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Governing sustainable transformations of urban social-ecological-technological systems

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Cities have grown rapidly—while they provide opportunities for many, they must also confront pervasive and rising inequality, unsustainable consumption, and growing vulnerability to the impacts of climate change. Recent research emphasizes the need to improve urban resilience and sustainability in the face of climate change, but offers circumscribed approaches that mostly focus on either (1) resource management and service provision, (2) social processes and capacities for transformation, or (3) governance and power relations among actors. Here, we embrace the emerging approach that considers urban areas as interdependent social-ecological-technological systems (SETS) and consider the implications for sustainable service provision; the role of bottom-up efforts in initiating urban transformations; and how governance may, under certain conditions, coordinate these efforts to effect broader change.

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INTRODUCTION

While rapid urbanization has been an engine of economic growth, it has also resulted in the encroachment on agricultural land and ecologically sensitive areas. In many places, it has also resulted in unequal access to opportunities and the inadequate provision of public services. Furthermore, climate change, biodiversity loss, economic crises, and other global processes are increasing the frequency and severity of disturbances, such as floods, droughts, storms, heatwaves, and sea level rise[1], as well as the spread of epidemics and economic volatility. These shocks, in conjunction with unsustainable urban developments, pose challenges for cities, exposing their vulnerabilities and inadequate management paradigms[2,3]. For example, extreme water shortages in São Paulo have resulted from a confluence of increasing water demand, encroachment on urban watersheds, and deforestation in the Amazon[4,5]. These shortages have different impacts on urban dwellers in central and peripheral neighborhoods, disproportionately affecting already marginalized communities[6]. They are also a harbinger of future climate impacts on the city as a whole[7].

The functioning of cities depends on complex and interdependent social, ecological and technological systems. Citizens access water, electricity, food, health, and other services through complex networks of technological infrastructure and institutional arrangements that obscure the relationship between urban resource provision and the ecosystems that sustain them. The interdependencies in these systems mean that shocks can reverberate broadly, creating unanticipated and cascading crises. Shocks can propagate along supply chains, mobility networks, and across sectors, such as finance and health, and from local to global and back to local levels through non-linear feedback mechanisms[8]. For example, hurricanes hitting cities on the southern US coastline reveal the interdependencies between extreme weather events exacerbated by climate change and critical infrastructure systems and the sensitive ecological context in which they are situated. New Orleans has repeatedly seen the simultaneous breakdown of water supply, drainage services, and transportation networks, due to electricity system interruptions in response to coastal and riverine flooding or other storm impacts[9]. Furthermore, the poisoning of soil, water, and air from flooded and damaged oil refineries and other heavy industries disproportionally impacts marginalized communities because of pre-existing housing and insurance regulations[10], as well as the region's ecosystems. Similarly, the Covid-19 pandemic left cities scrambling to respond to an unprecedented health crisis, but also knock-on economic effects that led to shortages of jobs, affordable housing, and food[11]. These multi-hazard events and cascading crises, and their intersection with systemic racism and other environmental justice issues, highlight the need for coordination across sectors and scales. Furthermore, cities are embedded into international trade networks that deliver goods and services from around the globe[12]. Decision-making at the local scale therefore has the potential to influence resilience and sustainability both locally and globally[13–15].

Coordination across complex and interdependent urban systems requires adequate forms of governance. Since almost all future population growth is projected to be in urban areas, identifying which governance arrangements allow for inclusive decision-making, management, and planning, while allowing for system-wide transformations, is crucial not only for the well-being of urban dwellers but also for achieving climate goals and maintaining the biosphere[16]. Despite the urgent need for governance aimed at increasing urban sustainability[1], there is limited research on the complexities of governing urban systems across sectors and scales[17]. Adequate frameworks and guidelines for how to govern such systems could help close the gap between the normative goal of urban sustainability across scales and the

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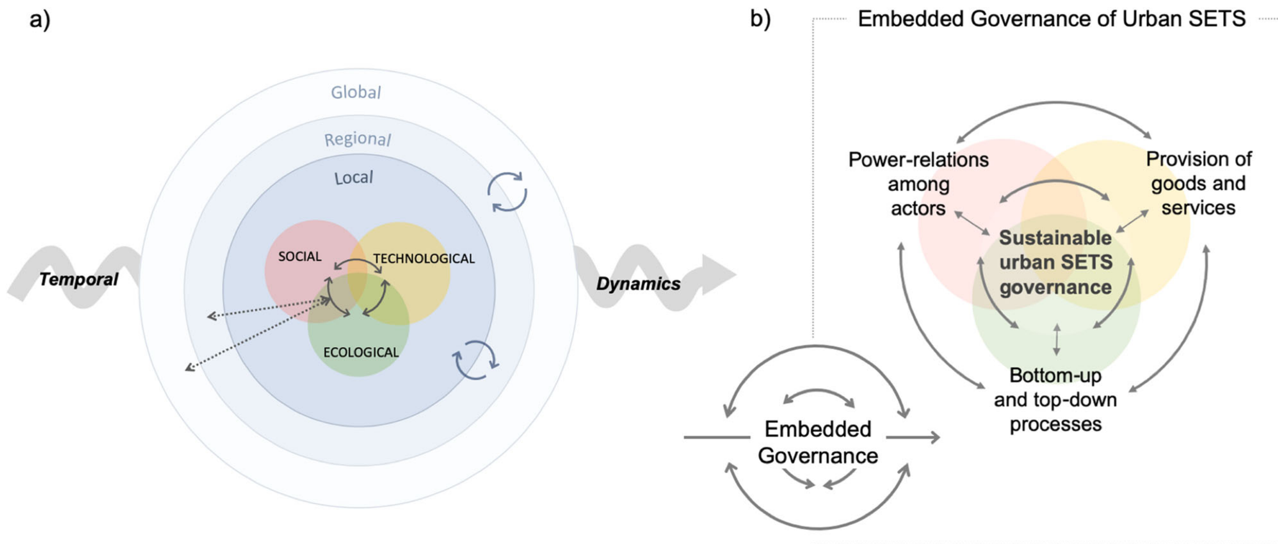

Fig. 1 Governance of Urban Social-Ecological-Technological Systems. a Dependencies across time and space. Shocks and stressors have the potential to impact one or all elements of the SETS across spatial scales, and determine the evolution of the urban system (arrow 'Temporal Dynamics'). Figure adapted from[175]. **b** Embedded Governance: Embedded actors and SETS elements interact to shape the governance of urban SETS, negotiate the interfaces of the SETS elements, and coordinate transformation processes towards sustainability across spatial and temporal scales. We focus on three interacting elements of particular importance: (1) Equitable and reliable access to resources in urban areas ('Provision of goods and services'). These are an important basis for urban livelihoods and for inclusive social, economic, and political processes to take place. (2) The interactions of bottom-up processes and economic activities with top-down efforts by government actors ('Bottom-up and top-down processes'). A balance between 'top-down' and 'bottom-up' dynamics can enable local innovation and experimentation to result in systemic transformations. (3) 'Power-relations among actors' determine the choice of policies, the distribution of resources and social influence, and thus, the trajectories of urban SETS. Arrows in (**a**) and (**b**) represent the embeddedness of governance.

need to ensure resilience to shocks with on-the-ground practices[18,19].

While the concepts of resilience and sustainability are often used interchangeably, it is important to make the distinction between the two[3,15,20]. Resilience describes the perseverance of a system and its functions, especially its ability to recover from and reorganize in response to disturbances[3,21]. Resilience can therefore also describe systems in an undesirable regime (e.g., resource-intensive or socially unjust), where overcoming unsustainable practices is impeded due to the system's resilience. Resilience approaches focus on the process of responding to disturbances, and building adaptive capacity to cope with unknown shocks and stressors[22,23]. Sustainability, on the other hand, is grounded in the maintenance of the biosphere, which is critical for human well-being and societal development[3], and the equitable distribution of resources and services for current and future generations. Sustainability requires balancing societal and ecological goals across scales and over time[20,24]. It also requires transformative capacity—the ability to create fundamentally different human-environment interactions when a current system becomes untenable[25]. Sustainability approaches integrate normative values and anticipatory thinking to identify desirable future options and strategies to attain those options[24,26,27].

Governance refers to the ways in which individuals and organizations, public and private, manage their common affairs[28]. The *process* of governance (or the act of 'governing') encompasses *"the activities of social, political, and administrative actors that can be seen as purposeful efforts to guide, steer, control, or manage the pursuance of public goods"*[29]. The governance process is not limited to public goods and services, but also private goods, common-pool resources, and club goods. Governance of sustainability transformations must combine resilience and sustainability approaches[24]. This requires identifying and setting sustainability goals, facilitating the process of achieving these goals through proactive planning, learning, unlocking, and overcoming undesirable system states and path-dependencies[30], while also anticipating and responding to unknown shocks and stressors[22,23]. Under certain conditions, socio-political shocks and natural disasters may provide a window of opportunity for transformative change[31,32]. Proactive governance may be able to harness these opportunities by responding to changing pressures and steering urban transformations towards sustainability[31].

In this review, we synthesize recent literature on the governance of urban sustainability transformations from a social-ecological-technological systems (SETS) perspective[33,34]. The conceptualization of cities as urban SETS highlights their complex and interdependent nature, the particular governance challenges this poses, and the importance of identifying governance structures that are able to coordinate across distinct sectors, spatial areas, and time. We bring together literature on sustainable resource management and service provision, social processes and transformative capacity, and governance and power relations among actors. The academic fields that this literature review integrates typically operate in isolation. However, their integration is crucial for enabling a deeper understanding of systemic urban sustainability transformations, as they provide insights into different aspects of the transformation of urban SETS.

The remainder of this article is organized according to the elements of Fig. 1. In section 2, we introduce the concept of interdependent urban SETS across scales (Fig. 1a), and the role of governance in determining the evolution of urban SETS. Sections 3-5 represent the three elements in the outer circle of Fig. 1b: In section 3, we review innovations in sustainable resource management and service provision, which are fundamental to urban livelihoods, and require effective coordination across sectors and scales. In section 4, we turn to the role of 'bottom-up' experimentation for building sustainable and resilient communities, and the interplay between bottom-up and top-down efforts in initiating and enabling transformation processes. In section 5, we discuss the role of polycentric and multilevel governance arrangements, power-relations among governance actors, and the importance of governance 'embeddedness' in sustainability transformations. We summarize the elements of Fig. 1 and how they relate to the sustainable functioning and transformation of urban SETS in section 6. We conclude in section 7.

Urban social-ecological-technological systems across scales

Our definition of 'urban' includes formal and informal settlements within a metropolitan area, as well as the footprints that an urban area produces through its supply chains and emissions. Thus, the spatial and institutional boundaries of 'urban' vary depending on the particular governance issue being considered. For example, the planning of bicycle lanes in a city has different boundaries than the issue of urban food security, which includes regional and global trade networks.

Considering cities as SETS, and governance as embedded within these SETS, foregrounds the interdependencies, tradeoffs, and feedbacks across system elements at different scales and the implications of these dynamics for sustainability transformations[16,34,35], as depicted in Fig. 1. Ecosystems include forests, oceans, rivers, lakes, groundwater, soils, and the atmosphere, which provide resources, including water, food, fuel, fiber, and other ecosystem services. The ecosystem dimension of SETS also includes the space or land that support urban economies and on which cities are built. The social system represents relevant actors and their interactions, including state authorities and agencies, individuals and civil society organizations, academics, business actors, and others, who gather information and make decisions over how to access and distribute resources, manage ecosystems, organize SETS in space, and consume or utilize the goods and services provided by ecosystems. The interactions among actors are mediated not only by norms, rules, culture, and power dynamics, but also by their ecological and technological environment. The technological system, or physical infrastructure, includes buildings, facilities, and infrastructure networks, which transport flows of resources, people, and information, and which mediate the interaction between ecosystems and social actors.

One example of social-ecological-technological interactions is flood protection infrastructure (technological), which is planned and designed by decision-makers and built to protect urban populations (social) from storm surges, riverine flooding, and rising sea levels in coastal and riparian areas (ecological). Another example of SETS interactions that highlights the broad spatial dependencies are food supply chains. These include soils, water, plants, animals, and energy from the sun (ecological system), infrastructure deployed for planting and harvesting, for processing and storage, and for transportation and sale (technological), as well as the people involved along the supply chains and the citizens who depend on the delivery of food into urban areas (social system). Sustainable governance of these systems must ensure the inclusivity of the design and planning process, as well as the equitable and ecologically viable production and distribution of these goods and services.

Governance, as defined here, determines the evolution of the SETS as a whole: how people live together and how they live within their social-ecological-technological environment, or, to take the specific examples from above: what types of flood protection measures are chosen, who is involved in the decision-making process, what type of food is grown where, for and by whom, using what technologies. Governance tools extend beyond formal laws and regulations to include informal and collective action mechanisms, such as access to reliable information, effective communication, monitoring and sanctioning of rule-breakers, and processes for resolving conflicts[36,37]. They also include nudges or messaging to promote more sustainable behaviors, the creation of 'enabling environments' for bottom-up processes and social movements, the building of adaptive capacities, and participatory mechanisms of co-production and management[24,38–43], among others.

Governance is also highly context- and path-dependent[44,45], which is reflected in the diversity of sociopolitical and governance regimes around the world, the way in which cities are planned and built, the inclusiveness of the political process, and the distribution of resources, rights and services to citizens. That said, quantitative research has also identified regularities in how cities evolve across scales. This body of work has identified a set of scaling relations that can be used to predict the social, spatial and infrastructural properties of cities of different size and at different levels of development, and to inform urban planning strategies[46–48].

A sustainable governance system is able to anticipate and buffer temporal dynamics that arise from internal change processes or external pressures, and can adapt the urban system to ensure inclusive processes in determining how goods and services, such as transportation and health[49], are provided. When critical links within the governance system and essential mechanisms of governance are missing, or when shocks are unanticipated, they can lead to catastrophic and cascading effects. For example, adequate anticipation, proactive and inclusive planning, and learning could make coastal cities, such as New Orleans, more prepared to respond to repeated hurricane threats. Tighter cross-scale and cross-level feedback loops, for example, between different cities, countries, and sectors, as well as anticipatory planning could have avoided some of the detrimental impacts of the Covid-19 pandemic and measures introduced to mitigate its spread[50].

Furthermore, efforts that do not take a holistic, cross-scale, and cross-level view but endeavor to transform one part of the system, may meet resistance, tradeoffs or unexpected responses from other system elements and scales[35]. For example, decisions by governments and private actors to reduce greenhouse gas (GHG) emissions has led to remarkable technological developments along the entire supply chain of production. As a case in point, in 2015, Apple partnered with its suppliers in China to install two gigawatts of renewable energy, reducing its supply-chain GHG emissions[51]. This shift in energy supply may entail other externalities. For example, the mineral resources required for a renewable energy transition are unevenly spread across the globe and require intensive, disruptive, and often exploitative mining practices[52]. The company, while improving its carbon footprint, has also been criticized for massive human rights abuses, including labor forces drawn from so-called 're-education camps' for Uyghur people[53]. So, while a more conscious (urban) customer base is pushing powerful actors to address climate pressures through technological innovations, the abuse of labor rights and the existence of low labor standards remain unaddressed due to the disconnect between urban consumption and the production processes occurring in distant locations.

The imbalance across different domains and dimensions of sustainability goals can be exacerbated by policies or incentives that are narrowly focused on one of the SETS elements rather than simultaneously considering sustainability across social, ecological, and technological systems. Therefore, sustainability transformation goals and processes should consider all of the SETS elements, including how they are embedded across sectors and scales.

Sustainable urban resource management and service provision

Home to the majority of the global population, cities are the largest consumers of natural resources, and the largest producers of CO_2 emissions and other environmental pollutants[54]. Thus, the way in which cities manage their resource demands and flows is decisive for the sustainability of urban areas, including the global ecosystems they rely on for the delivery of their goods and services. Conventional urban systems operate linearly: resources are extracted, used, and released as waste into the environment[55]. For example, cities access energy through extensive networks[56];

extract industrial and construction materials, such as metals and sand[57,58]; import food from across the globe[59]; reach hundreds of miles to extract water from distant rivers, lakes, and groundwater bodies[60]; and release pollution, such as domestic and industrial wastewater (with limited treatment) back into the environment[61,62]. These linear urban supply systems lack the necessary feedback between ecosystems and consumers to signal when ecosystems are being degraded or overexploited[63,64].

In contrast, cross-sectoral approaches focus on the synergies between the inputs and outputs of different sectors[65]. Systems of reuse and recycling[66,67] have been deployed to address the problem of scarcity, such as implemented for Windhoek's water supply system (Namibia)[68], and in Singapore's NEWater recycling system, both of which redistribute treated wastewater to customers[69]. Networked systems of water, energy, and food (WEF) can produce mutual benefits from their coordinated management[17,70]. WEF nexus approaches link the wastewater sector with agriculture through treated wastewater used in irrigation and recovered nutrients for the fertilization of crops[71]. Wastewater-energy co-benefits occur, for example, through the methane released from sewage sludge, which can be used for electricity production, such as implemented in Berlin (Germany), Melbourne (Australia)[72,73] and urban China[74]. Food-energy co-benefits include the biodiesel produced from used cooking oil[75] by several companies in North Carolina (USA)[76]. These cross-sector systems require intense coordination among social actors, ecosystems, and technologies[16,35]. For example, water suppliers and wastewater managers need to coordinate to ensure that water brought to the city and turned into wastewater can be adequately treated and discharged, and that the nutrients and biosolids extracted from sewage sludge adhere to quality standards to avoid soil and crop contamination (e.g., heavy metals contained in wastewater can contaminate agricultural soils, rivers, and groundwater).

The circular economy (CE) and related concepts, such as urban metabolism, industrial ecology, cradle-to-cradle, material flows and life-cycle analysis, are recurring themes in the urban sustainability literature that stand in contrast to conventional, linear systems[17,77,78]. These CE approaches are gaining attention in both Global North and Global South cities[79–81]. Narrowly defined, the CE describes systems that reduce, recover, reuse, and recycle resources and materials across sectors[19], similar to the networked WEF nexus. Other interpretations of the CE include well-being and inclusiveness as goals, and the need for a radical transformation of society, including shifts in mindsets and norms, policy-making, and business models, in order to decouple economic growth from resource consumption[18]. Safe and just operating space models[15,82,83] combine ecological limits (i.e., the Planetary Boundaries[84]) with societal well-being. These approaches recognize that climate change and degrading ecosystems have disproportionate impacts on the urban poor, and, like other shocks, have the potential to increase existing inequalities[85]. Thus, building transformative capacity for climate adaptation planning and implementation must address existing inequities, unmet needs and the adaptive capacity of the urban poor[86].

Different social and political contexts take different approaches to addressing sustainability challenges. For example, China and Europe are leading the way regarding the adoption of circular city concepts, albeit with different drivers (i.e., governmental or 'top-down' in China vs. societal or 'bottom-up' in Europe) and implementation strategies (i.e., technological innovation vs. socio-technological and socio-ecological approaches)[67]. In China, the introduction of laws and financial incentives related to the CE and the resulting implementation of streamlined technological processes increased resource efficiency by 35% and reduced waste intensity by 47% between 2005-2013[87]. European strategies have developed from increasing material efficiency, similar to those implemented in China and elsewhere[87], to broader and more diverse efforts initiated at the sub-city and other levels of governance. These include urban living lab initiatives, social and industrial start-ups promoting and implementing CE approaches in various domains, including urban agri-food, textiles, plastics, recycling of building materials, water, mobility, and others, supported by civil society organizations that provide advice about the CE[67]. European CE efforts and related discourse thus extend beyond material flows to include the development of social, inclusive and collaborative values, green identities, sharing economies, and community gardens and spaces for creative exchange[88]. Such initiatives involve actors across levels, including businesses, non-governmental organizations (NGOs), state-level actors, and civil society, and, depending on the specific goals of resource flow efficiencies or community development[88], are characterized by different levels of integration of SETS elements.

Different approaches to the CE also reflect distinct origins, with some approaches emerging from the natural/engineering sciences and others from the social sciences. There is an ongoing convergence of CE concepts across different disciplines. Thus, much of the recent academic literature adopts holistic and transformational concepts of circularity, which include material flows, equity, justice, inclusion, and a balanced distribution of power in their definitions[18]. In contrast, governments and practitioners often define CE in technocratic terms. In both interpretations, the ability of the CE to achieve sustainability goals faces several fundamental challenges, such as the decoupling of economic development from consumption; rebound effects resulting from increased resource efficiency;[89] and resource tradeoffs in the bioeconomy, such as the use of biofuels, which in some cases can be more environmentally damaging than fossil fuels[18,90].

Many urban sustainability efforts focus on local improvements in ecosystem protection, which are often achieved through the outsourcing of production and polluting industrial processes to other regions or countries, such as the case for feed crop production and heavy industry[59,91], or focus on only one aspect of sustainability (e.g. GHG emissions) at the expense of others, as in the example of Apple discussed in Section 2. However, goods also flow into urban areas as indirect resources. Water is embedded in imported energy, and water and energy are embedded in imported food[14,92], resulting in large ecological and water footprints[15] and climate impacts. CE and WEF nexus approaches can lead to certain efficiency improvements, and recent, high-level policy developments, such as the European Green Deal and the US Green New Deal, contain elements of the CE, with implications for urban resource management. However, many practical challenges remain, including social and technological barriers and a dearth of legal and political frameworks to guide implementation of the CE[19,93]. Furthermore, reducing the footprints of consumption will ultimately require behavioral changes, such as shifts from meat- to plant-based diets[94–96]. These will in turn require carefully and holistically designed policy and governance interventions, such as the realignment of subsidies, price floors, trade regulations, and pricing of externalities to favor plant-based diets, as well as efforts to emphasize the link between food production and consumption[97]. Governance mechanisms that prioritize inclusive policy and decision-making arrangements can bridge bottom-up behavioral changes with top-down incentive structures and regulations. Broader definitions of sustainability goals that account for cross-scale and cross-sector interactions are needed to avoid externalities resulting from outsourcing and problem-shifting.

Bottom-up and top-down processes in urban sustainability transformations

Different governance contexts will favor technocratic or social innovations, and will determine whether these are implemented through top-down control, emerge from bottom-up initiatives[98], or result from a mix of the two. Urban SETS planning influences not only the efficiency of land and resource use, CO_2 emissions, public health outcomes[99], and the resilience of cities to climate impacts[100]; it also has major implications for socio-political processes, such as the emergence of local interest groups and social movements, and the equity and inclusiveness of urban development[101]. Both spatial planning and large-scale technology implementation in the urban context, often top-down processes, can enable or suppress transformative forces in urban settings. Throughout history, this has been demonstrated by the important function of physical urban spaces as places for congregations and the voicing of public demands, but also for the suppression and segregation of social groups[101]. For example, the restructuring of Paris after the French Revolution aimed to make it easier to control the urban population and quench potential uprisings[101]. Similarly, after the demonstrations and political upheavals during the 'Arab Spring', Cairo's Tahrir square went from being the main square for public congregation to a camera- and police-patrolled, traffic-regulated space in which gatherings are prohibited. Online media platforms (new technological systems) have also had a critical role in the emergence of socio-political movements, but also the control of political opinions[102,103]. This has been demonstrated by the role of the Facebook and Twitter platforms in the mobilization of civil society in the Arab Spring movements and global Black-Lives-Matter protests, as well as right-wing supporters of former US president Trump. The role of space ('ecological systems') and technology in mediating social relations is critical for understanding the emergence of bottom-up processes, as well as the interaction between bottom-up and top-down processes, in overcoming the status quo and driving sustainability transformations.

Lock-in is often related to the durability of urban infrastructure systems and the legacy effects of the built environment, including buildings, facilities, roads, and water and electricity supply networks; but it can also characterize entrenched political systems, formal and informal institutions, and social discourse[104]. This observation has prompted renewed attention to the question of which social dynamics can lead to transformative change, and the relationship between social tipping and ecological Earth system processes[40,105]. Social tipping points describe abrupt shifts in social norms or patterns of behavior[40]. The tendency for social conformity[106] means that, under certain circumstances, localized policy interventions, messaging by formal institutions[38], or bottom-up experimentation and innovations can trigger widespread changes in values or behaviors[40,105,107]. However, it must be recognized that social conformity can also work to undermine collective benefits, as was demonstrated in the fascist era during the first half of the twentieth century.

One focus of the urban sustainability transformations literature is on identifying enabling environments for local experimentation as a potential way to overcome path-dependencies and lock-ins that rigidify the status-quo[108]. This 'urban tinkering' approach emphasizes the role of bottom-up, distributed change and the need to engage a range of social actors in the continuously unfolding process of urban SETS transformations. This perspective of the urban transformations and sustainability science literature[24] has parallels with adaptive ecological systems, which are characterized by diversity, open exchange, modular organization and redundancy[109]—features that can increase adaptive capacity. Bottom-up initiatives generate these characteristics by building on the creativity and diverse knowledge of unique sets of local actors working together to develop context-specific approaches and solutions. These local initiatives and institutions create modular structures, which can operate separately, but work best when they are interlinked to a moderate degree to facilitate coordination and exchange[110]. Diversity, redundancy and modularity contribute to general resilience by enhancing buffering capacity; that is, by dampening the spread of disturbances across modules[111,112].

Different capacities are needed during distinct phases of an urban transformation, including, among others, the ability to dismantle drivers of unsustainable practices ('unlocking'), and the ability to create innovations that contribute to sustainability and resilience, and to embed these innovations in governance structures, practices and discourse ('transforming')[113]. Furthermore, social learning and reflexive stakeholder action are important to ensure that transformative processes remain adaptive and aligned with evolving sustainability goals[114]. Social or collective learning is particularly important for managing the multidimensional contingencies of urban SETS, which require the integration of knowledge across scales and sectors, and are difficult for any single actor or entity to grasp[115].

Enabling conditions and capacities for local governance at the urban scale vary vastly, even under seemingly similar democratic regimes. For example, cities in India, Brazil, and South Africa, the three largest democracies in the Global South, had strikingly similar spatial and social forms in the 1980's, marked by high levels of inequality and state-sanctioned differentiated citizenship with unequal access to formal housing and basic services[116]. In the 1990's, all three countries implemented reforms aimed at decentralization, which shifted power from the central state to the municipal level, in order to promote more participatory forms of governance[116]. The degree of state-civil society embeddedness and different dynamics between top-down and bottom-up processes have led to significantly diverging developmental outcomes. India remains largely elite-dominated and controlled by the central state with very weak local capacity for governance and autonomy, and unequal and often poor outcomes for basic service provision, including access to housing. South Africa is characterized by strong capacities of local government, but remains technocratic, centrally controlled and fragmented by design of the apartheid regime, including only certain segments of the population in governance processes. In contrast, Brazil is characterized by strong, autonomous local capacity and broad-based, participatory governance processes. While not without challenges, and with significant heterogeneity across cities, more inclusive and empowering policies, such as new legal instruments that regularize 'squatted' land in informal settlements, have enabled the extension of infrastructure services and the improvement of living conditions in historically neglected neighborhoods[116].

Certain environments or junctures in time may create enabling conditions for the emergence of small-scale experimentation or interventions. These may, incrementally or abruptly, alter established paths and act as building blocks towards transformative change[40,117,118]. The existence of public spaces as meeting points, including community gardens, public parks and squares, such as the Tahrir Square prior to its closure to the public, and central Paris until its transformation after the French Revolution, may stimulate sociopolitical debate creating new narratives and ideas for change, and, through a sense of shared concern or interest, promote the emergence of community organizations and a local public sphere[119,120]. Resulting efforts, locally adapted, socially inclusive, decentralized initiatives can play a key role in urban sustainability transformations[121].

The COVID-19 pandemic has shown that rapid and large scale reorganization of daily life is possible, at least in the short-term. Many governments worldwide enforced social distancing measures, and closed their borders and 'non-essential' parts of their economies to mitigate the spread of the virus. These were enforced as top-down measures. While economic activities and associated carbon emissions are quickly returning to normal, such shocks can temporarily destabilize entrenched practices and narratives, potentially creating a critical juncture or 'window of opportunity' for institutional reform and systems change[32,122]. For example, COVID-19 drew heightened attention to many pre-existing social inequities and the inadequacy of existing social welfare, as well as the lack of preparedness by many urban areas to address a crisis on this scale. This, as well as compounding pressures from extreme weather events, have led to calls for improved healthcare, social safety nets, and broader sustainability transformations[123,124]. At the same time, the pandemic itself has also created growing inequality within countries and globally[125]. Unfortunately, systemic shocks can result in increased inequality, unless specific governance structures and mechanisms for reducing inequality are in place before and during such 'windows of opportunity'[85]. Whether disruptions such as the pandemic become critical junctures for positive systemic transformations or instead accelerate existing unsustainable trends depends critically on proactive governance responses, and the structures that allow or prevent those responses from effecting wholistic change[8,31,126] and avoiding maladaptation[31,127]. In contrast, transformational change can also be continuous, rather than spontaneous and disruptive, but requires a transformation of the governance system itself[128]. This relates back to the discussion of capacities and enabling conditions for sustainability transformations discussed above. Rather than transformed through an outside force, such as an epidemic, or through technical interventions, transformational change from within the governance system is achieved through deliberative acts that focus on changing the governance process that enables emergence, adaptation, and implementation of new paradigms, i.e., how things are done, rather than what is done[128].

Theories about the enabling conditions for urban transformation often depart from the on-the-ground reality of urban governance. Sectors are often managed by siloed entities, disconnected across sectors and spatial scales[113]; local sustainability initiatives (bottom-up) are often fragmented, lack funding, and rely on engaged individuals, which creates obstacles for lasting impacts and system-wide transformations[119]; and government initiatives (top-down) are typically short-term and responsive rather than long-term and mitigative, anticipatory or preparatory[113]. In the following section, we discuss the importance of governance structures that are able to create bridges across sectors, spatial scales, and institutional levels.

Power relations and embeddedness of governance in urban SETS

Power relations and embeddedness can be critical factors in determining whether bottom-up and top-down initiatives are able to transform urban SETS[116,119,129]. In this section, we focus on the relationship between the embeddedness of governance, power relations among actors and the sustainability of urban systems. The scholarly literature describes embeddedness as the interdependence and relations among societal actors, and links the concept of embeddedness with those of capacity and agency in governance processes[116,130]. Embeddedness forms the basis for coordination, conflict resolution and addressing collective action problems. The degree of embeddedness and the connectivity of actor relationships across sectors and levels of governance can be crucial for ensuring an inclusive political process in urban settings[116].

The relational quality of embeddedness is tightly connected to the relational concept of power[130]. Relational power is understood to be incorporated in social practices, embedded in social-ecological-technological relations, and productive, meaning that it "*shapes, creates and transforms social relationships, practices and institutional arrangements*"[130,131]. Recent scholarly work integrating complex adaptive systems thinking with the governance of sustainability transitions recognizes the need for a concept of power-relations that is based not only in the interactions among social agents, but also in SETS interactions[130]. We use the term embeddedness to refer to the relations among governance actors across levels and sectors and their relationship with ecological and technological elements in the urban system.

Governance can be structured in diverse ways. Polycentric (PG) and multi-level governance (MLG) structures have received substantial attention in climate governance discourses[29,37,110]. Both PG and MLG are used to describe the interdependent, multi-level and multi-scalar nature of governance and the overlapping decision-making authority of relevant actors. The focus of these approaches on the interdependence between stakeholders at different levels and scales is particularly important for the conception of cities as dynamic SETS. Locally embedded, self-organizing structures are emphasized in PG. Bottom-up, modular PG systems with cross-level and cross-unit linkages can benefit sustainable and equitable resource management by increasing institutional fit, and enabling mechanisms of mutual monitoring, learning, accountability and conflict resolution, and increasing adaptive capacity[37,110]. Thus, PG is particularly important in the context of resilience and sustainability of urban SETS due to its focus on interactions across units of governance and on local contexts, which enables anticipation, learning and adaptation. MLG accounts for the increasingly international context of policy and administration, and emphasizes the redistribution of power and control away from the state. This redistribution occurs in three directions: (1) upwards to international actors and organizations, (2) downwards to cities, regions, and communities, and (3) outwards to civil society and non-state actors[29]. The process of globalization contributes to the redistribution of power, a change in the focal scale of governance from local to global, and can lead to a disconnect between policy design and implementation and the local context. Thus, the relationship between MLG and PG is especially relevant for urban governance, which must take into consideration both local and global sustainability issues.

Governance of urban sustainability transformations is often associated with democratic, inclusive, multi-level, and multi-scale characteristics[132]. The degree of embeddedness varies across contexts. In Europe local initiatives and authorities collaborate with state, business, non-governmental, and academic actors and organizations at the local, sub-national, national, and European scale[88], ensuring a certain extent of governance embeddedness at horizontal and vertical scales. In the federal system of the U.S., states are important actors in the design of environmental policies, some of which can be implemented and enforced at the local level. States with large enough markets can also shape industries and drive national standards, as in the case of California leading automobile emissions standards, as well as pioneering air pollution and plastic waste policies[133,134]. In India, cities have limited capacity for local self-governance in part due to a lack of cross-level embeddedness between the central state, municipalities and civil society and a highly skewed distribution of power concentrated in the central state[116,135].

Embedding governance vertically, from within the city up to the regional and global levels, and horizontally, across sectors, cities and regions, can help ensure that local sustainability improvements are not achieved at the cost of global sustainability[15,136]. Furthermore, voluntary coalitions—such as international city networks like ICLEI, C40, or the World Mayors Council on Climate Change—enable the sharing of information, the spread of innovations, and strengthen governance capacity and the potential impact of bottom-up or decentralized efforts[137]. City networks have existed since the early 1900s, but have proliferated in the past 30 years into a broad ecosystem of over 200 global partnerships between local authorities[138,139]. These range from publicly to privately initiated and from public membership networks to ones that include multiple types of stakeholders. In recent years, they have begun to play a pivotal role in defining and making progress towards global sustainability agendas, in part due to the increasing acknowledgment that decisions at the urban scale drive many global change processes[140,141]. Theory based on model analyses also predicts that these voluntary coalitions will be more successful in addressing climate change and other global sustainability challenges than efforts to achieve global consensus among national players[142,143]. These networked urban governance systems support sustainability initiatives through mutual efforts towards agreed upon goals, such as emissions reductions, but also by facilitating knowledge co-creation and dissemination through the systematic organization of learning across locales, and by offering institutional support[144,145]. In general, decentralized initiatives that are embedded in broader coalitions can generate a diversity of responses to sustainability challenges, allowing those that are most successful to spread to other locations[41,119,146]. However, disconnects between civil society initiatives and the local state or other municipalities can limit the potential for the diffusion of innovation across locations[119].

Shifts in power and decision-making authority from public to non-public actors[147], typical of multilevel governance settings[148], can both strengthen and undermine the agency of citizens and cities to influence sustainability[149,150]. For instance, critical infrastructure systems around the world have been transferred from public authorities to private actors. This has often compromised social inclusion, for example, by limiting access to healthcare for lower income groups in Europe and South America[151–153]. Similarly, the management of local infrastructure services, such as water supply, by transnational corporations has increased social inequities and negative ecological impacts[154–157]. Thus, while diverse public and private governance actors have the ability to usher in sustainable change[51,158], shifting decision-making authority can also result in the concentration of power in private, political and economic elites at different scales. This can lead to policy capture and vested interests, which entrench high-carbon trajectories, instead of enabling transformations through participation and inclusion[24,129]. Strengthening governance embeddedness between the state, civil society and private entities can help maintain the balance of power among actors that is needed for sustainable urban development and transformations[116].

While governance interventions may aim to address climate risk, the sustainable management of natural resources, and social inclusion, their effectiveness depends on the vertical embeddedness of local governments with civil society and with higher level authorities at sub-national, national and international levels. For example, local actors in the Aburra Valley (Colombia) created an inter-city risk response network to address the increasing vulnerability of growing numbers of urban dwellers in areas at high risk of flooding and landslides. This horizontally and vertically embedded PG structure includes civil society, local and national government, international city networks, and international organizations and requires high levels of trust among these actors[159].

Governance inevitably requires attention to multiple issues and constituencies, and the prioritization of certain goals and values over others[160]. Inclusive, deliberative decision-making processes, such as multi-criteria decision approaches, can be used to explore synergies and tradeoffs between technological, social and ecological objectives[161]. A critique of such decision-making processes is that addressing climate change requires urgency and pragmatism. In addition, accounting for multiple interest groups increases the complexity of decision-making, increasing the time-, resource- and data-intensity as well as delays due to contested (political) interests that must be addressed by more transparent processes[161]. However, attention to power dynamics and measures that increase accountability and protect vulnerable populations are crucial. Participatory governance approaches aim to redistribute power by equitably involving diverse actors in the planning, decision-making and implementation of policies[162]. For such inclusive systems of governance to be successful, the incorporation of a range of judicial, popular, and political safeguards are needed to ensure lasting cooperation among actors and avoid opportunism and power imbalances[163]. For example, New York City's water supply system relies on a set of institutions that ensure the balance of power among diverse actors, including local civil society, municipal, state, and federal government actors. Within this institutional framework the involved actors must continuously negotiate their various interests[163].

The sustainability of urban SETS requires the social actors involved, including state and non-state actors, to assume critical roles of governance[164]. Central to the role of the state and other actors in a regulatory or management position is the ability to manage uncertainty, maintain the rule of law and order, coordinate policies, and redistribute wealth, resources and opportunities[165]. To ensure that this 'state power' remains within certain limits, non-state actors and civil society need to monitor and check the state and elites through political and public action, which creates feedbacks between civil society and the state[116,164]. When this state-society embeddedness is lost, power concentrated at the national or state level can lead to hollow local states, even in democratic contexts[116]. This can result in (and be reinforced by) inequitable public services, including water, transport, and public health, and the degradation of natural resources and the built environment, despite significant economic growth[116,166]. Indian cities, such as Chennai, are typical examples, in which only half of the urban population has access to water on their premises, soil and water pollution and resource decline are accelerating, leaving taps dry and rivers contaminated[167]. In US cities, too, such as East Chicago (IL) and Flint (MI), out-of-balance power relations and the lack of response to feedback between SETS elements have exacerbated social inequalities[168]. In Flint (MI), sustained lead poisoning resulted from corroding lead water pipes after the change of the water source. One the other hand, efforts that promote sustainability locally, such as investments in public transit, bike- and pedestrian-friendly neighborhoods, and urban green space, can drive up property values and lead to gentrification through private property investment. This can, again, have major implications for low-income residents[169–171]. In such cases, state regulation (top-down) can help maintain the social cohesion of neighborhoods undergoing sustainability transformations. The urban governance cycle shown in Fig. 1b illustrates the two-way links between the equitable provision of urban services, top-down and bottom-up processes, and the power relations of the governance system.

The provisioning of critical infrastructure services produces and maintains human well-being. It also conditions the ability of the state to provide legitimate order, facilitate effective economic development, and promote social inclusion[165]. In contrast, mistrust in the state and a rejection of state power and government can impede sustainability efforts[51]. In extreme cases, fragmentation of state-civil society contact can lead to the emergence of competing sovereignties, which can weaken the legitimacy of a central state[172]. For example, in many of the informal settlements housing the urban poor in Mexico City, a flourishing informal sector has replaced the state in providing sources of income, as well as basic infrastructure services, such as water and electricity. The state, focused on rapid macroeconomic growth rather than socio-political inclusion, tolerated the rise of the informal sector, whose leaders gained support and power by providing the services that the state failed to provide. Accelerated by increased violence and coercion emanating from the informal sector, the loss of legitimacy and erosion of the formal state has created a parallel rule by drug cartels[172]. Once eroded, regaining an inclusive governance system is a steep, uphill struggle. In contexts where trust, consent and reciprocity have been eroded, and 'relational tipping points' have been reached, governance must balance the urgency of ecological sustainability transformations with the slow process of rebuilding social relations[173]. These are crucial for sustainability efforts that are inclusive of marginalized populations, such as indigenous people[173].

In all of these examples, it is the governance context, its embeddedness with SETS interactions, and power dynamics, which provide the enabling (or disabling) environment for sustainability transformations to take place from local to global scales.

SETS transformations and the urban governance cycle

The growing gap between the normative goals and responsibilities of urban governance systems described in sustainability narratives and on-the-ground practice highlights the need for a more systematic understanding of how urban governance can facilitate coordination and transformation of urban SETS. In this last section, we discuss how the literature included in this review contributes to understanding the interplay of sustainable resource management and service provision, bottom-up processes and top-down interventions, and power relations among actors in the transformation pathways of urban SETS.

Sustainable provision of urban services. The way in which social actors employ technologies to interact with ecosystems and to extract and allocate resources are the basis for the provision of basic services, including water, energy, food, health, transportation, etc. As discussed in section 3, much of the empirical literature on the sustainable provision of services and resource management in linear, circular and nexus approaches is focused on achieving either environmental *or* social goals. Combining these goals requires addressing the pressures and stressors on natural ecosystems, including climate change and the degradation of global ecosystems, as well as the need for adequate access and just distribution of resources and services. Sustainable service provision is therefore not merely a question of circular material flows and the protection of ecological systems, but must also address social equity issues and cross-scale impacts on social, ecological, and technological system dynamics[174]. The multiple, entangled resource inflows and outflows of the urban metabolism, as well as various stakeholder interests, make defining and achieving sustainability goals a political challenge for SETS governance.

Bottom-up and top-down processes. Identifying promising paths for sustainability transformations requires processes of experimentation in the social, ecological and technological spheres. Bottom-up processes are particularly relevant in this context as they generate diverse and locally adapted responses. Embedded governance allows successful experimentation to be transmitted through social learning dynamics. As such, these bottom-up initiatives and voluntary coalitions can be crucial for overcoming lock-in and breaking path-dependencies. Local initiatives can engender widespread behavioral shifts and norm dynamics, which can in turn spread along horizontally interlinked city networks. Furthermore, as modular building blocks of polycentric governance structures, local, bottom-up initiatives that are interlinked across scales also provide system-wide redundancies and buffering capacities that are crucial during periods of change, including the recovery from shocks and transformation processes.

Governmental and other forms of top-down support are crucial for ensuring that adequate spaces for social exchange are maintained, and for promoting and upscaling promising local innovations that may help the transition to sustainability. Governments must also develop and uphold regulations to constrain power imbalances among actors and ensure the separation of legislative, judicial and executive powers. The built environment and (digital) technologies interact with these social processes, both through bottom-up movements and through top-down control. Widespread sustainability transformations can be triggered from the bottom-up if they are embedded in a SETS governance context and supported by structures that are built through bottom-up, top-down and multilevel interactions.

Power Relations among actors. Urban SETS are complex, cross-boundary, multi-scale systems, whose governance is best described as multilevel. The diverse ecology of actors in multilevel governance creates power dynamics that can easily become unbalanced if they are not safeguarded and protected in an anticipatory manner. The authority of cities in determining how to best adapt or transform in response to the diverse pressures resulting from internal change and external shocks depends on the distribution of power and the degree of embeddedness into several levels of vertical governance, including international, national, and sub-national levels. Within cities, vertical embeddedness and power relations describe the inclusivity of decision-making processes, which affects the degree of trust, consent, and the wellbeing of residents. How SETS interactions, service provision, and social processes evolve thus depends on the embeddedness of governance across the SETS elements and from local to global levels.

CONCLUSIONS

At the cross-roads of climate change, the decline of healthy ecosystems, rapid urbanization, and increasing socioeconomic precarity and vulnerability, human settlements must be prepared to deal with recurring shocks of increasing frequency and magnitude. We propose that an integrated, cross-scale perspective on the governance of social-ecological-technological systems enables a better understanding of what it takes to overcome the SETS challenges associated with urban sustainability transformations. We bring together perspectives from multiple disciplines, highlighting principles that contribute to the sustainable governance and the ability to move from unsustainable to sustainable regimes. Based on the discussions laid out here, we conclude with three main take-aways:

1) Sustainable urban resource and service provision must go beyond the management of material flows. It must make social equity issues and inclusion, as well as the impacts from the development and use of technologies, physical infrastructure and urban planning, an integral part of its planning and management. While initiatives addressing global sustainability challenges are implemented locally, they must account for cross-scale impacts of global supply chains and resource flows.

2) Building adaptive, flexible urban systems that are resilient to shocks and disturbances but also able to radically transform SETS interactions is paramount. Key to this are governance arrangements and top-down responses that encourage locally adapted, diverse responses to emerge from bottom-up initiatives. It is critical to recognize the role of the urban space and technologies in these processes. Interconnected in modular structures of polycentric governance, bottom-up initiatives can serve as seedbeds of scalable innovations and systemic change.

3) All stages of the urban governance cycle, including the equitable provision of basic services, the promotion of bottom-up initiatives and innovation, and the building of resilience to shocks and changing urban dynamics, require that the urban governance system is embedded across local, regional, and global scales. However, this embeddedness is only effective to the extent that power is evenly spread across actors and opportunism is avoided. This requires safeguards that monitor and correct the distribution of power at all scales, and the recognition that the future course of urban SETS is ultimately set by many implicit negotiations occurring among diverse actors with distinct priorities.

While we think that these principles are applicable across contexts, the exact form of the governance system, and indeed the desired form, will depend on local contexts and histories. Future research is needed to adapt this broad perspective to specific contexts. We hope that the interconnected urban SETS perspective put forth in this article offers a framework for urban case study analyses. Case studies built around this wholistic framework would provide insights into how the different elements interact to spur or hinder transformations towards urban sustainability in specific contexts.

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EHK and SMC share lead authorship. EHK formulated the initial concept, EHK and SMC revised the initial concept, reviewed the literature, wrote the draft, created the figures, edited and reviewed the final article. MAC, EUW, TE, and SAL contributed to the conceptualization, edited and reviewed the manuscript.

COMPETING INTERESTS

Co-author TE is Editor in Chief of npj Urban Sustainability.

ADDITIONAL INFORMATION

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