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Sensemaking for entangled urban social, ecological, and technological systems in the Anthropocene

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Our urban systems and their underlying sub-systems are designed to deliver only a narrow set of human-centered services, with little or no accounting or understanding of how actions undercut the resilience of social-ecological-technological systems (SETS). Embracing a SETS resilience perspective creates opportunities for novel approaches to adaptation and transformation in complex environments. We: i) frame urban systems through a perspective shift from control to entanglement, ii) position SETS thinking as novel sensemaking to create repertoires of responses commensurate with environmental complexity (i.e., requisite complexity), and iii) describe modes of SETS sensemaking for urban system structures and functions as basic tenets to build requisite complexity. SETS sensemaking is an undertaking to reflexively bring sustained adaptation, anticipatory futures, loose-fit design, and co-governance into organizational decision-making and to help reimagine institutional structures and processes as entangled SETS.

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CRISIS OF CONTROL

Over the last decade, the Anthropocene has emerged as an era of planetary human dominance as well as a scientific and cultural concept that underpins the complex, wicked, and multi-scalar challenges we must grapple with[1]. Change and complexity are accelerating so rapidly across multiple Earth systems that they are outstripping the ability of our institutions and knowledge to keep pace. As such, there have been calls for interdisciplinary research, more sophisticated models, and a variety of policy actions to slow change, enhance understanding, and keep humanity within planetary boundaries[2–4]. To try to understand the evolving relationship between modern society and Earth systems, many authors have taken a more critical approach, exploring how the Anthropocene is a creation of capitalism and capitalist modes of production[5]. Others have put the focus on colonialism and corresponding structures of violence directed toward both humans and non-humans[6–8]. Some have framed the Anthropocene as a natural and accelerating technological progression that has radically altered human design spaces (across scales, from the planet to cells)[9].

In this paper, we take a different tack by focusing on urban systems as critical interfaces between destabilizing conditions of the Anthropocene and social resilience. Urban systems are not only the built, physical elements but also include the institutions that design, manage, and maintain them; the social norms and expectations regarding use and service delivery; and the ecological systems that interact with or are increasingly a part of them. They also are home to most of the human population. Engineered infrastructures are but one dimension of urban systems, and to date have been utilized to control natural variability to ensure the effective and reliable delivery of services (e.g., water) and avoidance of disservices (e.g., flooding). Our cities, their infrastructures, and the institutions that design, build, manage, and maintain these systems are the social-ecological-technological structures we have utilized to exercise control over natural systems. We have harnessed and shackled a wide range of ecological systems, goods, and services using scientific knowledge, predictions, social institutions, and the engineering infrastructure to generate livable and desirable social, ecological, and technological systems[10]. The focus on control appears increasingly at odds with the destabilizing conditions humans have created in the Anthropocene.

The paradigm of control emerged during a time of ecological and climatic stability (the Holocene) and was built on a foundation of assumptions about techno-scientific knowledge and technological efficacy that are no longer tenable. At the dawn of the Anthropocene, accelerating and increasingly uncertain conditions prevailed that together produced complex social-ecological-technological systems (SETS)[11,12] with dynamics and emergent outcomes that are increasingly beyond our grasp[13]. Underpinning this paradigm of control are fundamental modern, techno-scientific assumptions about our relationship to nonhumans and the technologies we create[14,15]. Science and technology studies scholars have shown how scientific and technological practices and concepts have maintained these boundaries among humans, ecologies, nonhumans, and technologies, and how these boundaries evolve and change depending on historical, cultural, and political contexts[16–19]. We Moderns have attempted to separate social, cultural, ecological, and technological domains to support the epistemic mechanisms of techno-science and assert control and dominance over nonhuman actors[20,21].

There is a long history of work that frames Socio-Technical Systems (STS) and Socio-Ecological Systems (SES), and the recognition of the importance of technology as a separate but interrelated domain has recently grown. We utilize the social-

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ecological-technological systems (SETS) conceptual framework[11,12,22,23] as a useful starting point for examining the interlinkages or 'couplings' between social, ecological, and technological dimensions of urban systems. The SETS framework acknowledges infrastructure, technology, and institutions that are increasingly recognized in the literature as critical to maintaining, managing, and designing urban systems but have not been adequately or explicitly included in other definitions and frameworks for complex systems including cities. With the SETS framework, it is possible to compare individual, coupled, and fully interacting social, ecological, and technological contributions to resilience, stability, or other systems properties and dynamics, providing opportunity to examine various "solutions" for solving complex urban challenges. The SETS conceptual framework complements recent scholarship in social–technical or social–ecological systems research and has been used in multiple cases and projects to enable examination of the interactions and interdependencies of human, environment, and technological–infrastructure interactions[24]. SETS thus aim to overcome the limitation of a purely socio-technological approach, which tends to exclude ecological functions[25], or of social–ecological approaches, which may overlook critical roles of technology and infrastructure[11], all of which are fundamental constituents and drivers of urban system dynamics. The SETS framework can therefore broaden the spectrum of the options available for intervention and is a useful foundation to explore sustainability or resilience plans, actions, and initiatives, while identifying barriers to change within existing actions, governance frameworks, economic constraints, and value systems[23].

Our knowledge systems and institutional structures, which are often based on single-domain principles, are increasingly incapable of making sense of complex SETS and managing them effectively[26,27]. The knowledge that underpins the construction and management of urban systems assumes that social, ecological, and technological (infrastructural) systems are separate, stable, predictable, and ultimately, controllable (Fig. 1). Further, this knowledge presumes that legacy urban systems will be able to operate in a certain set of conditions successfully and efficiently (and rests on still further assumptions about how existing data reflect the full spectrum of potential conditions). Finally, this paradigm of control reflects the values of dominant actors in society, particularly the values of utility and efficiency, while marginalizing normative concerns related to equity, justice, and ecological value[17,28,29]. As a result, many of our urban systems are designed to deliver only a narrow set of human-centered services, with little or no accounting or understanding of not only how actions will undercut long-term human well-being but also how non-humans and ecological systems will be reshaped.

Controlling paradigms attempt to simplify conditions to a limited set of variables. This paradigm of control has generated a crisis of control where our sensemaking capabilities to effectively engage with increasingly complex environments are increasingly insufficient[30]. By sensemaking, we broadly mean the ability of institutions to understand and give meaning to new experiences and complex conditions, take action, and continue to generate new understanding as conditions change[31,32]. When the variables that the system is able to engage with and make sense of are limited, organizations are unable to effectively and creatively respond to changing conditions that introduce new variables or result in new dynamics. This concept underpins the theory of requisite complexity[33,34]. Novel sensemaking creates space for innovative understanding and for responses to emerge as the environment creates chaotic and unforeseen conditions[35,36].

To move beyond the paradigm of control and bolster our novel sensemaking capabilities, we must rethink and redesign many of our knowledge-generating practices, decision-making tools and frameworks, and engineering assumptions that underpin the design, management, and maintenance of urban infrastructures. To do so, we explore how interconnected SETS provide a framework for moving from control to a new understanding of our entanglement as and across SETS (Fig. 1). Towards this end, we: i) start by framing urban systems and their infrastructures as SETS, ii) position SETS thinking as novel sensemaking to create repertoires of responses to increasingly entangled system dynamics commensurate with environmental complexity (i.e., requisite complexity increases the variety of system responses to surprises that are as nuanced as the problem), and iii) describe modes of SETS sensemaking of urban infrastructures as basic tenets to build requisite complexity to engage with environmental complexity. We focus on urban systems, but the takeaways are generalizable to urban and non-urban systems across scales. Urban systems offer a particular richness and complexity of SETS dynamics to discuss. While SETS thinking has received increasing attention as a framework for pluralism among key domains of urban systems, ultimately, we intend to position SETS as a

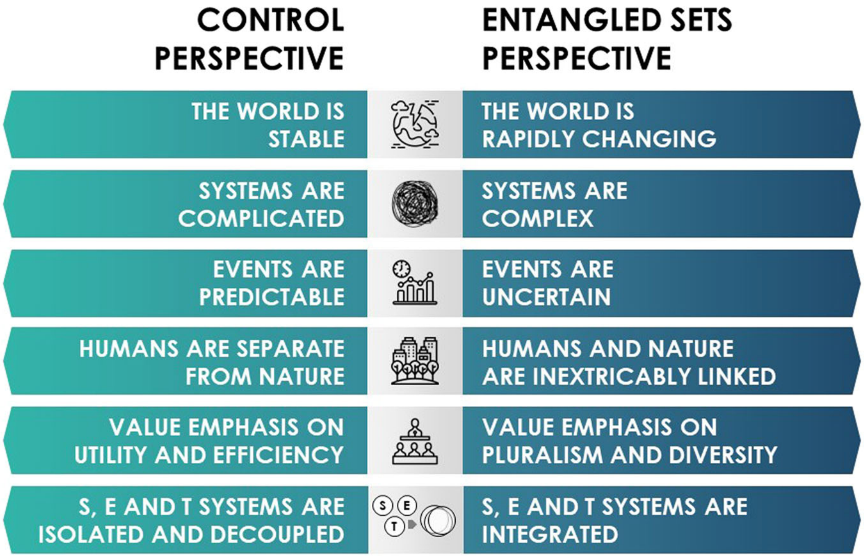

Fig. 1 Control and entangled urban systems perspectives. These perspectives represent spectra of control and entangled SETS — urban systems typically fall somewhere between the two contrasting ends of these spectra.

sensemaking framework that will allow cities to engage more effectively with complexity.

URBAN SYSTEMS AS SETS

DEFINITIONS

- Control is purposeful influence toward a predetermined goal. Influence is an agent changing behavior in another agent. Purpose is the directing of influence toward a goal.
- Entanglement - increasingly complex dynamics defining how the social, ecological, and technological urban domains operate and interact.
- Sensemaking - the ability of institutions to understand their positions and to develop and deploy actions that augment the ability to adapt and transform at pace with increasingly complex and changing environments.
- Requisite Complexity – A system response repertoire commensurate with environmental variety.
- Reflexivity – A process that compels organizations to use a SETS lens as a mirroring and sensemaking tool to turn back to itself and question whether its values, structures, and functions reflect or align (or not) with the social, ecological, and technological domains of urban systems.
- Knowledge systems - the social relations, practices, routines, cognitive styles, methods, and tools that organizations use to 'see' and 'know' the world (both nature and society), and to make decisions based on that knowledge.

SETS are systems that have diverse components among social, ecological, and technological dimensions[22,23,37,38]. Their structure is the types of components and how they are arranged and connected, including the scale at which they occur or operate. Their function is simply what each component does (at each scale), yet through the interactions among components, ultimately yielding a collective, system-level function (what the systems do, i.e., emergence). Social components might include individuals, households, neighborhoods, government organizations, community organizations, and so forth, but also the cultural norms, governance structures, and institutions associated with these components. Ecological components include individuals (organisms, such as trees, birds, bacteria, and insects) and their populations and communities, but also the physical environment (soil, air, water, climate, and topographic features). Technological components include built structures like roads, buildings, and pipes for water delivery or waste removal, as well as the knowledge and information systems that govern their operation. The combining of social, ecological, and technological structures and functions across scales, including feedback loops, results in complex and emergent systems that are challenging to understand, navigate, predict, or control[22,39,40].

Technology—as the application of knowledge by humans—has often been framed as a subset of social systems, but as technologies have become more complex, automated, distributed, accessible, and intelligent, there is a growing need to frame the domain commensurate with social and ecological structures and dynamics[41]. As such, resilience researchers are increasingly embracing a SETS framing towards describing complex urban dynamics in the context of adaptation[2,12,22–24,37,42]. In doing so, while recognizing that the structures and functions of social, ecological, and technological systems can behave differently, a SETS framing gives system domains equal importance, providing opportunity to elucidate how their interactions affect the changing complexity of urban systems and their emergent dynamics.

For an institution to effectively adapt to increasingly complex environments, it needs a repertoire of responses at least as diverse and nuanced as what the environment produces. Requisite complexity recognizes that for a system to engage with complexity, it needs to be able to function by producing knowledge and reorganizing for the diversity of conditions produced by the system's environments[33,34]. As social, ecological, and technological domains become more entangled, it is necessary to restructure normative goals, ontologies, technologies, and knowledge generation to produce adaptive capacities capable of enabling change at pace with changing environments. A reliance on legacy knowledge-generating processes, goals, and technologies that describe the dynamics between social, ecological, and technological domains is likely to contribute to a decoupling between how quickly our urban systems need to adapt and how slowly they're capable of adapting[30]. Novel sensemaking underpins requisite complexity, in that it provides space for new structures and functions to emerge as the environment creates chaotic and unforeseen conditions. As such, sensemaking is the cognition of the internal and external dynamics of coupled social, ecological, and technological systems. SETS sensemaking recognizes that there are increasingly complex dynamics defining how the domains operate and interact (i.e., entanglement) and creates awareness of these interactions (reflexivity) and that these dynamics produce complex emergent behaviors.

SENSEMAKING IN ENTANGLED SETS

The organizations that manage urban systems currently operate under the modern bureaucratic paradigm of control that assumes that governing actors and organizations are themselves outside and detached from the SETS processes they govern[43,44]. Because this practice goes against the complex, interactive reality of SETS, the system inevitably pushes back on the organization and generates risks and externalities, causing the organization to react by directing most of its attention and resources towards exerting even more control. An example of this pushback is extreme climate events where a focus on hardening strategies produces robust-yet-fragile unintended outcomes[45–47].

To avert this crisis of control, we need to shift to an understanding of the relationship between human, ecological, and infrastructural systems as one of entangled SETS (Fig. 1). Entangled SETS embrace an understanding that social dynamics are fundamentally intertwined with ecological and technological systems. Social actors are inextricably tied to a larger assemblage of ecological, nonhuman, and technological actors[15,48]. We should acknowledge the fundamental instability of the barriers we have built between social, ecological, and technological domains and dynamics. This entanglement is not simply an epistemological challenge that can be met with more interdisciplinary models or better data. This is a paradigm shift from human-centeredness, isolation of domains, and control to SETS as an ontology for the basic interrelatedness between human activities, ecological and nonhuman actors, and technological artifacts. Humans, ecologies, nonhumans, and technologies are braided and co-constitutive[14,15]. This requires institutions to work within entangled SETS (rather than against them) by acknowledging our positions within the complex environment[15,44,49].

To enable the requisite variety of responses to Anthropocene disruption, we must restructure the relationships between social, ecological, and technological systems towards novel sensemaking that open up action spaces that can deliver more transformative and systemic solutions. We define sensemaking in the context of entangled SETS as the ability of institutions to understand their positions and to develop and deploy actions that augment the ability to adapt and transform at pace with increasingly complex and changing environments. This requires that institutions are aware of their position in interconnected SETS, reflexively interrogate how epistemic and normative assumptions affect their understanding, and deploy actions (e.g., policies, decisions, new technologies) that are adaptable and tightly coupled to feedback mechanisms. This perspective change is shown in Fig. 2.

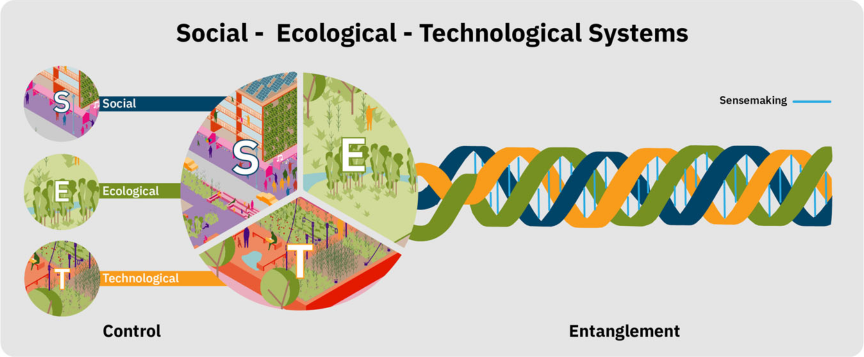

Fig. 2 From control to entangled SETS. Social, ecological, and technological systems can be brought together to improve sensemaking but need to move beyond traditional systems thinking approaches to advising understanding and decision-making within and for entangled SETS. This is represented as a helix of intertwined, dynamic social-ecological, technological systems (SETS) where blue lines are ongoing efforts to make sense of complexity as it evolves and responds to itself and outside drivers and disturbances. SETS helix adapted from[2].

Novel sensemaking necessitates intentional self-critique and scrutiny over the values, normative dimensions, knowledge, and assumptions about how the world works and how we respond amidst this uncertainty[44,50]. Through sensemaking, institutions can re-imagine and restructure their relationship with SETS, scrutinizing if their values, structures, and functions reflect the entangled social, ecological, and technological domains, thus building towards requisite variety. Even more important, sensemaking requires that governance actors critically question what kinds of urban systems are being co-produced by our institutional goals, designs, and knowledge-generating and management operations[51]. In the following section, we develop several modes that build requisite variety for institutions and facilitate sensemaking in entangled SETS.

SETS MODES FOR SENSEMAKING

Novel sensemaking is needed for increasingly entangled urban systems to move from control to reflexivity. In doing so, requisite complexity must be produced in recognition that under increasingly complex conditions, institutions cannot fully understand what they are observing and must therefore plan for contingencies[52]. New operational modes (i.e., interacting capabilities) can support this requisite complexity and thereby improve sensemaking in the service of transformation and innovating systemic solutions. Systems that can effectively engage with complexity exhibit modes that support sustained adaptation (ability to adapt to future surprises), anticipatory futures (ability to search for game-changing signals), loose-fit design (organizational self-organizing), and co-governance (organizational structures and cultures that emphasize knowledge co-production and distributed decision-making). These modes commonly appear in complex adaptive system literature[30,53–57]. As such, we describe how these modes can be specifically practiced within a SETS perspective, including their potential applications. For each mode we describe how requisite complexity is supported, interactions with other modes, and implementation challenges. Examples are provided.

Sustained adaptation

Sustained adaptation recognizes that the conditions for which urban systems are designed will change, the services demanded of the system may change, adaptation efforts will require innovation, and boundary conditions will need to be rearticulated[58]. Legacy infrastructure, however, are obdurate (as both technologies and governance), with path dependencies that limit their ability to respond to change[59,60]. These path dependencies result from an emphasis on control resulting from foci on efficiency, long lifetime technologies, stable operating conditions serving as the basis of design, and an emphasis on past goals that are steered by legacy social, financial, and regulatory priorities[61,62]. Combined, there is little space for innovation when infrastructure systems are siloed from the capacities and dynamics afforded by social and ecological systems. Reflexive co-governance and an ability to anticipate the future will be needed to transition to new paradigms from existing ones. SETS dynamics recognize the interrelatedness, interconnectedness, and interdependence of urban systems and provide a framework to explore novel approaches for sustained adaptation.

A realignment towards entangled SETS fundamentally challenges the existing value orientation of control and, specifically, efficiency because SETS introduces a multitude of tradeoffs that, when incorporated into design, necessitate expanding solution spaces. Efficiency, the ability to provide a service or product with minimum resources[63], is a dominant force in urban system design that perpetuates technological emphasis as the default operational mode[28]. It is critical for infrastructure systems to experiment, so they are able to adapt to growing complexity[64,65]. For example, safe-to-fail strategies are novel, experimental strategies that acknowledge interdependency and complexity in urban infrastructures and work across SETS to manage surprise and failure[47,66,67]. It is important to provide space within design and implementation for experimentation across social, ecological, and technological capabilities by recognizing the roles each plays in providing services to enhance human capabilities. Indeed, the fact that SETS are constantly changing provides opportunity to harness this dynamism for experimentation (e.g., loose-fit design) and relational thinking in ways that can provide iterative learning for sustained adaptation[68–70].

Sustained adaptation necessitates advancing how a system addresses resilience tradeoffs and manages adaptive capacities[58,71–74], and framing urban systems as SETS appears poised to improve both[22]. A SETS orientation would naturally question normative infrastructure risk management approaches that emphasize robustness across technological, epistemic, institutional domains (as a few examples). Robustness is the ability to withstand a disturbance, and it typically manifests in engineering as physical infrastructure armoring, strengthening, or hardening[58]. Armoring infrastructure depends on identifying a worst-case scenario in which to design[75], which is agnostic to the capabilities needed to confront change introduced by social and ecological systems. By embracing the structure and dynamics of SETS systems, opportunities are created for identifying new positions that previously would have been unavailable. For instance, there is growing recognition of the ability of natural and nature-based infrastructure to reduce hazard risks, which has varying tradeoffs in comparison with conventional built infrastructure in terms of services, costs, and space. Green stormwater infrastructure, living shorelines, and coastal and watershed restoration not only help lessen impacts of flash flooding, sea-level rise, heat risk, etc. in urban spaces but provide opportunities to improve water quality, provide food, create habitat, and supply recreational and cultural space[38,76]. These new positions can be explored by infrastructure managers through visioning anticipatory futures. Each of these additional services contributes a variety of solutions—more than merely technological responses—and creates a broader solution space (i.e., embracing requisite variety) to adapt to changing needs over time.

Anticipatory futures

We need advanced approaches to urban systems planning that incorporate longer-term and dynamic time horizons that look across multiple spatial scales and sectors/domains/disciplines[77]. Futures approaches help to anticipate, proactively respond, and shape desirable futures[78–80]. These approaches facilitate institutions in gathering anticipatory knowledge (e.g., Horizon Scanning, Seed of a Good Anthropocene, Wild Card - Weak Signals), exploring dynamics of change (e.g., Axes of Uncertainty, Driver Mapping, Futures Wheel), articulating and making sense of what the future might or should be (e.g., backcasting, future visioning, scenario planning), and developing and testing interventions and policies (e.g., STEEP Implication Analysis, stress testing, roadmapping). However, fixed (i.e., limited set of time periods) and near-term (e.g., shorter time periods such as less than 15 years) initiatives are likely to face and adopt a shallower perspective on uncertainty. Similarly, spatially limited approaches will lack consideration of how regional, state, national, or international events and dynamics can have an impact locally, as well as how local actions will have global impacts. And solutions that address only one system domain are unlikely to prove to be resilient in the future (or across multiple domains). For example, the European Commission has used elements of horizon scanning to inform long-term policy and planning in the transportation sector, and this process led to the acknowledgment that signals of change (e.g., electrification, automation) do not necessarily emerge within the transport sector[81]. In the absence of elements of horizon scanning, the siloing that occurs has the potential to lead to lock-in without room for sustained adaptation, or incomplete solutions and unintended tradeoffs (i.e., making one part of the interconnected system better while introducing vulnerabilities elsewhere).

An institution's dominant time horizon, spatial scope, or sector will influence its goals and other functions, such as how it conducts planning explorations, addresses uncertainties, and interacts with other and different knowledge systems. Anticipatory futures as a SETS capability serves to expand the problem and solution space considered. For example, horizon scanning has been used to identify emerging needs and potential collaborative actions related to trade-offs between renewable energy adoption and wildlife/environmental conservation[82]. Similarly, it has helped identify priorities and research gaps for water management and climate change in the Upper Indus Basin across social, ecological, and technological systems[83]. Dynamic, longer-term time horizons can allow for the identification and exploration of problems that unfold across longer and multiple time horizons[84,85]. This enables anticipatory responses to more distant but emerging megatrends (e.g., population relocations due to climate refugees, and future demographic shifts). The consideration of longer time horizons also allows for the exploration of interventions that require greater spans of time to prepare for and implement changes (e.g., solutions that require emerging technologies, shifts in values and worldviews, and transformed system goals that exist in the present only as weak signals[86,87]. A broader approach to anticipatory futures with longer and variable time scales, larger and multiple geographic scales, and SETS interconnections is likely to encounter more uncertainty and thus benefit from explicit consideration of deep and epistemic uncertainty. The ability to anticipate future entangled SETS will require a more adaptive and dynamic approach to planning than is currently practiced, one that is more conducive to diverse knowledges, contingencies, and deviations[78] and more responsive to slow variables, megatrends, and weak signals[88].

Loose-fit design

Loose-fit design provides the flexibility for organizations to restructure urban systems to better confront chaos and change. Fundamentally, loose-fit describes the ability to self-determine how to function and locally adapt[89], and is contrasted with tight fit, where organizational elements and processes are rigidly predetermined based on normative assumptions and history[90], i.e., locked into a fixed, rigid structure and set of functions. Urban systems, particularly infrastructures, typically appear tightly coupled with their elements (people, assets, hierarchy, rules, etc.) and rigidly predetermined to meet performance indicators that often reflect legacy goals[30]. While tightly coupled systems are valuable for periods of stability and relatively little environmental variation, errors of tightness emerge when organizations constrain their capabilities relative to the growing complexity of their environments[91,92]. These errors of tightness can result from organizations becoming large and focused on sub-specialization, constrained by rigid relationships (e.g., divisional bureaucracies), thereby constraining their sensemaking capabilities[90].

Approaching urban systems as SETS structures and functions relaxes rigid or locked understanding of the system, opening up loose-fit capabilities for engaging with complexity. At their core, SETS approaches create conditions for S, E, and T elements to be responsive and distinctive, i.e., localized adaptation. S, E, and T elements have unique capacities and relationships, and the particular challenges that a city faces necessitate flexibility to leverage the respective capacities as needed. In one city or problem context, it may make sense to relax T capabilities to give space for E capabilities (e.g., green infrastructure being used to attenuate flooding). Whereas in other contexts, T capabilities may be preferred. While the tradeoffs among S, E, and T capabilities matter deeply, perhaps more important are the novel structures and functions that are allowed to emerge when a loose-fit design with a capacity for local adaptation is prioritized. Legacy systems that emphasize T appear too tightly fit to allow this to happen.

The challenges to implementing loose-fit designs in support of SETS may include siloed jurisdictional governance and organizational goals that emphasize efficiency-focused solutions. Governance of city systems often is structured as jurisdictional siloes that generally affect outcomes within a single domain (S, E, or T) with limited opportunity to build novel solution strategies across multiple domains (S, E, and T)[51,93]. There have recently been pushes toward cross-jurisdictional collaborative management models to confront wicked challenges[94], and in climate adaptation, SETS appears to be emerging as one such model[24]. Yet there remain considerable barriers to systematic planning and decision-making in cities that cross S, E, and T boundaries to create novel adaptation strategies, including funding streams, bureaucratic processes, education, and entrenched legacy goals[95]. These barriers tend to emphasize exploitative strategies where resources are focused on refining an existing capacity within the system, instead of explorative strategies where novel searching, experimentation, and invention occur[91,96]. Exploitative strategies work well during periods of stability, however, exploration is needed during instability to create new capabilities[97], i.e., requisite complexity. To be successful in the long term an organization must be able to pivot between exploitative and explorative strategies—loose-fit design[91,96,98]. Loose-fit can provide opportunities for exploration and in doing so support creative processes that integrate S, E, and T capacities as the urban system engages with chaos.

Loose-fit design can be seen in several resilience efforts focusing on entangled/complex SETS. Communities that have embraced retention basins that double as parks (and can help attenuate flooding) reduce their rigidity by relaxing the reliance on engineered infrastructure while reducing vulnerability and augmenting S and E capabilities[99]. Similarly, the strategic placement of cell phones with community leaders that are integrative knowledge aggregators for their building or neighborhood augments social capabilities and reduces the reliance on centralized emergency management systems[100,101]. These examples highlight how the giving of space and resources to S and E systems not only adds new capabilities but also provides more opportunities for localized adaptation in a loose-fit structure.

Reflexive co-governance

The way in which institutions and organizations structure their knowledge systems, decision-making processes, and operational structures directly impacts opportunities for novel sensemaking and adaptation to increasingly complex environments. Knowledge systems are the people and their social relations, practices, routines, cognitive styles, methods, and tools that allow organizations to 'see', 'know', and respond to the world around them (both nature and society) based on that knowledge[26]. A SETS perspective views knowledge as more than data and information that feeds into a decision process, but as deeply entangled with the shared values, worldviews, politics, and identity of the people and groups that design and manage an organization[51]. Thus, knowledge is both an outcome of the normative and sensemaking processes of the organization and it creates the conditions for it. This is the reason why the overreliance of our current urban governance systems—particularly those that manage infrastructure—on the logics and reasoning styles of techno-scientific knowledge can create the normative and empirical illusion that we can control isolated domains[102]. This then narrows the information and signals about one domain of the system, limiting an organization's ability to make sense and build a repertoire of policy responses that better match the variability of complex SETS.

The governance structure of many urban systems is characterized by a divisionalized form[43,103], which creates a primarily centralized operational structure and highly siloed knowledge system. This vertical hierarchy delays decision-making at the operational level as operators await approval or disapproval of system changes, leading to slow response capacity. In moments of chaos, operators—those 'on the ground' most closely interfacing with the environment—need to process information, act, and learn quickly to mitigate negative consequences. Furthermore, governance organizations design, manage and maintain our urban systems as if those systems operated independently of each other, thus closing their organizational boundaries to other organizations and governance networks. As SETS dynamics continue to change, those managing urban systems will need to make sense and respond more quickly, and it may be useful to provide the operators with a degree of autonomy through decentralization of the organization's knowledge system and operational structure and by building capabilities to collaborate with other organizations that have critical governance functions.

Reflexive co-governance enables organizational change and re-alignment towards entangled SETS. Reflexivity as a governance practice involves 'opening-up' the organization to do the kind of novel sensemaking needed for requisite variety[52]. As with loose-fit design, opening up an organization's knowledge system and operational structure reframes the system as SETS through the inclusion of external and diverse values, ideas, and knowledge, and builds flexibility in the governance system to better appreciate, anticipate, and orient its priorities to navigate complexity. Knowledge co-production approaches to climate resilience and adaptation planning, for instance, provide spaces for infrastructure managers, urban planners, etc. to collaborate with climate scientists and adaptation practitioners in a process of inter-organizational learning and anticipation of problems and solutions that integrate a plurality of perspectives and knowledge systems[104–107]. However, 'opening up' creates an efficiency paradox because it implies a balance between relaxing organizational boundaries along with the need to 'close down' (or tight fit design) to make decisions and get things done when conditions require it[108,109]. The issue is not a matter of either/or, but of sustaining both capabilities when addressing complex problems[109,110].

Organizations must be able to reshape their structures and collaborate as part of a larger governance network across multiple scales and sectors of complex SETS in order to design, manage, and operate urban systems as interdependent[43,64,111]. A growing number of examples from across the private and public sectors show that organizations that engage in interorganizational collaborative governance improve not only their performance but their learning processes as well[26,112]. Changes in how these institutions interface and interact with those governance networks facilitate their capacities to coordinate and experiment with strategies that cross SETS domains, evaluate trade-offs, and enhance adaptability[30,113].

TOWARD REQUISITE VARIETY FOR SETS

As we navigate an ever-evolving array of social, ecological, and technological change, the established perspective of a world that is relatively understandable and controllable appears to be at odds with the complex, wicked, and multi-scalar challenges associated with the Anthropocene. Without recognizing and grappling with this tension, the interconnected SETS that comprise our cities and their infrastructures run the risk of becoming decoupled from the environments and conditions in which they live and operate. This decoupling represents a growing disconnect between what our urban systems are capable of responding to and the growing complexity of their environments, which jeopardizes pursuits of resilient, just, and equitable outcomes and transformations. To at least slow, but ideally prevent, this decoupling, cities will need to be organizationally structured differently, which will require fundamental change rooted in commitments to sensemaking goals. Small tweaks to decision-making to better navigate complexity are likely not enough; cities will need to reimagine and restructure institutional arrangements and functions. As a response, we posit that reflexive and novel sensemaking can help to close the gap between what our systems need to do and what they are capable of doing.

Transitioning from a paradigm of control to one of entangled SETS will require a candid critique of existing knowledge systems and institutional structures followed by a willingness to change. Change management literature provides direction for understanding and navigating this paradigm shift[114]. Organizations must embrace ambidexterity, the ability to pursue both explorative and exploitative strategies[115,116]. The four modes of sensemaking—sustained adaptation, anticipatory futures, loose-fit design, and reflexive co-governance—are explorative strategies framed through SETS as a sensemaking lens. Implementing these modes will require that organizational leadership recognize the need for transformative change[77,116]. Organizations that struggle to institute change may leverage disruptive events and other windows of opportunity[77]. Ideally, decision-makers would implement the modes prior to significant destabilizing conditions. Examples of such proactive action exist. The Portland Water Bureau (PWB) developed a risk management approach by engaging all seven of the bureau work groups, fourteen regional and national utility managers, and fifty-five community partners.

PBW generated 675 strategic risk ideas, which were then narrowed down to 67 risk strategies. They also created a cross-cutting committee on equity that reviewed each risk strategy from this vantage. The final approach emphasizes system reliability, community relationships, workforce and culture, organizational processes, and accountability and leadership. The last category, in particular, explicitly lists strategies for encouraging explorative behaviors such as "Identify new and effective ways to help staff engage in work and support the values of the bureau's guiding statements" (sustained adaptation) and "Support teams in recognizing, discussing, and managing conflict" (reflexive co-governance)[117].

The SETS modes for sensemaking are not achieved in isolation. Many of the capabilities provided by these four modes are closely interlinked (e.g., the interplay of sustained adaptation and loose-fit design both provide for continual adjustment and adaptation), and they combine to provide a landscape of capabilities to build and operate urban systems in a complex SETS world—towards requisite complexity. However, the implementation of any particular set of capabilities will vary widely, as determined by the institution's scale, time, place, and organizational positionality. However, towards operationalizing the proposed SETS sensemaking, we propose the following guidance:

1. Break cycles of lock-in by enabling city managers and stakeholders to challenge existing assumptions, decision-making processes, and design choices. Begin this process by taking stock of existing lock-in conditions and barriers to change (including how organizations are allowed to plan and resource across SETS dimensions) and empowering decision-makers to challenge assumptions, enabling organizations to question legacy goals and how institutions are structured. Create opportunities for organizations to identify their limitations, and how SETS capabilities can open up capabilities. For example, Mannetti et al. (2021) describe work in nine Latin and North American cities to co-develop desired future pathways and provide a participatory engagement guide to re-envision path dependencies, maladaptive structures, and power asymmetries[118].
2. Reimagine institutional goals (and decision-making process) to foster SETS knowledge integration, inclusion, and reflexivity. Changing goals and objectives can potentially result in a profound transformation of an organization's overall approach to achieving its desired outcomes, as it may necessitate a reevaluation of the organization's strategies, operations, and goals. This change in the system's goal may require a fundamental shift, which could ultimately affect the organization's culture, structure, and decision-making processes[77,119]. For example, the State of California has implemented new policies (specifically SB 375) to achieve sustainable transportation and land use goals. These policies focus on increasing walkability, reducing greenhouse gas emissions, and improving air quality by restructuring performance metrics related to infrastructure goals[120,121].
3. Develop capacities for opening up an organization's knowledge system and operational structure. Begin this process by creating institutional settings, practices, and culture for novel searching, experimentation, and exploration that navigate and create relationships between SETS, enabling organizations to change by engaging with changing environments and system dynamics. For example, Semarang City, Indonesia has implemented early warning systems that utilize deliberative planning to empower local communities to direct funding and resources towards generating co-produced knowledge, protecting vulnerable groups, and quickly responding to emerging hazards[122].
4. Create spaces and opportunities for city agencies and subdivisions to restructure themselves to address SETS challenges and leverage capabilities across domains. Begin this process by incentivizing practices such as teamwork, diversity, transparency, connectedness, and flexibility[115], enabling organizations to change by, for example, creating new cross-cutting agencies that are centered on addressing the multi-hazard, multi-sector, multi-scale challenges. This cross-cutting strategy to governance structure has been deployed within municipalities to address climate change, including New York City's Mayor's Office of Climate and Environmental Justice and Phoenix's Office of Heat Response and Mitigation.

As an epistemological shift, SETS sensemaking supposes rapid change, transformation, and surprise, to enhance decision-making—and to reimagine institutional structures and processes. Sustained adaptation necessitates that organizations commit to enduring change and uncertainty to meet their changing environments. In doing so they will need to develop anticipatory futures capacities to generate knowledge, scan for, and envision game-changing futures. Organizations will need to confront how tightly coupled their structures are, and whether self-determination of elements of the organization (loose-fit design) is sufficient given the environmental complexity. Organizational changes will confront forces and objective threats that intentionally and unintentionally lock-in organizational structures, knowledge, and goals. Underpinning these changes is co-governance, i.e., institutional designs that facilitate collaboration across S, E, and T domains and enable the reflexive questioning of knowledge and normative assumptions for how sustained adaptation, futures scanning, and loose-fit design are practiced.

Cities must engage with the growing complexity of their systems and environments by building the sensemaking capabilities that open up novel decision-making approaches for working within increasingly complex dynamics and changing boundaries. In doing so they must restructure around processes that produce a repertoire of responses commensurate with system and environment complexity. The integration of the modes represents critical competencies that support requisite variety in increasingly entangled SETS, abilities to reflect on the changing structures and dynamics of interacting S, E, and T systems. A commitment to SETS sensemaking is an acknowledgement of the necessity of changing ontology. The control-based modes of decision-making that our cities and their infrastructures are designed around are increasingly decoupled from their realities, and framing resilience as integrated SETS offers the best chance to navigate increasing complexity and uncertainty; reframe problems in terms of S and E, and T dynamics; open transformative solution possibilities; and incorporate diverse knowledge that can ensure equity and reconnect our human-built systems with their environments.

DATA AVAILABILITY

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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AUTHOR CONTRIBUTIONS

M.C. led the coordination of the author team and visioning of the perspective. T.M., T.M.E., A.H., D.I., T.M.P., E.C., N.G., and S.M. contributed equally to the framing of the sections. All authors read and approved the final manuscript.

COMPETING INTERESTS

All authors declare no competing interests.

ADDITIONAL INFORMATION

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