MultiSector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems

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Abstract

The field of MultiSector Dynamics (MSD) explores the dynamics and co-evolutionary pathways of human and Earth systems with a focus on critical goods, services, and amenities delivered to people through interdependent sectors. This commentary lays out core definitions and concepts, identifies MSD science questions in the context of the current state of knowledge, and describes ongoing activities to expand capacities for open science, leverage revolutions in data and computing, and grow and diversify the MSD workforce. Central to our vision is the ambition of advancing the next generation of complex adaptive human-Earth systems science to better address interconnected risks, increase resilience, and improve sustainability. This will require convergent research and the integration of ideas and methods from multiple disciplines. Understanding the tradeoffs, synergies, and complexities that exist in coupled human-Earth systems is particularly important in the context of energy transitions and increased future shocks.

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Abstract

The field of MultiSector Dynamics (MSD) explores the dynamics and co-evolutionary pathways of human and Earth systems with a focus on critical goods, services, and amenities delivered to people through interdependent sectors. This commentary lays out core definitions and concepts, identifies MSD science questions in the context of the current state of knowledge, and describes ongoing activities to expand capacities for open science, leverage revolutions in data and computing, and grow and diversify the MSD workforce. Central to our vision is the ambition of advancing the next generation of complex adaptive human-Earth systems science to better address interconnected risks, increase resilience, and improve sustainability. This will require convergent research and the integration of ideas and methods from multiple disciplines. Understanding the tradeoffs, synergies, and complexities that exist in coupled human-Earth systems is particularly important in the context of energy transitions and increased future shocks.

1 Introduction: Transitions & Transformations in a World of Interconnected Risks

The broader global community is navigating evolving climate risks, rapid energy transitions, and the growing recognition that sustainable future pathways will require fundamental transformations in our collective management of socio-environmental systems (de Vos et al., 2021; Elsawah et al., 2020; Levi et al., 2019; Levin et al., 2021; Markolf et al., 2018; Mora et al., 2018; Pecl et al., 2017; Trutnevyte et al., 2019). As we navigate the opportunities and challenges emerging from these issues, there is a need to reflect on our approach to human-Earth systems science itself. Improving our understanding of how interdependent global-to-local challenges are shaping critical pathways of societal change is a scientific grand challenge (Aven & Zio, 2021; Clarke et al., 2018; Dearing et al., 2014; Helbing, 2013; Moss et al., 2016; Raymond et al., 2020; Scanlon et al., 2017). Keeping pace with the accelerating complexity of pathways of change requires a deep integration of diverse perspectives and technical capabilities (Braunreiter et al., 2021; Filatova et al., 2016; Iwanaga et al., 2021; Moallemi & de Haan, 2019; Oikonomou et al., 2021; Trutnevyte et al., 2019). This commentary draws on active community engagement over the last several years through workshops, conference sessions, and thematic scientific working groups. We put forth a vision for how new modes of inquiry may yield valuable tools and insights for transforming our understanding of the benefits, risks, and resilience of complex adaptive human-Earth systems. Given the inherent complexity of human-Earth systems, the plurality of their candidate pathways of change, and their diverse sources of uncertainty, there is a need to rethink our traditional disciplinary approaches to human-Earth systems science as well as the ways scientific knowledge is produced (Bojórquez-Tapia et al., 2020; Funtowicz & Ravetz, 1993; Lubchenco, 1998; Council, 2014; Nowotny et al., 2013; Saltelli et al., 2020; Szostak, 2017; Wyborn et al., 2019).

Understanding emerging risks and achieving resilient futures requires a careful accounting of increasingly complex, interconnected, and interdependent societal systems (e.g., infrastructure, governance, and socio-economic) and their feedbacks with Earth and environmental systems (Helbing, 2013; Lempert, 2021; Magnan et al., 2021). Understanding energy transitions and climate challenges requires holistic analyses that account for the complex mix of human and natural systems they shape and are, in turn, shaped by (Levi et al., 2019). Extreme events, both naturally occurring and those exacerbated by anthropogenic factors, such as heat waves, droughts, floods, wildfires or storms, are compounding each other and increasing the potential for long-lived cascading societal effects (Mora et al., 2018; Raymond et al., 2020). Consequently, we must carefully reconsider our tacit decompositions and assumptions in the way change itself is studied. Numerous studies have shown that climate risks and energy transitions are co-evolving and are strongly interdependent (e.g., see the studies reviewed in Fisher-Vanden and Weyant (2020); Trutnevyte et al. (2019); Peng et al. (2021); Monier et al. (2018)). Societal change pathways encompass global supply chains; strained natural resources; infrastructure degradation and investment; growing and migrating population with evolving vulnerabilities; intensifying natural hazards; technological innovation; changing human values and preferences and their associated consumption patterns (e.g., dietary preferences). Human decision-making and actions have important feedback effects that can alter global to local environmental changes and their consequences (e.g., see Dolan et al. (2021); Hallegatte and Engle (2019); Levin et al. (2021); Schweikert and Deinert (2021)). There is a need for science innovations that can aid in exposing, navigating and prioritizing risk-benefit tradeoffs across possible multisectoral decisions.

Capturing and navigating the risk-benefit tradeoffs of multisectoral actions warrants a thoughtful reevaluation of the basic tenets of risk assessment itself (Field et al., 2012; Reisinger et al., 2020; Shukla et al., 2019; Society for Risk Analysis, 2018). Complex human-Earth systems' relationships give rise to systemic failures, extreme events, and 'hyper-risks' (Helbing, 2013) that emerge across interconnected multisectoral infrastructures. These dynamic relationships between agents, systems, and sectors transmit risk from one to another, leading to new risks or amplifying (or buffering) existing threats (Rinaldi et al., 2001; Vespignani, 2010; Zscheischler et al., 2018). Figure 1a illustrates a promising framework from Simpson et al. (2021) for the assessment of complex risks that expands on the traditional definition of risk as emerging from the interaction of hazard, vulnerability, and exposure, by explicitly recognizing that human responses to hazards are also a key determinant of risk. Importantly, Simpson et al. (2021) also distinguish that risk can emerge through interactions among multiple drivers present across the different determinants of risk. In the MSD context, this framework can enable the qualitative tracing and quantitative assessment of risk as it emerges from driver interactions.

Figures 1b-c illustrate the conceptual mapping of risk as proposed by Simpson et al. (2021) using the specific example of Winter Storm Uri and its risk to electricity supply and to basic electricity dependent services (heat, food, and water) during the February 2021 Texas power outage. As a hazard, Winter Storm Uri has precedence. The temperature extremes and energy demands during the event were less severe or equivalent to winter storms in 1951, 1983, and 1989 (Doss-Gollin et al., 2021). But the cold snap in 2021 caused rolling blackouts in Texas and highlighted systemic vulnerabilities in how the hazard manifested as a risk to utilities and people. In Figures 1b-c, we distinguish between the risk to the supply of electricity (borne by the electric utilities), and the risk to having basic energy dependent services for heating and access to water and food (borne by Texans). This distinction between two kinds of risk resulting from the same events highlights two important considerations. First, depending on the specific measure of risk used and the actors that bear it, the drivers identified as most critical may differ and, perhaps more crucially, the actions available to respond to the presence of a risk may be more or less relevant. Second, human responses are not only dominant drivers of potential outcomes, but also of how risks can interact with each other to buffer or amplify impacts across actors, systems, and sectors. In this particular example, the actions of electric utilities before and during the storm affected their ability to supply electricity to people (e.g., poor system weatherization and inadequate resource criteria) and, in turn, the actions of people (e.g., poor home insulation, buying alternative fuels) shaped demand stress on electricity supply. The complex interplay between diverse objectives and risks are clear (e.g., beyond those illustrated other objectives could include: reducing loss of life, reliability of services, equity of impacts, minimizing financial volatility, etc.). Figure 1 emphasizes the need for advances in our ability to model and understand interactions across multiple risks. This requires distinguishing if they are linearly aggregated (the accumulation of multiple independent risks), compounding (arising from the interaction of coincident or sequential hazards), or cascading (causal feedback relationships between multiple risks).

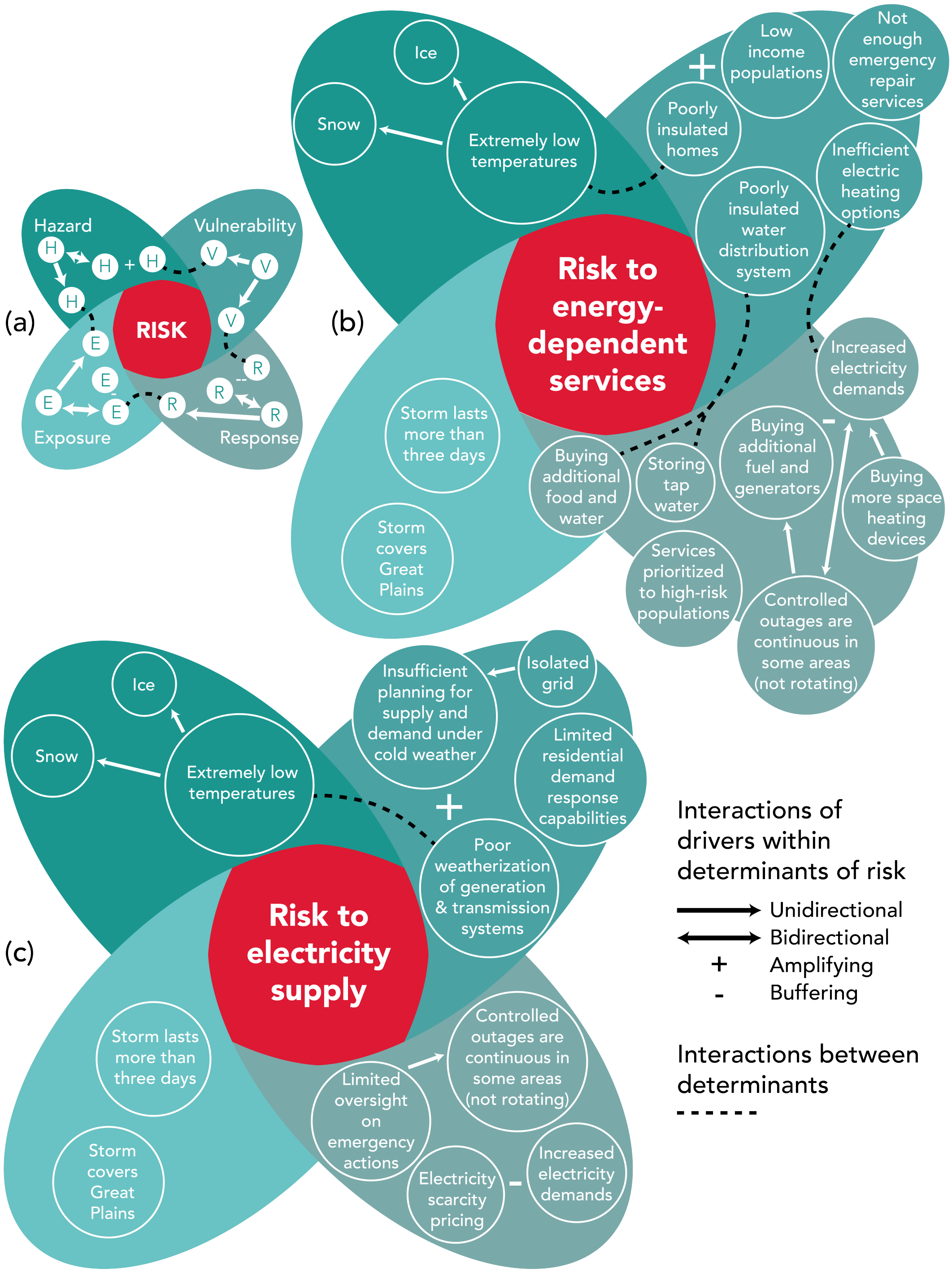

Figure 1. Risk as proposed by Simpson et al. (2021) is a dynamic and emergent outcome of its determinants (hazard, exposure, vulnerability, response) as well as their underlying drivers. (a) Generic example illustration of the different potential types of interactions across risk determinants and their drivers. (b) Winter Storm Uri illustration of the interactions that generated risk to the provision of basic energy dependent services (heat, water, and food). (c) Winter Storm Uri illustration of the interactions that generated risk to electricity supply.

Understanding systemic risk is inherently multisectoral and requires consideration of the interactions across human-Earth systems, as traditional single-sector risk analyses are prone to underestimate both overall risk but also multisectoral capacities to buffer it (Harrison et al., 2016; Lawrence et al., 2020; Raymond et al., 2020). Figure 2 demonstrates how the risks presented in Figures 1b-c relate to different types of systems (Earth and environmental, infrastructure, socio-economic, and governance). The risks arising during Winter Storm Uri are parts of a broader set of complex interactions between sectors and systems. For example, the risk to electricity supply was driven by processes and actions in Earth systems (climate change affecting local weather and producing more extreme low temperatures, see (Cohen et al., 2021)), governance systems (choices around the weatherization of generation and transmission systems), infrastructure (failures in generation and transmission systems), and socio-economic systems (people increasing their energy demands as a result of the lower temperatures). These interactions extend beyond the two risks illustrated and in fact beyond the reduced set of relevant processes shown here, which focus on the state of Texas and a select number of sectors as an illustrative example. Mapping and quantifying the extent and consequences of these complex interactions is a central challenge to MSD science.

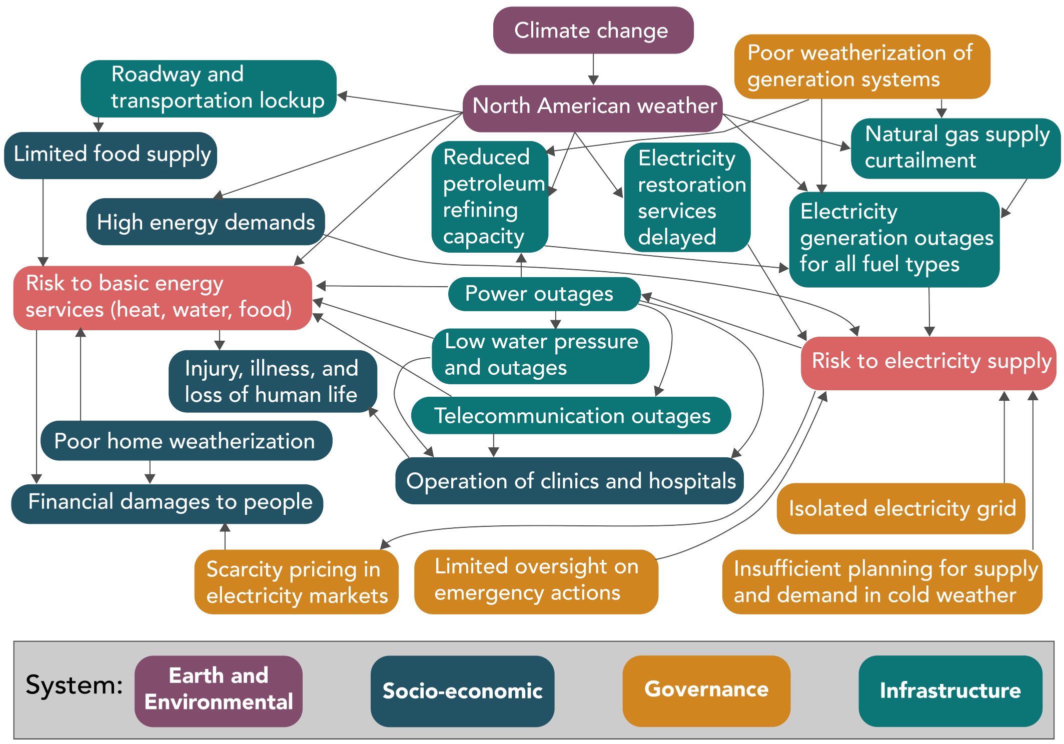

Figure 2. Complex interactions between systems relating to the risk to the provision of basic energy services (heat, water, and food) and the risk to electricity supply during the 2021 Winter Storm Uri. Process across Earth and environmental, socio-economic, governance, and infrastructure systems interacted to shape these risks and other outcomes during the 2021 cold snap.

Navigating these complex challenges requires fundamental advances to better understand the risks and the tradeoffs across multiple sectors. This will enable us to identify pathway opportunities for equitable and sustainable futures in the face of changing weather patterns and extremes, major technological advances, fluctuations in the supply and demand of natural resources and increased interactions between human-Earth systems. We need diverse perspectives to incorporate the full depth and breadth of multisectoral systems and uncover opportunities to address clean energy transitions, climate change risks, and sustainability. Embracing this challenge, our ambition and vision for MSD research are to work broadly and collaboratively across diverse research communities to make fundamental advances in complex adaptive human-Earth systems modeling, as well as in the analytical tools needed to accelerate our insights from it. The MSD CoP is focused on three scientific strategies for realizing the above research aspirations:

1. *Strengthening foundational research capabilities:* Through a commitment to and growing capacity for open science, we seek to accelerate our ability to explore diverse hypotheses by developing interoperable and reusable data, models, and analysis methods. Moreover, we want to grow and diversify the MSD workforce to broaden the backgrounds, technical skills, expertise, and experiences available to advance our understanding of societal risks.
2. *Advancing complex adaptive human-Earth systems science:* MSD seeks to better understand human-Earth systems by enhancing our ability to model major dynamic transitions, their dependencies and interactions across multiple scales, sectors, and systems. The field is focused on exploring a rich array of dynamic and adaptive behaviors, especially given the potentially compounding or cascading multisectoral effects of extreme weather and other stressors.
3. *Providing scientific and decision-relevant insights under deep uncertainty:* Through broadening the diversity and availability of human-Earth systems models, MSD seeks to enhance the insights and relevance of exploratory modeling studies for inferring consequential actions and outcomes for deeply uncertain societal transitions or transformations. The term deep uncertainty as used here refers to a lack of consensus for MSD problem framings including represented Earth system processes, candidate human actions, as well as the distributional likelihoods of key input factors (W. Walker et al., 2003).

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2 MultiSector Dynamics: Origin, Definitions, Questions, & Connections

A key originating event that helped shape the emergence of the MSD CoP is the 2016 US Department of Energy (DOE) sponsored and US Global Change Research Program (USGCRP) hosted workshop entitled "Understanding Dynamics and Resilience in Complex Interdependent Systems: Prospects for a Multi-Model Framework and Community of Practice" (USGCRP, (Moss et al., 2016)). From its origins, the MSD CoP has garnered broad participation and interest across many federal agencies as well as leading academic institutions, national laboratories, and other broader global research groups. The 2016 initiating workshop included representatives of ten federal agencies from various USGCRP interagency working groups and ten universities, labs, and research/consulting groups. The workshop set a foundation for the MSD CoP's emphasis on open science, advancing our understanding of complex adaptive human-Earth systems, and promoting translational science breakthroughs. The MSD CoP was formally established in 2019-2020 with DOE support to generate a vision for MSD as a global research area, clarify key questions, establish and assist scientific working groups, shape a strategy for community development, and foster synergies across interested research, government, and user communities.

A key charge for the MSD CoP is to provide a framework for formalizing the field's core terminology and higher-order science questions. Formally, we define MSD as:

Complex systems of systems that deliver services, amenities, and products to society. Examples of components of sectors include infrastructure, governing institutions (public and private), labor force capacity, markets, natural resources, ecosystem services, supply and distribution networks, finance, and a wide range of actors (e.g., firms, regulatory agencies, investors, consumers) involved in producing and creating demand for the services and products the sector provides.

Our definition of sectors focuses on the services and products that emerge from the interdependent dynamics of the underlying systems-of-systems that shape resources, demands, and impacts from global to local scales. Thus, the term "dynamics" in MSD refers to:

Pathways of change that result from geophysical, biophysical, economic, and socio-technical transitions and shocks. The emergent complexity of these pathways is shaped by their interdependence-interconnectedness, irreversible lock-ins, contested perspectives, cross-scale influences and effects, as well as the deep uncertainties that shape their evolution.

Interactions across Earth, environmental, infrastructure, governance, and socio-economic systems shape the emergent dynamics of change across sectors (Figure 3a). Figure 3a does not imply that all sectors or systems must be modelled in every MSD study, it does however emphasize that our decompositions, problem framings, and the boundaries of our numerical experiments should acknowledge the broader context of the interacting systems-of-systems and sectors that are not being represented. As illustrated in Figure 3a, infrastructure systems are related to the production and operation of services. They comprise inputs, outputs, technical characteristics of production systems, including core process operations and management, labor, and capital requirements. Earth and environmental systems capture processes and cycles in the Earth's atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Governance systems include the institutions, national and international agreements, procedures, and operations through which sectors are managed. Socio-economic systems include demographic processes, such as population growth and migration, markets, culture, norms, and value systems. Infrastructure, governance, and socio-economic systems are central to the behavioral dynamics that emerge from societal action across scales (from individual to collective). Such dynamics drive changes in consumption preferences, migration and demographic patterns, as well as value systems (e.g., growing preference toward decarbonization). These systems-of-systems and the complex influences they exert across scales are both central to our understanding of pathways of change and transformation for technologies, infrastructure, and institutions (Andersen et al., 2020; MacKinnon et al., 2019).

Connectedness, capital, and resilience are system properties that shape the dynamics of its evolution (Figure 3c). Connectedness reflects the strength and number of interactions between a system's elements, and by extension the degree of control that can be exerted on the system. As the system grows and accumulates more capital and resources, connectedness increases and the system becomes more organized and aggregated. In an air transportation network for instance, connectedness can reflect the degree to which airline flights connect different cities. The second system property, capital, can be thought of as system potential. It reflects the natural and human resources, monetary assets, or other capacities that accumulate as the system develops and grows, with the shock stage triggering a release of this capital. The last property, resilience, is often described as the capacity of a system to absorb a shock and adapt to maintain essentially the same function, structure, identity, and component interactions (B. Walker et al., 2004). Most importantly, these three properties of complex adaptive systems are not static and do not monotonically increase or decrease. As the system evolves and moves through its growth and disruption phases and through its interactions with other systems, connectedness, capital and resilience ebb and flow (Figure 3c).

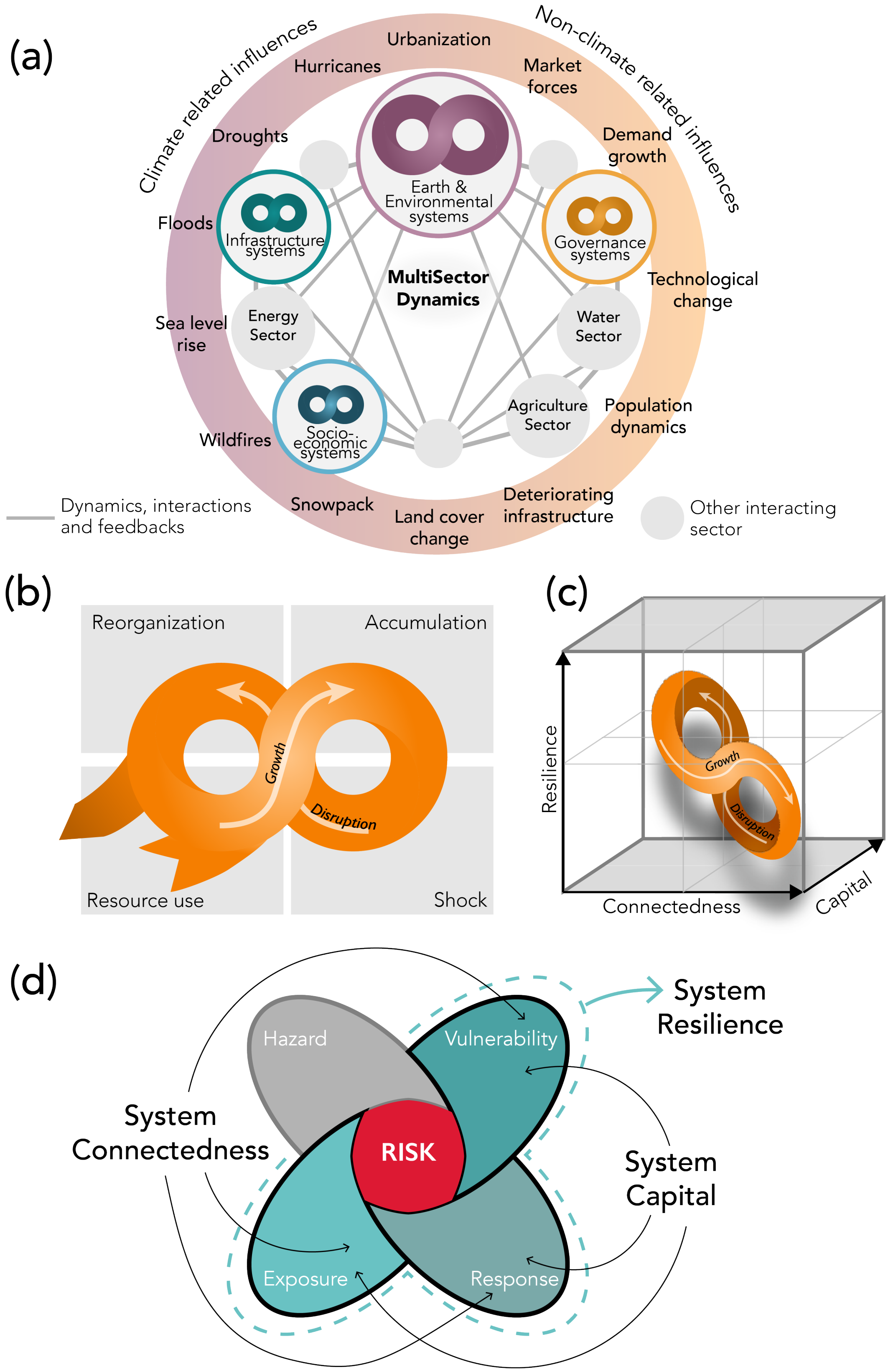

Figure 3. Key concepts for MultiSector Dynamics. (a) MultiSector Dynamics are shaped by co-evolving human and natural influences that emerge across interactions across sectors and systems. The Energy, Water and Agricultural sectors are shown as examples and other non-labeled sectors are shown in grey circles. (b) Adaptive cycles of growth and disruption of a complex system adapted from (Holling, 1985; Holling & Gunderson, 2002). (c) Illustration of the relationships between the adaptive cycle for a system and its key properties (resilience, connectedness, and capital). (d) Conceptual linkage between the risk and resilience for complex human-Earth systems.

Figure 3d shows how these properties relate to the four determinants of risk and their drivers, presented in Figure 1a. The degree of system interactions (reflected by the connectedness property) can shape resilience to hazards in both positive and negative ways: increased connectedness between drivers of vulnerability can result in cascading effects (e.g., critical services all relying on each other for their operation); increased connectedness in the response space may reflect more available options for flexible adaptation (e.g., readily dispatchable alternative sources of electricity or water). Similarly, the capital property may be a measure of more exposed assets (well looking at determinants of exposure), but it can also mean increased capacity to divert said assets to other management options. Resilience to hazards and stressors is therefore an emergent property of system interactions and other properties. It comes about in how hazard drivers are amplified or buffered by drivers of exposure, vulnerability and response. Lack of system resilience to a specific hazard or stressor can trigger hazards to other systems across scales and sectors (see Winter Storm Uri example Figure 1b-c). From a scientific and a modeling perspective, the implications of acknowledging that human-Earth systems are complex, adaptive, and have emergent dynamics changing their form and function poses a major challenge. There is a need to advance how our models 'endogenize' the interactive path dependencies of transitions/transformations, shocks, risks, and differences in resilience (see similar recommendations in Markolf et al. (2018)).

MSD as envisioned here needs to be a diverse transdisciplinary field. However, to ensure that MSD does not become the science of everything, a broad core set of research questions for the coming decade have emerged through community interactions over the last several years. Figures 4a and 4b summarize core MSD research questions focusing on broader societal and methodological challenges, respectively. As a transdisciplinary endeavor, the MSD research questions in Figure 4 emphasize the need to diversify model-based human-Earth systems problem framings across a broader array of perspectives, enabling detailed quantitative analyses of a broad suite of societal objectives (e.g., equity, reliability, resilience, vulnerability, robustness, economic efficiency, financial risk, stability, etc.). MSD has a distinguished central focus on developing the next generation of open-source models and analytical tools, and theoretical insights that enhance our ability to trace environmental, technological, and societal transitions/transformations.

Addressing the questions in Figure 4 from multiple sectoral perspectives requires care in capturing the dynamic co-evolutionary pathways of the underlying systems-of-systems governing them. Over the last century many scientific disciplines have been drawn to the formal framing of their research through the systems-of-systems perspective (Anderies et al., 2013; Gorod et al., 2008; Haimes, 2018; Holling & Gunderson, 2002; Iwanaga et al., 2021; Pescaroli & Alexander, 2018; Simpson et al., 2021), all of which emphasize the importance of capturing the hierarchy of systems' structures and their interdependent state dynamics. These traits are central to the challenges posed in trying to understand path dependencies, lock-ins, and the potential for emergent behaviors in natural, engineered, and socio-economic systems.

Figure 5 highlights synergies and connections between disciplines that complement and offer important contributions to MSD research. Each discipline represented in the figure explores aspects of complex adaptive human-Earth systems. Moving outward from the center of the graphic, dark orange text designates analytical challenges that are common across the disciplines. Amber text emphasizes interactions across human-natural systems, with disciplines each giving different weight and attention to individual components. Yellow text describes some of the research methods and focal points that are explored within sets of individual disciplines. Human systems contribute to changes in Earth systems that lead to many environmental and human impacts–impacts which are also shaped by decision feedbacks about how to abate and adapt to detrimental changes. MSD seeks to apply insights from many different research communities to innovate complex human-Earth system models, for example broadening the array of sectors/scales in-

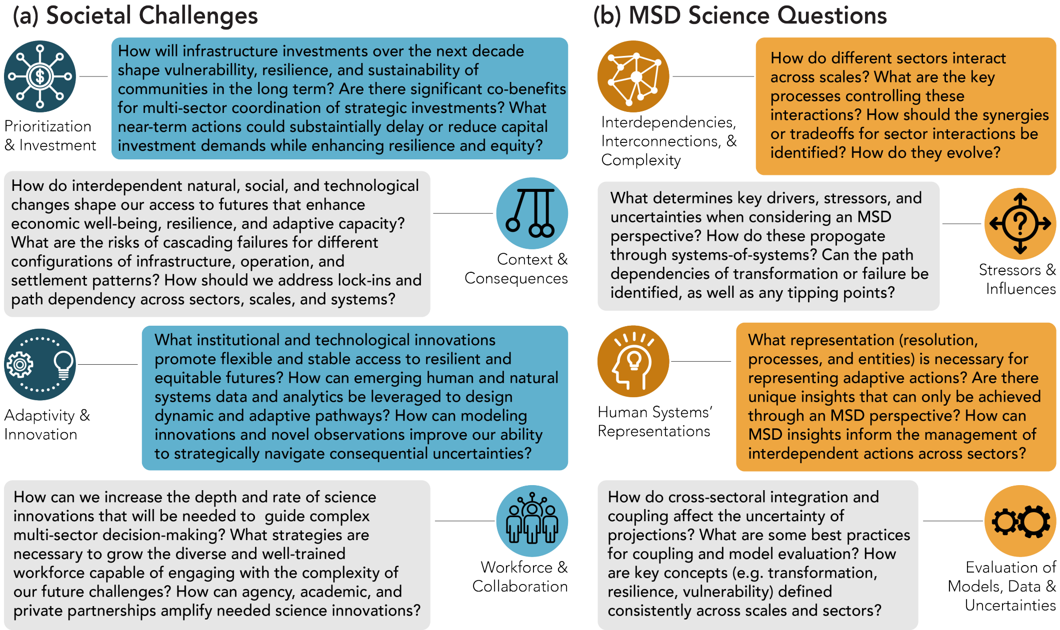

Figure 4. Societal challenges and MSD science questions

cluded, diversifying the representation of human systems and behaviors, and incorporating new ways to evaluate the implications of uncertainty. The integrative modeling capabilities of the disciplines shown in the left-hand side 'feathers' of Figure 5 were driven by the need to better integrate aspects of human-environment systems interactions, in order to inform abatement decisions related to global environmental issues, such as climate change, acid precipitation, and stratospheric ozone depletion. Innovations in economics, decision science, and socio-ecological-technical systems analysis are driven by a need to understand interdependencies between economic sectors, exploring why people make the decisions they do, and seeking generalizable perspectives on why only some communities succeed in managing complex, coupled social and ecological systems. Finally, the right-hand side disciplinary 'feathers' of Figure 5 represent important theoretically focused disciplines, exploring the properties and management of systems of systems and the implications of complex, nonlinear processes for individual and coupled systems. As noted in our definition of MSD itself above, Figure 5 emphasizes the core transdisciplinarity of influences and needs for our research vision to be realized. It should be noted that our summary of influential disciplines is not meant to be enumerative or exclusive, but to simply emphasize the breadth of perspectives needed to advance complex human-Earth systems science. We further elaborate the key research gaps and aspirations in the next section.

3 MSD Research Gaps & Aspirations

Figure 6 expands on the core research questions of Figure 4 to detail important MSD research gaps that need to be addressed to enable the field to engage with and better understand the dynamic and adaptive complexity of human-Earth systems. To address the research gaps summarized in Figure 6, the MSD CoP is focused on the following strategic investments (see Section 1.0): (1) strengthening foundational research capabilities, (2) advancing complex adaptive human-Earth systems science, and (3) providing scientific and decision-relevant insights under deep uncertainty. We provide a more detailed

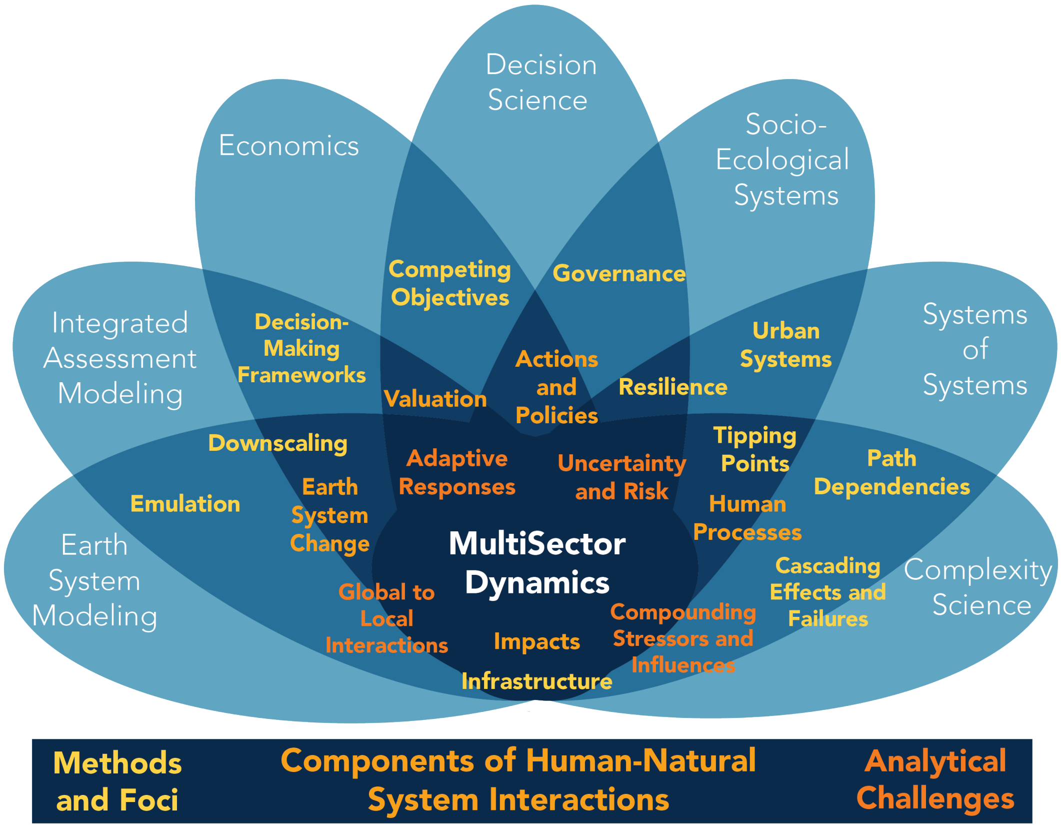

Figure 5. Focal and methodological connections of Multisector Dynamics with other disciplines

summary for each of these investments and the MSD research aspirations that underlie them below.

Strengthening Foundational Research Capabilities

Our foundational capability to model and gain insights for complex co-evolving human-Earth systems is a rate- and capacity-limited process (Haimes, 2018). The necessary lead times for research and development often mean that modeling and analytic capabilities that adequately capture key dynamics, systems' elements, and their evolving relationships are often no longer informative for decision making when actually available for use. Intelligently accelerating our ability to endogenize state-aware changes in the form and function of systems/sectors of focus represents an outstanding grand challenge for the scientific community. The major societal questions driving MSD research (Figure 4a) present an additional challenge to the rate and capacity limitations. Understanding transitions and transformations, risk, resilience and their distributional effects in complex human-Earth systems requires a significant investment in growing and diversifying the MSD workforce to broaden the backgrounds, knowledge, and experiences the community can draw on to advance our understanding of societal risks (Batchelor et al., 2021; Bernard & Cooperdock, 2018; Hofstra et al., 2020; National Academies of Sciences & Medicine, 2020, 2018). We must overcome workforce and workflow gaps (Figure 6) within the MSD CoP itself as an enabling mechanism for confronting the complexity of co-evolving human-Earth systems. Fundamentally, the community needs to exponentially scale inputs to MSD science (workforce, tools, hypotheses, teams, agencies, sectors, and scales) and the resulting outputs (results, papers, insights, and translational science benefits to society).

Who constitutes the MSD scientific community is integral to the community's capacity to meet its scientific objectives. Exponentially scaling hypothesis generation and exploration requires a broader and deeper workforce developed using active commitments to diversity, equity, and inclusion (DEI). Figure 7 summarizes the properties of community engagement models in a CoP. The continuum from traditional transmissive dissemination of goals (left-hand side of graphic) to transformative co-creation is fundamentally shaped by a community's defined membership, nature of interactions, and the balance of power to make contributions and set goals. Through community-led co-creation a CoP can enable the articulation of altogether new modes of framing and exploring scientific hypotheses that can potentially yield transformative changes. Institutional support of DEI has been shown to yield direct benefits to scientific outcomes. Nielsen et al. (2017) highlight that increasing the number of women, especially in team-leadership roles, has been shown to aid collaborative task completion while improving awareness of social dynamics, membership expertise mapping, and broadening the topics considered in framing research questions. Adopting DEI goals in MSD will require continuous adaptation to incorporate the best available information, particularly because most studies to date have focused primarily on the impacts of greater representation of white women in STEM. More research is needed to identify what practices best support scientists from other underrepresented groups and the impact of intersectional identities on key outcomes. One of the initial actions taken by the CoP will be to create a mission statement that addresses DEI and use community resources to implement evidence-based practices that support the growth of a diverse body of early career researchers in this community (Hill et al., 2010; Johnson et al., 2019; National Academies of Sciences & Medicine, 2020). DEI work (Tilghman et al., 2021) can support the science mission of MSD and is central to the aspiration of exponential growth to confront the complexity of human-Earth systems.

A second element of the MSD CoP's strategic focus on 'Going Exponential' is community level support of training opportunities and improved access to emerging MSD innovations. For example, Murphy et al. (2020) point out that the collaborative structure and broader social networks of open-science initiatives have led to more frequent high-status authorship for women, as compared to a narrower focus on reproducibility

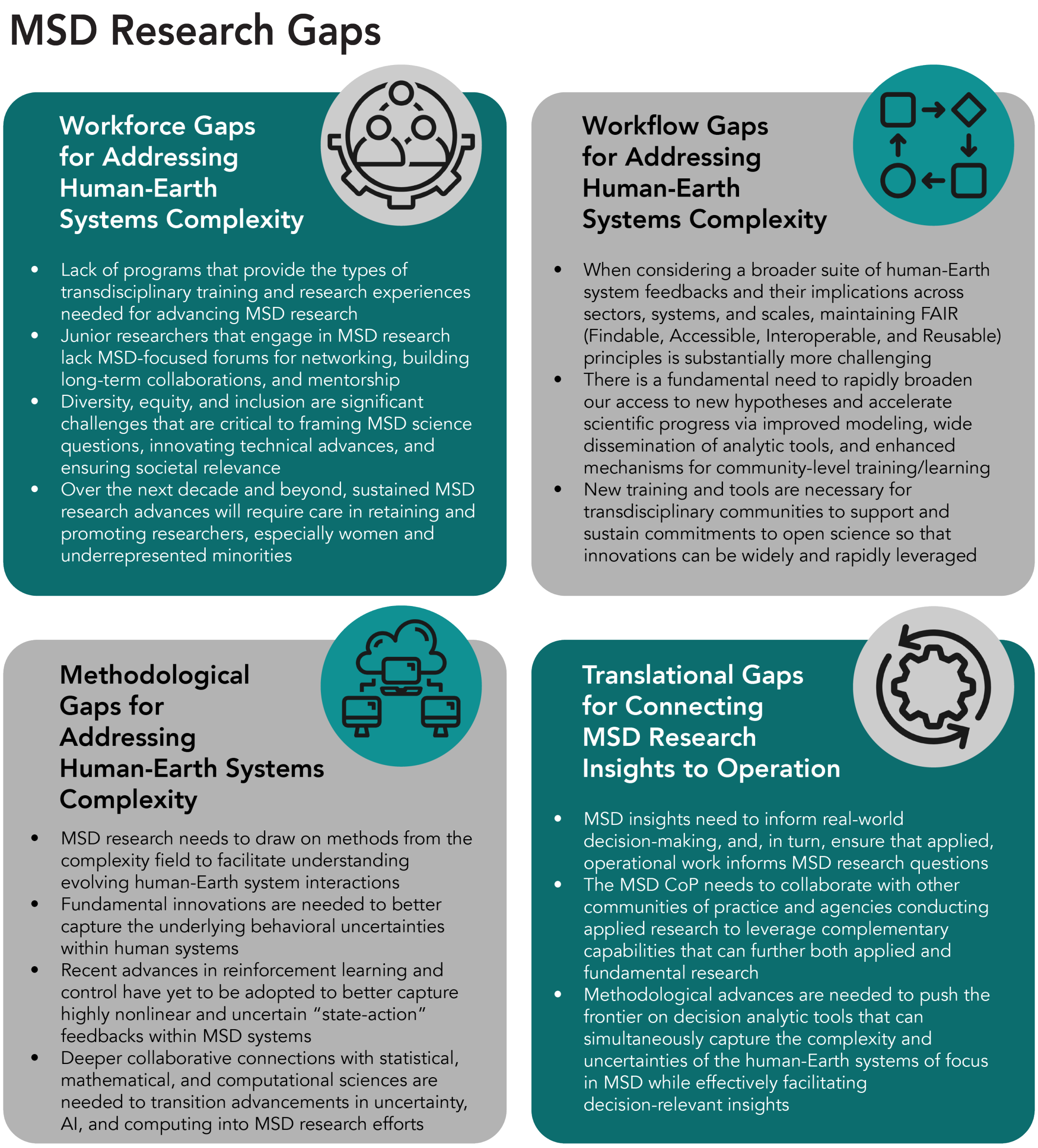

Figure 6. - MSD research gaps to be addressed over the next decade to enable the study and improved understanding of the dynamic and adaptive complexity of human-Earth systems and their implications for a broader array of societal objectives

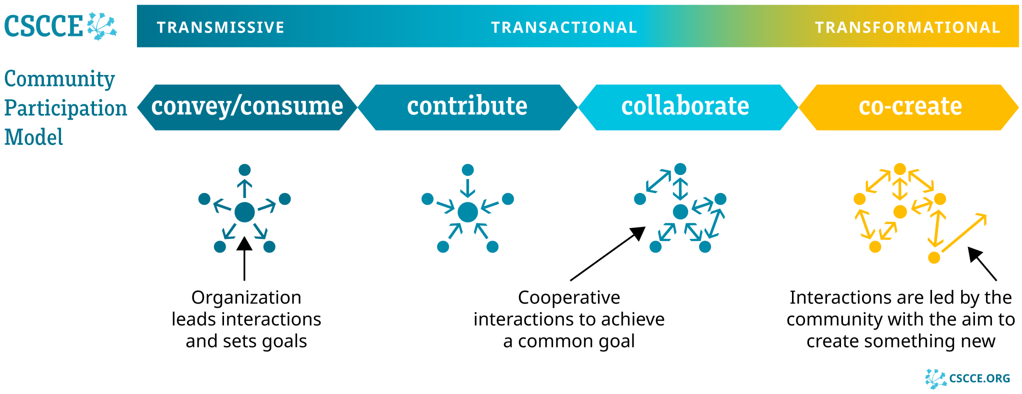

Figure 7. Four modes of community member participation based on the community participation model developed by the Center for Scientific Collaboration and Community Engagement (CSCCE). Center for Scientific Collaboration and Community Engagement (2020) contains the original description and elaborates on the community participation model. This graphic has been adapted from the original and is used here with permission by its authors.

principles. To exponentially accelerate collaborative science innovations the MSD CoP needs to undergo a transformational change in the ways that research is conducted (addressing workflow gaps in Figure 6). Elements of this transformation include: expanding the breadth and scale of explored hypotheses, encouraging researchers from diverse disciplines and backgrounds to join the MSD community, incorporating new technologies like artificial intelligence (AI) and emerging computing architectures (e.g., high-performance cloud/edge computing), facilitating collaboration across teams and projects, and developing new training and tools to support and sustain commitments to open science. Open science describes a set of principles around conducting, publishing and disseminating science, ranging from open access journals to reproducible research to open science tools like data repositories and open-source models (National Academies of Sciences & Medicine, 2018). Open science accelerates progress by reducing barriers to entry, gaining economies of scale, and avoiding duplication of effort (Allen & Mehler, 2019). Two key tenets of open science, reproducibility and extensibility, are central to MSD CoP's strategic focus on 'Going Exponential'. Reproducibility makes it easier to repeat and confirm the findings of others (McNutt, 2014; Pfenninger et al., 2017; Wicherts et al., 2011). Extensibility, the ability to quickly and easily build from the work of others, aims at reducing the large opportunity costs of adapting models, data, or analytic tools to a new purpose when they are not publicly available or they are poorly documented. Open science practices therefore present a major opportunity for innovation scaling in MSD breakthroughs.

Advancing Complex Adaptive Human-Earth Systems Science

As noted in Section 1.0, this commentary formalizes a vision for MSD as an emerging transdisciplinary field advancing our understanding of the local-to-global systems that fundamentally shape the interdependent dynamics, risks, and welfare of our modern world. The aspirations shared here seek to encourage transformative human-Earth systems research that address the major methodological challenges driving MSD research (see Figures 4 and 6). There are however methodological, data availability and computational gaps that are at present limiting the MSD community's ability to confront the complexity of human-Earth systems and their feedbacks. There is a need for: (i) better integration with complexity science (Haimes, 2018; Meerow & Newell, 2015; Montuori, 2013), (ii) improved modes of analysis for capturing uncertainties in how human systems shape dynamics (Axelrod, 2006; Filatova et al., 2016; Moallemi & de Haan, 2019; Polhill et al., 2016; Trutnevyte et al., 2019; Zellner, 2008), (iii) computational advances that enhance representations of highly nonlinear and uncertain "state-action" feedbacks (Bertsekas, 2019; Herman et al., 2020; Oikonomou et al., 2021; Powell, 2019), and (iv) solutions to overcome computational scaling and scientific inference barriers to MSD research insights (Bergman et al., 2019; Hendrickson, 2020; McGovern & Allen, 2021; National Academies of Sciences & Medicine, 2016). Addressing these gaps will require deeper collaborations with the statistical, mathematical, and computational sciences.

The representation of dynamic and adaptive human actions in human-Earth systems models represents a core challenge for MSD research (see Figures 4 and 6), particularly when considering the uncertainties regarding human actors and their interaction with the physical environment (Bland & Schaefer, 2012; Osman, 2010). Human systems uncertainties include: the identification of key individual, collective, and institutional actors; the representation of diverse objectives and tolerances to risk; and the functional modeling of actors and their actions. Trutnevyte et al. (2019) note that multisectoral modeling approaches typically represent human development trajectories in the form of exogenously defined assumptions, such as narrative scenarios of consumption rates and technology innovations Such approaches may ignore potential human-Earth system feedbacks on the implicit assumption that human actors do not adapt their land, energy, and water-utilizing activities (and the value-systems behind them) in the face of changing environmental conditions. In the case of global human-Earth system models that do attempt to endogenize human action, they typically assume rational actors with complete knowledge, operating within the context of an efficient global commodity market. Recent advances across disciplines present the MSD community with an opportunity to augment the rational decision maker paradigm and explore the implications of human actors exhibiting myopia, bounded rationality, incomplete knowledge, and dependence on past experiences, as well as behavioral heterogeneity across actors (Ajzen, 1991; Barsky et al., 1997; Chan et al., 2020; Kahneman & Tversky, 2013; de Koning et al., 2019; Simon, 1972; Weber, 2006).

The MSD research community must position itself to take advantage of the explosive growth of emerging data resources, algorithmic innovations, and analytic advances that facilitate model-based insights. Modeling frameworks have been rapidly evolving in how they capture dynamic and adaptive representations of human actors, infrastructures, and natural systems, as well as in how they account for the uncertainties surrounding them (Filatova et al., 2013; Herman et al., 2020; Knox et al., 2018; Morris et al., 2018; Taberna et al., 2020; Trindade et al., 2020; Turner et al., 2020; Yoon et al., 2021). These advances enable new scientific hypotheses by diversifying theoretical problem framings across a broader array of disciplinary perspectives., Further, they support quantitative analyses that explore ever-broader suites of societal objectives (e.g., reliability, resilience, robustness, economic efficiency, financial risk, stability, equity, etc.). The emerging frontier of computational modeling and analytics has also been embedding AI and agent-based modeling into highly adaptive software development processes and scientific workflows. Embedded intelligence can facilitate rapid iterative exploration of competing hypotheses and problem framings, and accelerate scientific insights across the MSD domains (Atkinson et al., 2017; Brown et al., 2020; Deelman et al., 2019; Yilmaz, 2019).

Providing Scientific and Decision-Relevant Insights under Deep Uncertainty

The recent advances described above can be applied to carefully assess and trace the effects of our representations of scales, interactions, and path dependencies (Filatova et al., 2016; Iwanaga et al., 2021; Levi et al., 2019). Capturing how human systems shape the determinants of risk (hazards, exposure, vulnerability, and response) even for a single extreme event poses nontrivial scientific challenges (see Figure 1). There is to date a dearth of modeling and analytic tools for better understanding how the co-evolutionary dynamics of multisectoral systems-of-systems shape risk. More formally, scientific framings of rapidly changing human systems, their multisectoral demands, as well as their feedbacks within the Earth system are themselves deeply uncertain. As a result, there is a broad range of plausible futures where there is no clear consensus on their likelihoods and consequences, often yielding complex tradeoffs across diverse MSD objectives (Dolan et al., 2021; Hallegatte & Engle, 2019; Jafino et al., 2021; Lamontagne et al., 2018; Lempert, 2021; Moss et al., 2021).

These challenges question rather common assumptions (either explicit or implicit) about predictability over long-time scales and for complex human-Earth system dynamics (Schneider et al., 1998; Schneider, 2002; Hofman et al., 2017). For example, recent literature on exploratory modeling under deep uncertainty (Bankes, 1993; Marchau et al., 2019; Moallemi & de Haan, 2019) highlights a need for scientific framings and scenario analyses that focus on generating diverse ensembles of plausible futures. These, often large, ensembles are carefully designed to capture the compounding and interacting effects of stressors and shocks faced by human-Earth systems, while encompassing a wide range of possibilities in how they might manifest (e.g., by considering more extreme conditions than those in the historical record). This shift away from deterministic single-future predictions moves the focus from predictive questions to questions of discovery, that aim at uncovering what futures, actions, and outcomes are the most consequential (Lempert, 2002). Given the large and long-lived capital investments associated with energy transitions, managing climate risks, and improving our national infrastructure systems, exploratory approaches aim at avoiding myopic lock-ins and unintended amplifications of risks by actions that fail to meet engineered, economic, and social requirements across many plausible futures.

The deep uncertainty around the likelihoods and consequences of pathways of change in human-Earth systems also implies that there exist irreducible uncertainties around the definition and representation of systems of focus, their boundaries, and nature of interactions (Kwakkel et al., 2016). Consequently, alternative framings of how–if at all–system relationships should be modeled need to be explored, especially in a multisectoral context, where pathways of change can be differentially relevant to the range of actors, systems and sectors present, or when modeled at different scales. Exploratory modeling frameworks, such as robust decision making (RDM) and its many-objective extension (MORDM), have iterative analysis of alternative framings at their core (Kasprzyk et al., 2013; Lempert, 2002). As such, exploratory modeling experiments enable human-Earth systems' modelers to elucidate the implications of their framing choices through transparent and traceable comparisons of their differences.

Applying exploratory modeling in MSD research represents a challenge as well as an opportunity to transform how human-Earth systems modeling is currently done. Innovative approaches to experimental design can (i) improve the representation of the deep uncertainties affecting a system (for example due to internal variability as well as uncertainties surrounding model structures and inputs), (ii) help to sample potential futures, and (iii) shed light on the impacts of uncertainties on consequential MSD outcomes (e.g., Lehner et al. (2020), Tebaldi et al. (2021)). Applying scenario discovery methods on the generated output space can identify critical combinations of uncertain factors, consequential human actions, or tipping points that drive poor outcomes (e.g., Dolan et al. (2021), Hadjimichael et al. (2020), Lamontagne et al. (2018, 2019)). Combined with many-objective optimization approaches, these methods create avenues to search through the space of potential actions and uncertainties to identify adaptive pathways of change across multisectoral objectives (e.g., Trindade et al. (2020), Herman et al. (2020)). This is an area of active research. While previous studies have provided valuable insights, they are often limited in terms of the considered scales, uncertainties, and multisector interactions. The fast growing body of research in data analytics and system modeling opens up opportunities to break important new ground.

4 Teaming to Address Complexity

The research challenges identified by MSD CoP include understanding long-term transitions and the effects of shocks, while capturing a wide range of environmental processes, and integrating knowledge and models of many systems. These challenges are comparable in complexity to modeling the dynamics of different components of the Earth system (e.g., oceans, atmosphere, land surface, and subsurface). Successfully addressing the research vision presented in this commentary will require an open science strategy that encourages collaborations across diverse fields and research communities. As summarized in Section 2.0, MSD CoP has grown from US DOE sponsorship of specific research projects as well as collaborative interactions with other US federal agencies facilitated by the USGCRP. Making progress at a rate commensurate with emerging global challenges will require an even wider set of international collaborations with diverse research communities including systems engineering, sustainable transitions, socio-environmental systems, socio-ecological systems, urban complexity science, Earth systems modeling, decision making under deep uncertainty, and others. Over the next decade our goal is to grow the MSD CoP to include a broad array of technical working groups, linkages with broader international research communities, and accelerate innovations in complex, adaptive human-Earth systems science.

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