutralize one another (Battiston et al. 2016a, b).

Integrating weak signals into strategic foresight frameworks alongside trends and megatrends helps reveal hidden dynamics and supports more proactive responses. Insights from complexity science reinforce this view. Socio-technical and ecological systems are often organized as “small-world” networks, where a minority of highly connected nodes—or hubs—exert disproportionate influence (Albert and Barabási 2002; Watts 2002; Newman 2018). Disruptions at these hubs can cascade through the system, triggering widespread change—a dynamic evident in areas from epidemiology (Vespignani 2010) to infrastructure resilience (Buldyrev et al. 2010). Targeting these leverage points is crucial for anticipatory governance (Meadows 1999; Centola 2015).

Related insights also emerge from research on critical transitions. These studies show how gradual pressures accumulate until a small, seemingly minor event tips the system into a new regime (Scheffer et al. 2012; Lenton 2013). Such events often begin as weak signals—subtle anomalies that gain systemic importance due to their location in the

interaction web (Dakos et al. 2015). Biggs et al. (2009) liken them to “keystone species” in ecology: their removal or amplification can reshape the entire system.

Foresight methods are beginning to reflect this relational understanding through tools like cross-impact analysis and scenario mapping (Pereira et al. 2021; Saritas et al. 2022; Jabbour et al. 2025). However, weak signals are still typically treated as discrete data points. Notable exceptions—such as Börjeson et al.’s exploratory scenarios and Rohrbeck and Kum’s (2018) work on corporate foresight—demonstrate the value of mapping inter-signal linkages. Yet even these approaches stop short of explicitly identifying high-centrality “super-nodes” that may influence and condition broader systemic behaviour.

This paper posits that the weak-signal landscape is structured rather than uniform or flat: while most signals remain peripheral, a small but influential subset functions as cross-domain hubs. Identifying and characterizing these super-nodes is essential for decision-makers aiming to allocate limited attention and resources effectively in volatile and unpredictable contexts.

The analysis and reflections presented in this paper build on recent work by the United Nations Environment Programme (UNEP) and the International Science Council (ISC), which emphasise the strategic value of weak signal detection for sustainable development (UNEP 2024; ISC 2024; Jabbour et al. 2025). Identifying and interpreting these signals enables decision-makers to anticipate challenges and opportunities more effectively—informing inclusive strategies capable of navigating complex, interconnected futures.

## Materials and methods

A key objective of the broader UNEP-ISC foresight exercise was the identification and analysis of emerging issues—weak signals of change—that could significantly impact planetary health and human wellbeing should they escalate. This involved a combination of foresight tools, including Delphi surveys, sensemaking workshops, scenario-building, horizon-scanning, and expert panel deliberations, including diverse perspectives from around the world and across a diverse cross-section of society. This process allowed for understanding of how emerging change is perceived differently in various regional contexts, recognizing the importance of diverse worldviews, levels of economic development, and sociocultural traditions.

This study employed an exploratory-sequential mixed-methods design, wherein qualitative exploration preceded and informed subsequent quantitative analysis. As noted by Creswell and Clark (2018), this approach is particularly appropriate for research areas involving emergent and

loosely defined constructs. The research unfolded in four consecutive phases that together spanned eighteen months (Fig. 1).

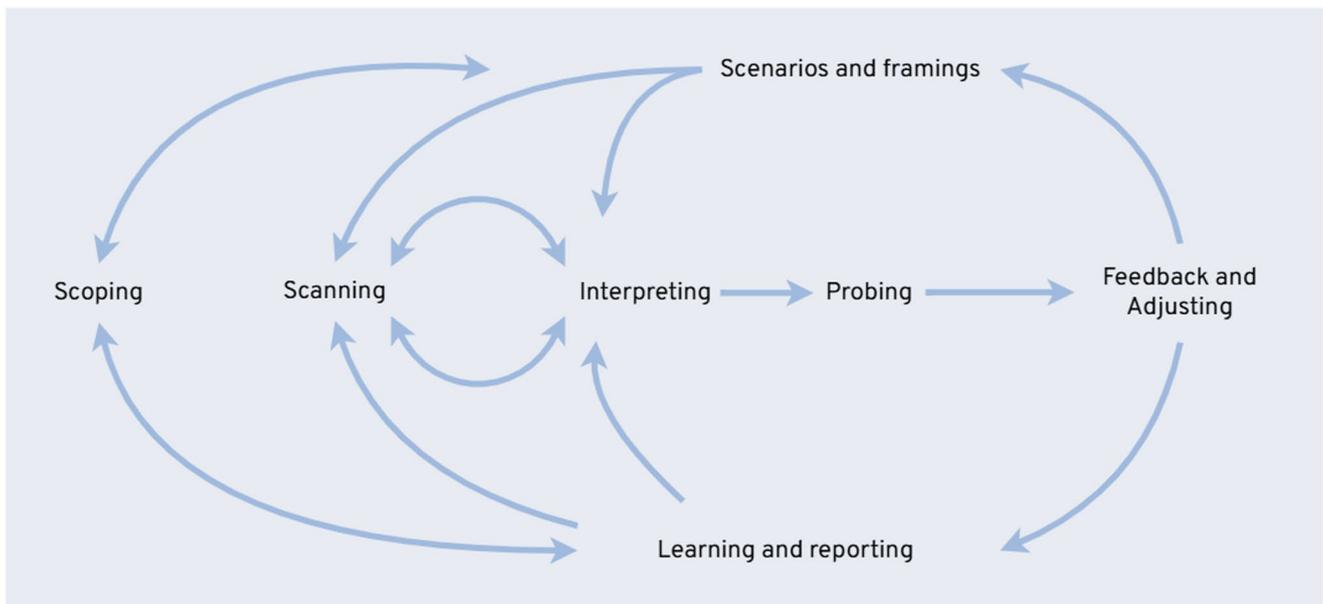
The first phase consisted of a global horizon scan anchored in a two-round Delphi process. A semi-curated mailing list comprising scientists, civil-society actors, foresight practitioners and policy professionals yielded 6000 invitations. To counteract sectoral bias and ensure cognitive diversity, invitations were stratified by age cohort and across all six geographic regions, aligned with the UNEP regional groupings: Africa, Asia and the Pacific, Europe, Latin America and the Caribbean, North America, and West Asia. A total of 790 respondents—representing 132 countries and balanced by gender—participated in the first round between May and July 2023.

Each participant could submit up to three early signs of change, accompanied by evidence and a short justification. Open text fields rather than predefined categories were deliberately used to minimise anchoring bias, a precaution motivated by Janis's (1982) work on groupthink. A total of 1200 unique raw entries were collected.

In the second phase three independent analyst teams subjected the raw entries to grounded-theory coding using ATLAS.ti. Coding proceeded through two calibration rounds and reached an inter-coder reliability of  $\kappa=0.82$ . Constant-comparative techniques generated twenty-nine second-order clusters. To assess cluster robustness, the research team developed four contrasting 2050 scenarios using the morphological method of Miles et al. (2016). Two facilitated workshops with 42 thematic experts evaluated cluster performance across these scenarios, revealing potential blind spots and hidden dependencies.

The third phase consisted of a second Delphi round designed to quantify each of the 280 candidate weak signals that had emerged from the qualitative work. Five hundred twelve of the original 790 respondents completed the questionnaire. Likelihood was rated on a seven-point probability scale, potential impact was scored on a three-point ordinal scale ranging from local-minor to global-catastrophic and perceived time horizon was captured in categorical form. A median absolute deviation threshold of one point on the seven-point scale served as the convergence criterion. Weak signals that ranked in the upper quartile on impact and at least the upper half on likelihood, or that were flagged as strategic wild cards by at least five respondents, were short-listed. A synthesis meeting of an interdisciplinary Expert Panel established by UNEP and ISC then applied a decision rule seeking domain balance and geographic relevance. The result was a final set of twenty weak signals that form the empirical core of the present article.

The fourth and final phase translated qualitative insight into a quantitative interaction network. In September 2024, 24 panel members convened in a hybrid format to complete a structured influence-mapping exercise. For every ordered pair of weak signals, participants assigned a value on a seven-point scale ranging from minus three, indicating that the first signal strongly restricts the second, to plus three, indicating strong promotion. After an initial scoring round, controlled feedback and facilitated discussion supported convergence in a manner analogous to the Delphi logic described by Linstone and Turoff (2011). The completed twenty-by-twenty matrix was then subjected to a second-order propagation calculation: the original matrix was squared and added to itself, with normalisation to the maximum attainable score



**Fig. 1** Conceptual model of an iterative foresight horizon scanning process. (Adapted from Bengston 2019)

following Sandström et al. (2020). Outgoing and incoming weighted degree centralities were extracted as indicators of, respectively, systemic influence and systemic dependence.

Identifying and minimizing the risk of group, representative, and individual bias in the survey responses was a critical focus of the foresight and horizon scanning exercise. Efforts to mitigate bias were systematically integrated throughout the process. Central to this was the role of a highly diverse expert panel—selected to ensure broad geographic, disciplinary, and epistemic representation—which helped foster cognitive plurality and reduce the risk of anchoring to established paradigms. Through iterative, structured expert debate and facilitated sensemaking sessions, the panel critically reviewed outputs from the second survey, working to surface blind spots, challenge prevailing narratives, and identify, document, and address potential biases—including their own. These structured debates also provided an important check on the design and framing of the survey tool itself, with the panel engaged in its review both before and after beta testing. Additional measures included anonymizing

first-round Delphi responses to reduce conformity pressure, while explicit prompts for novelty in weak signal identification countered availability bias. Grounded-theory coding enabled the emergence of new categories, ensuring data interpretation was not confined by existing assumptions. Furthermore, scenario stress-testing workshops engaged 42 thematic specialists from different domains in facilitated, interactive sessions to critically examine weak signal clusters within contrasting future scenarios.

While fully eliminating bias is not possible, these steps aimed to make the process more transparent, balanced, and open to weak signals and plausible but unconventional futures. Table 1, adapted from Bonaccorsi et al. (2020), summarizes the identified risks, their implications, and the mitigation strategies applied throughout the process. Additional methodological details, including a stepwise mapping of key decisions, are provided in a companion article (Jabour et al. 2025).

## Results

This collective intelligence building process identified eight critical shifts defining the world today and in the coming decades, as well as 20 weak signals of change (distilled and prioritized from  $N=280$ ) considered to be of high monitoring priority due to their potential impact (both positive and negative) on planetary health and human wellbeing. The 20 weak signals clustered into five groups, described below.

### Human health

Five signals represent processes with potentially grave human health implications, in large part due to the inability to treat such phenomena with currently available medicine. Recognizing their importance, and the high potential for their effects to be distributed through the population inequitably (e.g. Ahmed et al. 2024), can significantly enhance our ability to address health challenges pre-emptively.

To begin, rapid global warming has precipitated unprecedented warming in the Arctic (Rantanen et al. 2022), raising the spectre of the release of ancient microorganisms (Signal 1), including novel fungi, bacteria and viruses previously entrapped in permafrost (Wu et al. 2020; Alempic et al. 2023) to which natural human and animal immunity may be limited (Chiappelli and Penhaskashi 2022). Global warming, combined with land use change, is catalysing new human-animal interactions, creating conditions for emergent zoonotic diseases (Signal 2) (Plowright et al. 2021; Rush et al. 2021; Esposito et al. 2023; Plowright et al. 2024), for which current healthcare structures and institutions are unprepared. Recent zoonotic diseases - such as SARS,

**Table 1** Identifying and minimizing the risk of bias

Issue (potential bias)	Implications	Mitigation of bias
Longer timeframes	Greater uncertainty on both the impact and the likelihood of the risk/opportunity	Delphi design: Explicit emphasis on shorter timeframe
Over-focus on trends analysis - <i>availability heuristic</i>	Over influence by current/recent trends and events. Can lead to missing out on unforeseen innovation	Delphi design: Explicit emphasis on novelty, trend discontinuities combined with explorative scenario planning
Over reliance on previous assessments trends or Anchoring bias	Weaker signals may be under-rated or ignored. Tendency to rely too heavily on a single piece of information, which is often the first obtained)	Mapping megatrends and prevailing risks. Use of advocates both for and against a specific issue; multiple rounds of scoring in different orders during sensemaking
Mis-rating of risk, disruptions	Over representing of standard knowledge, understandable risks, under-rating of complex and difficult to understand risks	Baseline megatrends will identify prevailing risks; sensemaking and regional foresight validation will review clusters and ‘outliers’
Hysteria and fads/group think; salience bias	Over representing prominent or emotionally impactful issues, especially when particularly vocal or skilled raconteurs are advocating.	Clustering/ constant comparative analysis parameters, rules on advocating positions vigilantly, enforced during sensemaking
Knowledge asymmetries/ overrepresentation of signals	Over representing of standard knowledge, understandable risks, weaker signals go undetected/ under-rated	Regional foresight workshops. Careful curation of experts, inputs/ sensemaking experts invited to challenge rankings

influenza A/H1N1 and COVID-19 - have already illustrated the substantial losses of life and economic disruption that such emergent diseases can cause (Debnath et al. 2021).

The prolific deployment of antibiotics represents a third health-related weak signal, in the form of a global rise in the prevalence and growth rates of antimicrobial resistance (Signal 3) (Murray et al. 2022; Tang et al. 2023; Cella et al. 2023; UN 2023; Ahmed et al. 2024), leaving populations vulnerable to diseases that might otherwise have been managed with antibiotics. The World Health Organization has named antimicrobial resistance as one of the top ten global health threats faced today (WHO 2021), perhaps indicating the need for more proactive surveillance.

Unforeseen impacts of chemicals and materials in the environment (Signal 4) is our fourth health signal. Over 350,000 known chemicals are currently in use around the globe (Clarke 2024). Many make their way into the environment (Wang et al. 2020; Muir et al. 2023). Yet only a fraction of chemicals in the environment have been thoroughly tested for human health impacts, and the potential interaction among chemicals is even less well understood (Narwal et al. 2024; Escher et al. 2020).

Finally, the recent rapid escalation in *eco-anxiety* (Signal 14) in response to growing awareness of, and direct experience with, acute climate and environmental disruption is a serious health concern, particularly among youth (Hickman et al. 2021, 2024), with implications for mental health and wellbeing (Wu et al. 2020; Haseley and Lament 2024), reproductive concerns (van den Broek 2024; Mosca et al. 2025) and by extension civic and community engagement and productivity.

Recognizing and addressing weak health signals is vital. In many regions, however, especially the global south, health data quality remains a significant challenge (WHO 2020). Poor data quality weakens our ability to monitor health signals, making it difficult to detect emerging health threats accurately (WHO 2020), complicated further by the proliferation of unverified health information on social media (Aiello et al. 2020; McGough et al. 2017; Jawhari et al. 2016). Improving data quality, expanding data sources, reducing noise, ensuring timely reporting, resolving technical issues, considering demographic and cultural diversity, and adapting to evolving health trends can facilitate improved monitoring of these signals. This proactive approach would enhance the capacity to detect and respond to emerging health threats, ultimately safeguarding public health on a global scale.

## Economic implications

Four of the 20 signals (see Supplemental Materials) are processes that have economic implications foremost. The first

such signal, *uninsurable future* (Signal 12), originates from the increasing severity and frequency of extreme events destroying assets and livelihoods and undermining the ability of governments and communities to cope. In many regions of the world, agricultural insurance, particularly for smallholder farmers in developing countries (Mensah et al. 2023), and private homeowner insurance in, for example, certain regions in the states of Florida and California, have become unavailable or prohibitively unaffordable in areas that are more prone to climate-related flooding, wildfires and coastal hazards (Farmer 2023; Taylor and Knuth 2024). Major insurance carriers have started using advanced computer modeling and AI to assess risks in fire-prone areas, prompting several to cease issuing new policies or to non-renew existing policies for homeowners and renters in places like Altadena and Pacific Palisades as witnessed in the weeks following the destructive wildfires in Los Angeles in 2025 (Auer 2024; Ruiz 2025). Increasing uninsured risk and losses create additional burdens on the public sector, including limited access to disaster relief and recovery capital, and significant ripple effects through financial systems.

*Surging fossil fuel subsidies* (Signal 15), hitting a record US\$7 trillion in 2023 (Black et al. 2023), are directing global capital flows and investment decisions away from clean-energy technologies. This weak signal critically undermines the adoption and cost-competitiveness of clean-energy, which could trigger a massive regression in climate mitigation policies and backlash against the just energy transition, further entrenching inequalities (Cooke et al. 2016; Couharde and Mouhoud 2020; Coady et al. 2015).

While individual governments struggle to address global challenges, growing concern over wealth concentration and the prevailing structure of large-scale philanthropy has intensified, as their ability to undermine the basic principles of democracy and civil society increases (Signal 19). If left unchecked, this trend risks undermining democratic governance and aspirations of justice and transparency—whilst over-riding valid criticisms of the undue influence of a small number of privileged actors in setting agendas, defining problems, and designing interventions within institutions of global governance (Glucksberg and Russell-Prywata 2020; Callahan 2017; Lambin and Surender 2023).

These concerns stand out in environmental governance, where billions of dollars are being injected into international climate action and standard-setting initiatives (e.g. the carbon offsetting industry). In 2023, for example, 45 per cent of the budget for the Science Based Targets Initiative (SBTI)—the world's primary authority for climate certification responsible for standards and independent verification of corporate decarbonising—came from just two philanthropic foundations (Robiou du Pont et al. 2024; Bryan et

al 2024), raising major concerns about conflicts of interest when funding is closely tied to corporate interests.

In contrast, an encouraging signal is the growing global support for development of *new tools for rerouting global financial flows* (Signal 17) in ways that can help mitigate inequalities, eradicate extreme poverty and address environmental crises (Africa Climate Summit and its Nairobi Declaration in 2023; African Union Summit in 2024; Summit for a New Global Financing Pact and the Bridgetown Initiative; UN Common Agenda 2023). The recent environmental, social and governance (ESG) reporting initiatives (UN Principles for Responsible Banking; EU Corporate Sustainability Reporting Directive; Global Reporting Initiative) which provide tools for businesses to track and report their social and environmental impacts (Tsang et al. 2023; Chopra et al. 2024) could be amplified to better compare performance, hold firms to account and redirect financial flows. Innovations in rerouting global financial flows can facilitate access to insurance and alleviate the adverse direct and indirect impacts on the welfare of vulnerable groups when reforming the fossil fuel subsidy system (Cooke et al. 2016). Governments can also support the development of supportive regulations, tax incentives, and risk-sharing frameworks, including effective collaborations between insurers and the public sector (Feofilovs et al. 2024).

## Governance

As the primary platform for collective decision-making, fundamental shifts and disruptions in the nature and focus of governance have tremendous implications for planetary health and societal wellbeing. Five weak signals identified describe emerging processes that either have implications for, or are the consequence of, prevailing governance regimes, some of which have emanated from civil society. The first signal, with the potential for fast-tracking systemic change by challenging old ideas (Trencher et al. 2022; Davidson 2019; Trippel and Benner 2025), is described by the *emergence of exnovation* (Signal 6) across civil society: initiatives that seek to dismantle inefficient, unsustainable and otherwise harmful elements of modern societies (Hölscher and Frantzeskaki 2020; Schlaile et al. 2024). Decisionmakers have historically resisted the pursuit of exnovation to avoid threatening incumbent interests. However, increasing exnovation momentum in civil society (Pel et al. 2022), combined with growing evidence of the limited capacities of existing institutional regimes to address complex problems may weaken that resistance and strengthen the political viability of transition strategies through so-called “creative destruction” (Trencher et al. 2022).

Another promising weak signal with potentially positive disruptive impact is *local, network-driven resilience*

(Signal 18): growing assertions of collective agency at the local level in pursuit of sustainability goals (Steward 2018; Olmedo et al. 2023; Adger et al. 2018). Often exhibiting greater degrees of agility and creativity, and with the benefit of local knowledge and citizen buy-in (Datta 2018, 2024), cities and local communities have begun to outpace progress at the national and international scales in pursuit of sustainability. The third signal in this group, also originating in civil society but enabled by existing regulatory regimes, is *privatized micro-environmentalism* (Signal 11). This refers to the enclosure of and restriction in access to dwindling stable landscapes and ecosystem services for the wealthy (Bollig et al. 2023; Preston 2024). The rise of privatized micro-environmentalism exacerbates environmental injustices, and concentrates investments in sustainability in ways that serve a small, wealthy elite.

The fourth governance weak signal entails *decision-making increasingly detached from scientific evidence* (Signal 13), or more broadly, the lack of action and requisite policy response to vastly accumulating evidence on issues such as climate change and biodiversity loss – where the gap between rhetoric and reality continues to widen (UNEP 2024). This unresponsiveness is enabled in part by flourishing mis- and dis-information and political conflict fomented by certain vested interests (WEF 2024). Policy decisions made to combat systemic risks induced by urgent problems such as climate change and its impacts also tend to be made without due consideration of the complexity of those problems (Umit and Schaffer 2020; Scoones and Stirling 2020), generating unintended effects, including social and political resistance, that compromise policy effectiveness.

*Escalating risks of corruption in carbon offsetting* (Signal 16) represents the fifth weak signal with governance implications, describing the capitalization of opportunities for exploitation and corruption in certain climate mitigation efforts pursued by governments and corporations, including carbon offset markets (Battocletti et al. 2023; Espenan 2023; Gill-Wiehl et al. 2024; Ross 2024). These practices undermine both the effectiveness (or mitigative benefits) of climate policies and public and business support for them (Pande 2024).

## Technological developments

Four of the weak signals can be categorized as rapid changes in technological developments, many with unforeseen consequences, particularly if deployed at scale. These signals, ranging from autonomous weaponization to the rapid increase in orbital space debris, highlight the urgent need for comprehensive governance and regulatory frameworks to mitigate their possible negative impacts (Martin and Freeland 2021).

The increased availability and accessibility of robotic and AI applications for military purposes (Signal 8) pose significant risks. The deployment of AI-enabled autonomous systems in warfare could be exploited by criminal or other entities, leading to unintended and potentially catastrophic consequences (Crootof 2015). The risk of these technologies falling into the hands of rogue states or non-state actors exacerbates the threat, raising concerns about global security and stability (UN 2023). In parallel, the growing availability of synthetic biology applications (Signal 9) provides potent tools that could be used for bioterrorism (Carlson 2010). The dual-use nature of these technologies underscores the need for stringent oversight and international cooperation to prevent their misuse.

The rapid advancement of AI-enabled technologies and their impact on human agency (Signal 20) present profound ethical and societal challenges. Developments in artificial neural networks capable of simulating, and sometimes surpassing, human thought (Bojic et al. 2023) have accelerated the potential for emergence of superintelligent systems (OpenAI 2024). While these technologies hold immense potential, their unchecked development could lead to the erosion of human autonomy, especially if controlled by a select few or governed by opaque algorithms beyond human understanding (Guterres 2024). Establishing robust regulatory frameworks will be essential to ensure that AI technologies augment rather than undermine human capabilities and societal values.

The rapid deployment of emerging climate-altering technologies, such as solar radiation modification (Signal 7), also introduces high levels of uncertainty and risk. These technologies aim to limit global warming by modifying the amount of solar radiation that reaches the planet, rather than reducing GHG emissions. However, their potential effectiveness (i.e. climate benefits) and implementation remain poorly understood, while posing significant environmental, biophysical, social and geopolitical risks, necessitating a cautious and a multi-faceted approach to expand the knowledge base and prioritize research, robust policy and scientific debate on future governance considerations. The final signal in this cluster, the substantial increase in recent satellite deployment and commercial spacecraft (Signal 5), has already resulted in a significant rise in orbital space debris, posing potentially severe risks to the stratosphere, the potential for disruption of satellite communications, emissions and other environmental issues (Shareefdeen and Al-Najjar, 2024) with impacts at the troposphere to the ionosphere. The potential for collisions and the resultant debris could disrupt space operations and have far-reaching implications for satellite-based services and space exploration.

## Biophysical dynamics

The final signal, *uninhabited places* (Signal 10), denotes *biophysical dynamics* (e.g., to weather, land and water systems) precipitated primarily by climate change-induced extreme conditions that render some landscapes uninhabitable, compelling migration and loss of livelihoods and lives. Already a concern for low-lying island nations (Duvat et al. 2021; Mycoo et al. 2022) and many major cities (Cissé et al. 2022), the increased frequency, intensity and extent of climate impacts will expand the materialization of uninhabited places around the globe. As many as three billion people living in places likely to be rendered uninhabitable over the next 50 years could be affected (Xu et al. 2020).

## Examining interactions between weak signals

These weak signals do not exist in isolation. The escalation of one signal can enhance or restrict the development of another signal. For example, surging fossil fuel subsidies (Signal 15) can negatively affect investment flows to the development of solar radiation modification technologies (Signal 7). Of course, there are also examples where there is little or no influence between signals. For strategic foresight to enable improved decision-making, weak signals require identification and monitoring. Importantly, monitoring processes should adopt a systems-based perspective: monitoring each signal in isolation will not enhance our ability to anticipate and adapt to emerging trends. Emerging trends are almost always the result of several weak signals working in concert (Saritas 2022).

Using a combination of an expert judgement framework and systems analysis techniques, the Expert Panel established by UNEP and ISC analysed the interactions between the 20 weak signals and the system properties that emerged. A network of interactions (see Fig. 3) was built by studying pairwise interactions between all possible combinations among the 20 signals. Panel members were tasked with answering the following question: *What happens with other weak signals if a certain weak signal is amplified?* A quantitative scale from +3 ('strongly promoting') to -3 ('strongly restricting') with 0 indicating 'no influence' was used in the assessment. For example, the influence from Signal 18 on Signal 12 was scored as -2, meaning: 'If 'local, network-driven resilience' is amplified, this will moderately restrict the amplification of 'uninsurable future' (Fig. 3).

Notably, the grouping of weak signals in Fig. 2 is thematic, while the grouping shown in Fig. 3 is based on interactions between the weak signals. This illustrates the non-trivial dynamics of the web of weak signals interactions, which

means that an emerging trend (and critical shift) is built up by amplification of weak signals of different categories. Hence, a siloed approach to monitor weak signals will not be fit for purpose.

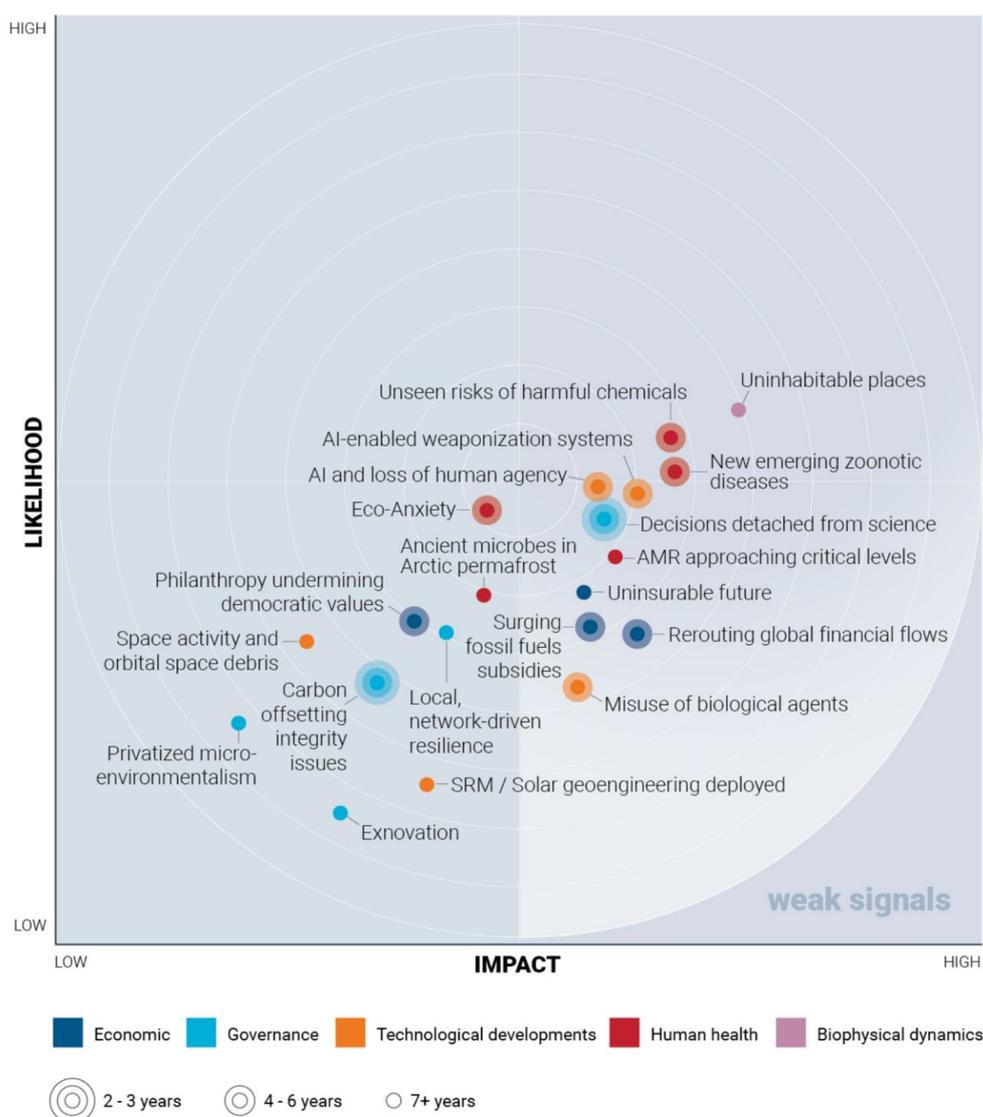
In addition to these direct links between signals, the analysis included second-order interactions to better capture systemic effects. In other words, signal *X*'s influence on signal *Y* includes the direct influence as scored by the experts, plus all interactions with all other signals. For example, a signal that promotes another signal which, in turn, promotes other signals can have a significant systemic impact, while those interactions in turn affect the original signal. In the analysis, the team was primarily tasked with identifying three groups of weak signals: (i) signals with the largest potential to promote the amplification or development of other signals, hence tending toward emerging trends (critical shifts); and signals which are (ii) most and (iii) least dependent on

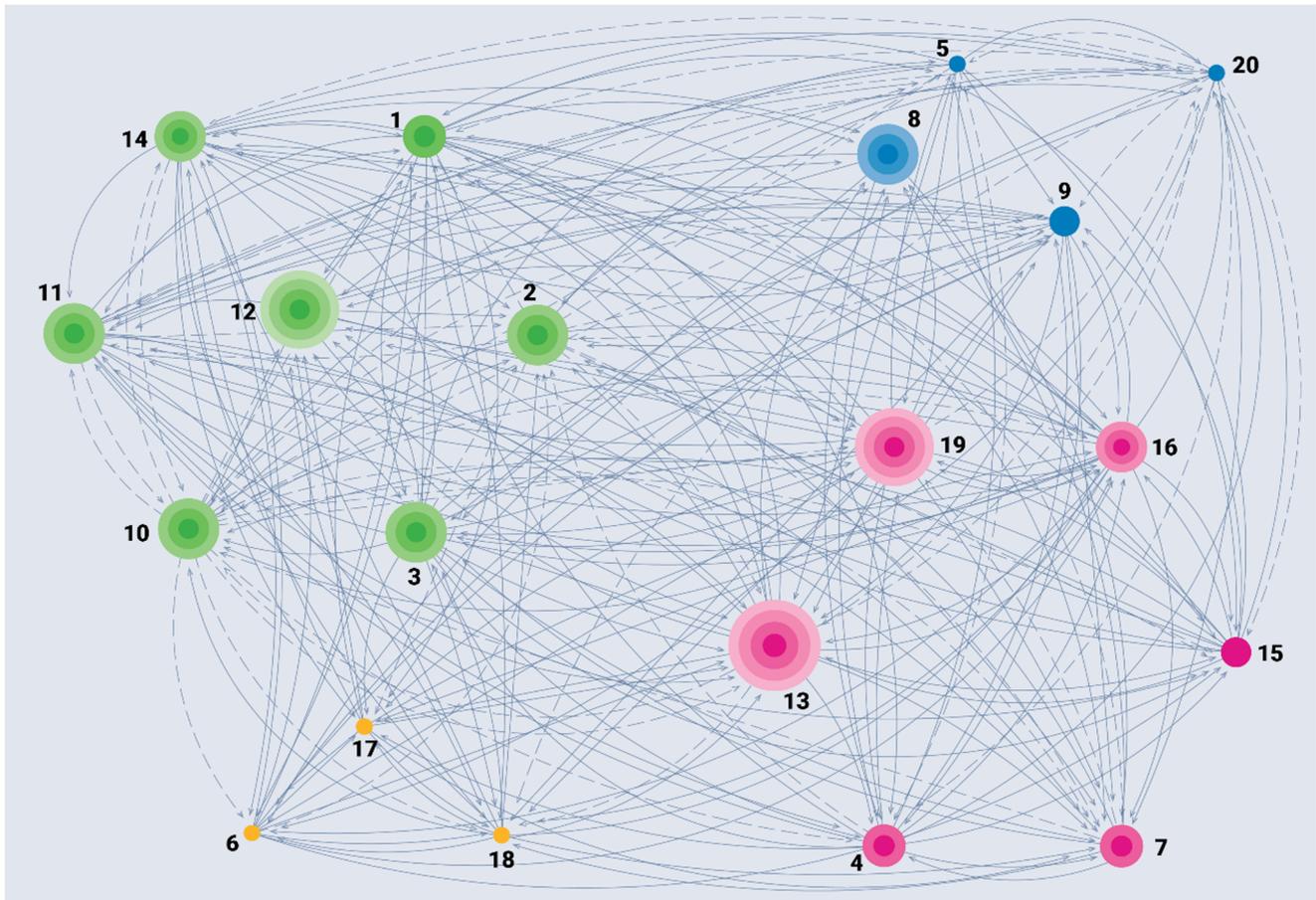
the development of other signals. Table 2 summarises the results.

Signal 13, *decisions increasingly detached from scientific evidence*, emerged as the most influential signal, strongly promoting eight other signals, including for example *surging fossil fuels subsidies* and *escalating risks of corruption in carbon offsetting*. Several of these eight signals in turn strongly promote other signals. The second most influential weak signal is *philanthropy undermining democratic values*. This signal also strongly promotes eight other signals, but it also strongly restricts three signals: *emerging mindset of continuous learning and exnovation* (6); *new tools for rerouting global financial flows* (17) and *local, network-driven resilience* (18) (Table 3).

The signal that is most influenced by other signals is number 14, *eco-anxiety*. This signal is strongly promoted by ten other signals, and only one signal, *emerging mindset of continuous learning and exnovation* (6) has a weakly

**Fig. 2** Twenty weak signals of change and potential disruptions depicted along three dimensions: likelihood, impact and time horizon. The average results for each dimension, generated from Delphi survey respondents, are displayed as follows: On the x-axis is intensity of impact (how much impact the signal of change could have) and on the y-axis is likelihood (how likely the signal of change is to occur). Respondents assessed likelihood on a 7-point scale ranging from exceptionally unlikely to virtually certain to occur and assessed impact on a 3-point scale ranging from low to high. The potential time horizon (when the signal of change and associated disruption could fully materialize) is represented by the shape/size of the icons and is divided into time segments of 2–3 years (circle), 4–6 years (hexagon) and 7+ years (triangle). The colors indicate which domain area the signal belongs to





### Interactions

———— Promoting    - - - - Restricting

#### Cluster 1

1. Ancient microbes in Arctic permafrost
2. New emerging zoonotic diseases
3. AMR approaching critical levels
10. Uninhabitable places
11. Privatized micro-environmentalism
12. Uninsurable future
14. Eco-Anxiety

#### Cluster 2

6. Exnovation
17. Rerouting global financial flows
18. Local, network-driven resilience

#### Cluster 3

5. Space activity and orbital space debris
8. AI-enabled weaponization systems
9. Misuse of biological agents
20. AI and loss of human agency

#### Cluster 4

4. Unseen risks of harmful chemicals
7. SRM / Solar geoengineering deployed
13. Decisions detached from science
15. Surging fossil fuels subsidies
16. Carbon offsetting integrity issues
19. Philanthropy undermining democratic values

**Fig. 3** Illustration of the interlinkages and the signals' systemic impact. Cluster mapping of 20 signals where the size of each signal of change is proportional to its systemic impact. Systemic impact here means

restricting influence on signal 14. We note that the second most influential signal, *philanthropy undermining democratic values* (19), is also the second most influenced signal. This indicates a central role for this signal in the whole network of interactions.

accounting for each signal's positive and negative influence on all other signals, by considering their direct and second-order impact. The interlinkages are context specific

### Discussion and conclusion

This study identified twenty weak signals spanning economic, governance, technological, health, and socio-ecological domains, each with the potential to shape planetary health and human wellbeing. Cross-signal analysis revealed

**Table 2** Results from systemic analysis of interactions between the 20 identified weak signals

Signals that influence other signals the most	Signals that are most influenced by other signals	Signals least influenced by other signals
Decisions increasingly detached from scientific evidence (13)	Eco-anxiety (14)	Exnovation (6)
Philanthropy undermining democratic values (19)	Philanthropy undermining democratic values (19)	Rerouting global financial flows (17)
Uninsurable future (12)	Uninhabitable spaces (10)	Surging fossil fuels subsidies (15)
New emerging zoonotic diseases (2)	Uninsurable future (12)	Deployment of Solar Radiation Modification (7)
Uninhabitable spaces (10)	AI-enabled technologies and human agency (20)	Local, network-driven resilience (18)

that these signals do not operate in isolation; instead, they interact in ways that can amplify their individual and collective effects. Notably, a small subset of signals demonstrated disproportionately high influence within the broader network, indicating the presence of certain “super-node” signals function as systemic accelerants of change.

The identification of these super-nodes carries strategic relevance for decision-making and anticipatory governance. Signals such as the *detachment of decision-making from scientific evidence* and the growing influence of *large-scale private philanthropy* emerged as especially impactful. These trends raise concerns about weakening democratic legitimacy and reducing institutional capacity to respond to risks such as climate change, biosecurity, and emerging disruptive technologies. However, they also point to actionable leverage points: enhancing transparency around private influence, diversifying advisory systems, and reinforcing open science may help mitigate negative system-wide effects.

Awareness of weak signals and their interactions can improve our ability to anticipate and respond to compounding disruptions. As we navigate a period of heightened global volatility—with disproportionate risks for already vulnerable populations—integrating weak-signal analysis into foresight and planning frameworks can enhance systemic resilience. While international governance processes understandably focus on large, well-established trends (e.g. 1.5 °C overshoot, biodiversity loss), our analysis indicates that failing to attend to the disruptive potential of weak signals—particularly as they interact with dominant trends—risks blindsiding policymakers. Weak-signal analysis emerges not merely as a diagnostic tool, but as a strategic instrument that identifies potential leverage points for

anticipatory governance. Several practical implications flow from this perspective.

First, public institutions, including UN agencies and national governments, should institutionalize continuous weak-signal monitoring, ideally through real-time digital platforms that combine expert judgment with data analytics (e.g. patent filings, media reports, online discourse). Second, cross-agency learning platforms should be developed to translate network-based foresight insights into coordinated policies. Third, integrating futures thinking and fostering a culture of organizational foresight can enhance cognitive flexibility, enabling more effective responses to emerging risks before they escalate.

Nonetheless, the study has limitations. Although the expert panel was diverse, representation from low-income countries—often most affected by global shocks—was limited. Additionally, the influence matrix captures a static snapshot, while real-world systems and dynamics are shaped by feedback loops. Expert elicitation, despite bias-reduction efforts, remains subject to the limitations of subjective judgment.

Future research should address these gaps by introducing longitudinal analyses to track how signal influence evolves over time. Machine learning applied to open-source intelligence may offer scalable, near-real-time tools to support weak-signal detection. In parallel, agent-based models could simulate policy impacts under alternative futures, offering decision-makers an empirical basis for anticipatory action. In sum, weak-signal analysis offers more than early warning; it provides a strategic lens to identify leverage points and guide proactive interventions in an increasingly complex and interconnected world.

As global crises become more frequent and interdependent, strategic foresight provides a robust, evidence-based approach to long-term planning. It enables policymakers to anticipate discontinuities, ask “what if” questions, and uncover both risks and opportunities that may be obscured by conventional trend-based thinking. The UN Summit of the Future (September 2024) underscored the importance of foresight, adaptability, and inclusive governance in building a sustainable and equitable future.

Building on UNEP’s foresight work, this analysis shows how futures thinking can reveal weak signals with disruptive potential—both positive and negative—and uncover overlooked risks. By reframing how threats are identified, it helps align preparedness with emerging challenges. However, fully leveraging weak-signal analysis demands a shift in mindset. The Western scientific method often dismisses outliers and sub-threshold anomalies as noise, sidelining early warnings that could pre-empt systemic disruption. This ingrained caution limits our capacity to anticipate the unexpected.

**Table 3** List of the weak signals of change– description and potential disruption; – perception impact score from the Delphi survey results

Signal	Description	Novelty	Probability	Impact scale	Disruptive potential	Time horizon
<i>Economic</i>						
12. Uninsurable future	Growing strains on nation-state revenues due to demands for disaster relief, most prevalently for the agriculture sector, municipal infrastructure sectors, and the real estate sector	High	Highly likely	Local	Catastrophic	Acute
15. Surging fossil fuels subsidies	Rapid increases in fossil fuel subsidies since 2020 expected to persist, posing a barrier to decarbonization goals	Low	Highly likely	Global	Major	Slow onset
17. New tools for rerouting global financial flows	Growing demands for fundamental reforms to the global financial system including restructuring of the climate financing architecture amidst rising income inequality and extreme concentrations of poverty worldwide	Medium	Highly likely	Global	Major	Slow onset
19. philanthropy undermining democratic values	Growing tensions between sources and destinations of private wealth have exposed potentially grave threats of philanthropy in areas that could undermine democratic values and set back aspirations of justice, equality, freedom, voice and transparency. Without countervailing forces, the unrestricted use or conversion of private assets (vast accumulations of wealth) for public influence, may eclipse the popular will and allow individuals to assert private power and political influence without accountability	High	Highly likely	Global	Major	Slow onset
<i>Governance</i>						
6. Emerging mindset of continuous learning and ‘exnovation’	Previously receiving strong resistance, there is now growing support for initiatives targeting the dismantling of structures associated with unsustainability, such as fossil fuel reliance	High	Highly likely	Global	Major	Slow onset
11. Privatized micro-environmentalism	Creation of private-access, enclosed habitats that offer stable ecosystem services to highly paying members, limiting equal access to nature-based quality of life and bypassing shared responsibility for conservation	High	Highly likely	Local	Catastrophic	Slow onset
13. Decisions increasingly detached from scientific evidence	Lack of sufficient environmental diplomacy and science that attends to potential unintended effects of policies including negative social and environmental impacts	High	Highly likely	Global	Major	Slow onset
16. Escalating risks of corruption in carbon offsetting	Nature-based solutions promoted as carbon offset interventions can undermine global mitigation efforts and exacerbate existing social inequities if they fail to deliver verifiable mitigation gains and accommodate the complex social and ecological contexts in which they are implemented	Medium	Highly likely	All scales	Major	Slow onset
18. Local, network-driven resilience	Growth in local-level engagement in resilience planning, contributing to governance capacity building in communities, which may improve sustainability decision-making	High	Highly likely	Local	Major	Slow onset
<i>Technology</i>						
5. Rapid expansion of space activity and orbital space debris	The rapid and substantial increase in satellite deployment, and in commercial spacecraft generating space debris, and the return of infrastructure to earth at the end of its life may have unintended consequences for the stratosphere and other environmental issues	High	Highly likely	Global	Major to catastrophic	Slow onset
7. Deployment of solar radiation modification	Rapid deployment of emerging climate-altering technologies intended to limit warming temperatures by modifying the amount of solar radiation that reaches the planet, associated with high levels of uncertainty and risk	High	Highly likely	Global	Catastrophic	Acute
8. Autonomous and artificial intelligence weapons systems	Increased availability and accessibility of robotic and AI applications for military purposes, which could be deployed for malicious purposes	Low	Highly likely	Global	Major	Acute
9. New technologies amplify risks of biological agents misuse	The growing availability of synthetic biology applications provides potent tools to potential bioterrorists and rogue states	Low	Possible	Global	Catastrophic	Acute

**Table 3** (continued)

Signal	Description	Novelty	Probability	Impact scale	Disruptive potential	Time horizon
20. AI-enabled technologies and human agency	While AI-enabled autonomous systems hold immense potential for environmental problem-solving, their environmental impact hinges on responsible development and implementation. AI can optimize resource use and drive sustainability efforts, but concerns about bias, data security, and over-dependence on technology necessitate careful consideration. Ensuring human oversight, robust safeguards, and responsible data management are crucial for ensuring AI serves as a tool for environmental betterment, not a source of new challenges. By prioritizing environmental sustainability in AI development, we can harness its power to create a cleaner, more secure future	High	Highly likely	Global	Catastrophic	Acute
<i>Health</i>						
1. Ancient microbes hidden in thawing permafrost	The thawing of vast permafrost areas may result in the release of previously dormant ancient microorganisms and viruses, posing a threat to both humans and non-humans	Medium	Possible	Global	Catastrophic	Slow onset
2. New emerging zoonotic diseases	Deforestation, urbanisation, wildlife trafficking, and unsustainable agricultural practices lead to heightened interactions between humans, animals, and their pathogens, precipitating the emergence of zoonotic diseases	Low	Highly likely	All Levels	Catastrophic	Slow onset
3. Antimicrobial resistance rising to dangerous levels worldwide	Increased antimicrobial use and misuse, in combination with other microbial stressors like pollution, are fostering antimicrobial resistance, raising the potential for untreatable disease epidemics	Low	Highly likely	Global	Catastrophic	Slow onset
4. Unforeseen impacts of chemicals and materials	The implications of exposure for ecosystems and human health to thousands of chemicals and materials in the environment and their interactions are unknown	Low	Highly likely	Global	Major to catastrophic	Slow onset
14. Eco-anxiety: An emerging crisis hidden in plain sight	Rising uncertainties and threats at the global scale have negatively affected the mental health of many people, translating into compromised coping capacity and losses in labour productivity	Medium	Highly likely	Global	Major to catastrophic	Slow onset
<i>Biophysical</i>						
10. Uninhabitable places	Environmental changes, declining socio-ecological systems, extreme weather events, conflicts and socio-economic vulnerabilities are affecting the habitability of some areas of the globe. Habitability encompasses human safety, resilient livelihoods, and household and community resilience to risks	High	Highly likely	Global	Catastrophic	Slow onset

A systematic, evidence-based foresight approach that embraces uncertainty and cross-scale dynamics can better equip decision-makers to anticipate—and potentially avoid—cascading shocks to socio-ecological systems. In doing so, it allows us not just to brace against the winds of change, but to navigate by them.

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