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A social-ecological-technological systems framework for urban ecosystem services

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Perspective

A social-ecological-technological systems framework for urban ecosystem services

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SUMMARY

As rates of urbanization and climatic change soar, decision-makers are increasingly challenged to provide innovative solutions that simultaneously address climate change impacts and risks and inclusively ensure quality of life for urban residents. Cities have turned to nature-based solutions to help address these challenges. Nature-based solutions, through the provision of ecosystem services, can yield numerous benefits for people and address multiple challenges simultaneously. Yet, efforts to mainstream nature-based solutions are impaired by the complexity of the interacting social, ecological, and technological dimensions of urban systems. This complexity must be understood and managed to ensure ecosystem-service provisioning is effective, equitable, and resilient. Here, we provide a social-ecological-technological system (SETS) framework that builds on decades of urban ecosystem services research to better understand four core challenges associated with urban nature-based solutions: multi-functionality, systemic valuation, scale mismatch of ecosystem services, and inequity and injustice. The framework illustrates the importance of coordinating natural, technological, and socio-economic systems when designing, planning, and managing urban nature-based solutions to enable optimal social-ecological outcomes.

INTRODUCTION

Urban areas globally are already home to 4.2 billion people in need of critical urban services to support urban livability and livelihoods. Further population growth challenges cities' ability to provide fundamental urban services that are equitably available to all. Urbanization differentially amplifies vulnerability and exposure to the hazards of climate change, and together urbanization patterns and climate change drive increasing urban risk and impacts.[1] Transforming cities and settlements to reduce these risks, meet the Sustainable Development Goals (SDGs)[2], build climate resilience, and provide sustainable living spaces for current urban populations and the additional 2.5 billion people expected to inhabit cities by 2050 will require significant upscaling of investment into diverse urban infrastructure.[1,3,4]

Conventional infrastructure design for the provision of urban services remains largely dominated by centralized gray infrastructure and technological efficiency.[5–7] Gray infrastructure—designed as fail-safe—is often at risk of failure due to age and a lack of adaptive capacity during increasingly frequent and extreme weather-related events.[8,9] To help overcome this infrastructure challenge, there is renewed interest in reconnecting, restoring, and designing nature into the built environment to provide a wide suite of benefits for urban residents, infrastructure, and economies,[10,11] which include climate-change regulation, local food production, recreation, human health, and many other benefits. Indeed, the International Panel on Climate Change (IPCC)[1,12], the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[13], the World Economic Forum[10], and many other recent reports from international bodies have emphasized the importance of such an approach and encourage the implementation of nature-based solutions around the world.

Ecosystem services have become an important framework for designing nature-based solutions that can mitigate the shortcomings of traditional infrastructure.[14,15] Ecosystem services have been defined in many ways but are fundamentally the benefits people and cities receive from ecosystems[16–18] and nature's contributions to people.[13,19] More recently, ecosystems in cities have been framed, acknowledged, and invested in as critical urban ecological infrastructure (UEI).[7] UEI, which comprises all ecological structures and functions including green (terrestrial vegetation), blue (aquatic systems), turquoise (wetlands), and brown (vacant, unvegetated) ecological infrastructure, has a powerful role, along with more traditional gray infrastructure, in improving lives in cities through its potential to supply ecosystem services.[7] We note that green infrastructure is a widely used term and has many definitions. Green infrastructure can be considered a subset of UEI and often incorporates ecological and built-engineered infrastructure components that provide social, ecological, and technological functions and benefits.[20] Urban nature-based solutions have emerged as a framing to leverage UEI.[21,22] Globally, enhancing ecosystems within cities is touted as a win-win solution for advancing sustainability and resilience.[2,12,23,24]

Despite the growing recognition of the importance of ecosystem services in the design of nature-based solutions, research and practice rarely use a systems approach to understand the contextual factors[25–27] that affect the production, demand, and management of ecosystem services. Multiple review and perspective articles have pointed out the challenges of mainstreaming nature-based solutions and the need for more systemic understanding and management of their social-, ecological-, and technological-infrastructure dimensions.[11,27–29] Ecosystem services and their benefits emerge as outcomes of dynamic interactions among components and dimensions of urban systems—including people, nature, technology, infrastructure, economies, politics, justice, and institutions.[30] As complex adaptive systems,[31,32] cities and urban regions are dynamic, highly connected (both within and between cities)[33], and full of contested spaces, including UEI. Studying, planning, or managing dimensions of urban ecosystems in isolation fundamentally neglects critical system interactions that influence ecosystem service production across multiple scales. It is only by working with this complexity that can we hope to achieve the ambitious goals we have for urban nature to help meet SDG targets and deliver the services we need.

For example, urban vegetation, such as street trees, require local management to provide cooling through shading and evapotranspiration with regional-scale impacts on the urban heat island and local-scale impacts that reduce heat stress to individuals.[34–36] Social, ecological, and technological infrastructure all interact to drive the cooling potential of trees and climate regulation across scales.[27,37] From a social perspective, land managers and environmental stewards enhance the efficacy of street trees in providing local cooling.[38] Young trees require irrigation,[34,39] and this requires both infrastructure and labor. Ecological impacts of non-native species in the system, for example through insect herbivory, can limit cooling potential. Transpiration—one of the most important ecological functions of urban trees—differs by climatic region, species, and leaf area,[40–42] and water-stressed trees may exhibit reduced cooling effects and transpiration when these processes are most desired during hot summer days.[36,43–45] The cooling effects of trees are dependent upon microclimate related to factors such as planting density, height, canopy area, and shade provision[36,46] and the influence of tall buildings that can shade vegetation, in turn reducing photosynthetic activity and evaporative cooling.[39,43] At the same time, trees that shade buildings can reduce building heat loads and energy consumption for air conditioning,[47,48] underlining the importance of urban infrastructure to cooling benefits. Ensuring that street tree benefits are maximized requires managing the social, ecological, and technological dimensions of street tree functioning. In the absence of a more holistic and systems-oriented approach to planning, designing, and managing UEI, we will not be able to supply critical ecosystem services effectively and sustainably over time.

In this perspective, we provide an interdisciplinary social-ecological-technological system (SETS) framework to understand and guide research and practice on nature-based solutions and urban ecosystem services to more explicitly integrate the many social, ecological, and technological factors that affect them. We offer testable hypotheses to accelerate future research with this system framing. Further, underlining the need for more holistic system approaches, we identify four cross-cutting challenges for managing, designing, and planning ecosystem services in the context of complex urban-systems dynamics. These challenges include (1) assessing the multi-functionality of ecosystems and their services and how to then maximize synergies and limit tradeoffs; (2) improving the valuation and potential substitutability of diverse services; (3) recognizing the importance of a spatial and temporal scale in the delivery and management of ecosystem services; and (4) including an explicit focus on equity and justice in the delivery and provision of services. Adequately addressing such core challenges requires more integrated systems approaches to improve the ability of ecosystems to provide ecosystem services and nature-based solutions for expanding challenges of urbanization and climate change.

URBAN ECOSYSTEM SERVICES CHALLENGES

Multi-functional challenges

Ecosystems perform multiple functions and thus provide "bundles" of multiple ecosystem services simultaneously.'[49–51] However, trade-offs may arise among different ecosystem services because not all co-benefits can be maximized at the same time, and disservices may be generated under certain scenarios.[25,52,53] Management choices to maximize individual social, ecological, or technological dimensions can modify the ecosystem services bundle by impacting the quantity, quality, or spatial and temporal distribution of benefits.[49,54] Yet, analyses of trade-offs and synergies have been mostly centered on the ecological dimensions of productive landscapes (e.g., agriculture) exploring trade-offs between provisioning and regulating functions.[55,56] These analyses often do not account for trade-offs and synergies associated with the services from other urban-system components important to the production of that service. For example, urban food production and the many co-benefits provided by urban gardens may be better accounted for by acknowledging the supporting social and physical infrastructure necessary to maintain food production and urban gardens. Thus, accounting for the many ecosystem-service synergies and trade-offs is challenged by lack of a systems approaches needed to improve management and effectiveness.

Valuation challenges

Ecosystems offer a variety of benefits that can be captured in diverse ways, including economic valuation in monetary[57] or other terms, assessment of their biophysical capacity to provide services, or understanding of their socio-cultural values.[18,58,59] Valuation studies often focus on built infrastructure solutions, with less consideration of the value of urban ecosystem services.[37] For example, the cost and efficiency of stormwater management may vary depending on support from green infrastructure (e.g., wetlands), gray infrastructure (e.g., pipes, water-storage facilities), and hybrid approaches (e.g., bioswales).[60–62] Urban wetlands can capture stormwater and provide habitat and recreation areas.[63,64] Green roofs contribute to both stormwater regulation and native bird habitats, but the quality of a rooftop habitat may not be valued similarly to a bird habitat in a wetland. Without improved understanding of the diverse values and substitutability of natural and human-made capital, decision-makers will continue to struggle to incorporate nature-based solutions into cost-benefit-driven decision-making. Additionally, substitutability studies often evaluate trade-offs between cost and efficacy but often only within single social, ecological, or technological dimensions, missing the opportunity to more comprehensively understand substitutability of services across system dimensions.

Scale challenges

The production of urban ecosystem services is dependent on the structure and function of multiple systems—social, governance, ecological, and infrastructural systems—and relationships between systems across spatial and temporal scales. However, mismatches in the spatial scale at which services are supplied, delivered, and needed can reduce the benefits received and impair effectiveness of ecosystem-services management.[65–68] For example, if green roofs, which provide local cooling, are not extensively implemented in high heat exposure neighborhoods, then local cooling benefits may be minimal. Further, some services are only supplied at particular points in time.[25] The heat-mitigation services provided by urban deciduous trees—providing shade during warm summer months—follow the seasonal demand for cooling. Food production in urban gardens also varies seasonally, with higher production in summers and low to no production in winter months, yet food demands remain constant year-round. Without accounting for the variation in ecosystem services supply and demand at different scales, it will be difficult to ensure that ecosystem services are produced where and when residents need them. Understanding how different systems dimensions interact with scale mismatches can help to support and maximize the effectiveness of ecosystem services across time and space.

Equity and justice challenges

Ecosystem services and their benefits are not distributed equally, equitably, or in a just way.[69–71] Urban physical form and the structure of social systems often drive inequitable access, management, and distribution of ecosystem services,[72–74] create legacies, and perpetuate environmental injustices.[75] While a substantial amount of research has investigated the benefits urban residents receive from ecosystem functions and services,[27,29,76] more attention needs to be paid to ensuring the equitable and fair access and distribution of those benefits.[77]

Social- and environmental-justice issues remain a persistent problem in cities such that low-income, minority, and immigrant communities have less access to and availability of services, including ecosystem services.[78,79] This has been strikingly demonstrated in Phoenix (AZ, USA), where the benefits of cooling from large shade trees are primarily experienced by wealthy residents.[80,81] Green infrastructure placement for pluvial flood management revealed greater preparedness in wealthy, White neighborhoods and greater vulnerability in poorer neighborhoods with a larger minoritized population in Atlanta (GA, USA), compared with Phoenix and Portland (OR, USA).[82] As investments in green infrastructure and other nature-based solutions for urban climate resilience scale up in cities around the world, planning and management must not only recognize potential negative impacts of these strategies but ensure that they do not reinforce the systemic and all-too-common status quo of disproportionate access and benefits in low-income and minoritized communities.[75] For example, gentrification that includes green infrastructure investments may increase attractiveness of neighborhoods, leading to higher property values that force low-income residents to move and may perversely increase exposure of vulnerable populations to the hazards that nature-based solutions seek to manage.[83–85] More work is necessary to scrutinize differences among preferences, who will benefit and who will not, and how green infrastructure investments may drive other unintended negative consequences.[83,86]

CITIES AS SETS

To address the previously discussed cross-cutting challenges multi-functionality, scale, substitutability, and equity for managing and designing nature-based solutions maximizing ecosystem

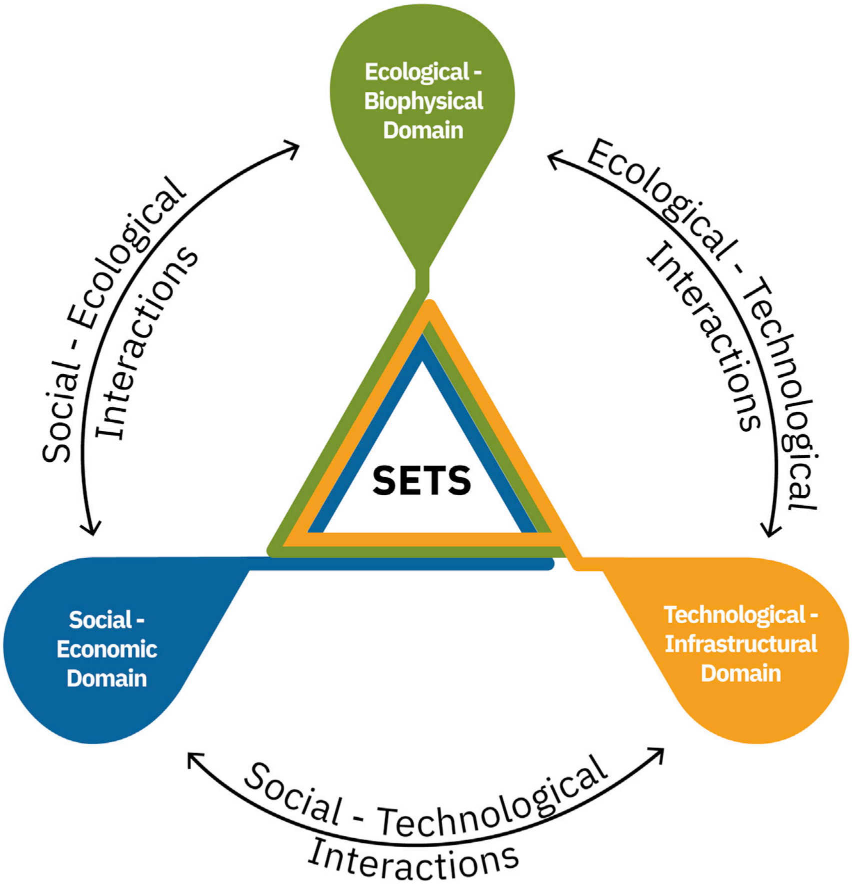

Figure 1. The social-ecological-technological systems (SETS) conceptual framework

The SETS conceptual framework focusing on linkages among broadly defined social, ecological, and technological dimensions of complex systems adapted from Depietri and McPhearson[91] and concepts from Grimm et al.[60] and McPhearson et al.[93,95,96]

services, we provide a more comprehensive conceptual SETS framework for understanding the production and management of ecosystem services and their benefits in diverse cities. In the SETS conceptual framework for ecosystem services, ecosystem services are not simply a product of ecosystem structure and function, as they are often defined.[18,87] Rather, ecosystem services are deeply embedded in local and regional contexts[25,24] and are generated by the combined structure and function of interacting social, ecological, and technological dimensions in each city,[88,89] along with their connected peri-urban and rural systems.[60,90–92] Social dimensions of ecosystem services may include management, planning, policy, finance, institutional capacity, stewardship, human labor, perceptions, values, and cultural norms. Ecological dimensions may include climate, weather, biodiversity, species traits, ecosystem structure and function, and community-scale interactions that affect ecological functioning. Technological-infrastructure dimensions can include physical components (e.g., dams, levees, pipes, culverts), weather sensors, engineered basins, structural support, automated systems, irrigation, and construction material.

Furthermore, urban ecosystems are complex systems characterized by irreducible uncertainty, emergent properties, and nonlinear behavior that can respond to and learn from changing conditions. Framing cities as complex SETS[93] provides a conceptual foundation for examining how SETS dimensions interact and affect their individual and collective contributions to ecosystem services.[18,60] The SETS framework explicitly acknowledges the interactions and interdependencies among social-cultural-economic-governance systems (social), climate-biophysical-ecological systems (ecological), and technological-engineered-infrastructural systems (i.e., the built or technological environment; Figure 1).[9,30,88,89,94] With ties to different sectors of urban planning and overall governance, the SETS framework provides opportunities for further mainstreaming ecosystem services in urban development. Ecosystem services may serve as a tool for coordinating the emergent outcomes of SETS interactions, making ecosystem complexity more manageable by overcoming sectoral fragmentation and siloed urban sustainability efforts across sectors.

We apply the SETS framework to urban ecosystems services, building upon emerging literature that describes how diverse urban dimensions influence supply and demand for ecosystem services.[25,26,97] We assert that using the SETS framework will broaden research and practice on ecosystem services. A SETS conceptual framework is important to advancing a systems theory for cities,[93] one that bridges multiple disciplines and can be applied in any local or regional context. Applying the SETS framework to ecosystem services highlights the benefits people derive from the interdependent interactions of coupled social, ecological, and technological structures and functions. Advancing beyond the traditional ecosystem services cascade,[98,99] Millennium Ecosystem Assessment, and IPBES models of ecosystem services provisioning, the integrated SETS framework incorporates often-neglected dimensions important to ecosystem service provisioning in cities. For example, the SETS framework acknowledges infrastructure, technology, and institutions that are increasingly recognized in the literature as critical to maintaining, managing, and designing ecosystem services but have not been adequately or explicitly included in other definitions and frameworks for ecosystem services.[18,20,72,95,100,101]

With the SETS framework, it is possible to compare individual, coupled, and fully interacting social, ecological, and technological contributions to ecosystem service provisioning designed to improve urban sustainability, resilience, and equity. We hypothesize that *all ecosystem services are fundamentally influenced by the interaction of all SETS dimensions, whether or*

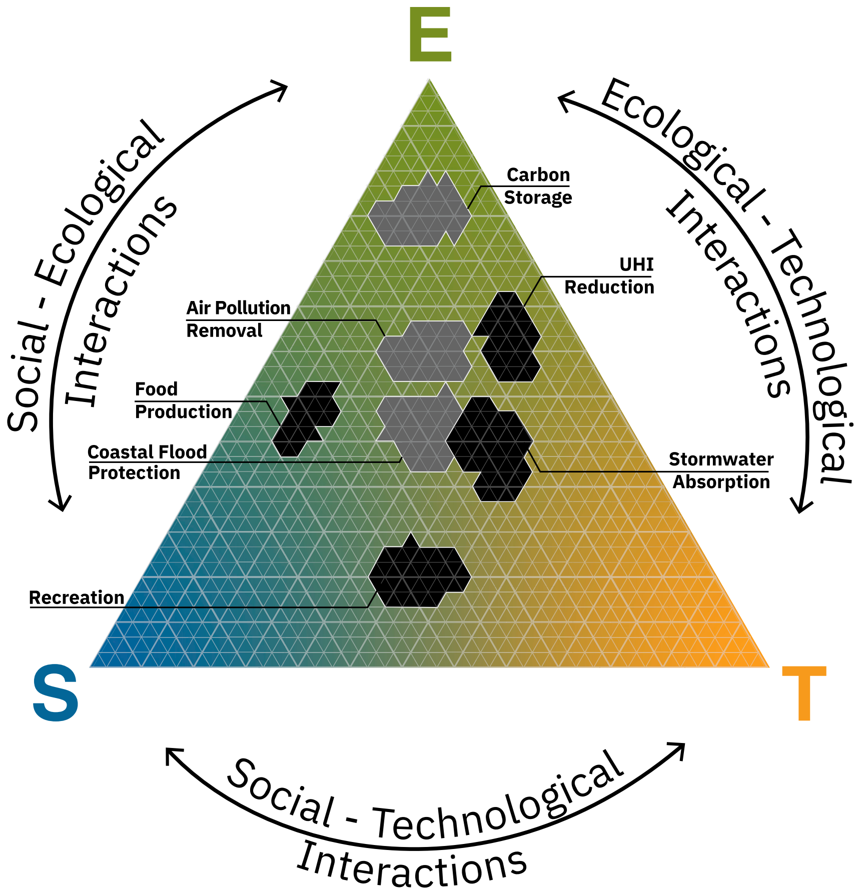

Figure 2. A SETS approach to ecosystem services
Multiple ecosystem services examples illustrate how different and interacting SETS dimensions affect the production and supply of each ecosystem service and often do so with proportional inputs from S, E, or T dimensions. Blue at the left point represents 100% S, green at the apex represents 100% E, orange at the right point represents 100% T, and color gradations between them represent gradients of S, E, and T interactions. Black shapes illustrate hypothetical contributions of social, ecological, and technological dimensions that affect each service—food production, urban heat-island (UHI) reduction, stormwater absorption, carbon storage, recreation—as discussed in the text. The gray shapes illustrate hypotheses of additional key services for climate-change adaptation and mitigation—coastal flood protection, air-pollution removal, carbon storage—and to illustrate how the framework can be used to examine other ecosystem services or specific nature-based solutions. The relative location along the S, E, and T axes represent potential hypotheses to be tested within and among different cities and urban contexts, as SETS dimensions, interactions, and proportional contributions may be similar in some cities and very different in others.

not this is explicitly recognized. We further hypothesize that *the social, ecological, and technological dimensions contribute variably to ecosystem services provisioning, such that some system dimensions play a larger role, and that the relative contributions shift in time and space*. Understanding when, where, and why relative contributions change and how to ensure that all dimensions are part of planning and management is important to the production of and/or management for ecosystem services. Through empirical examples reviewed from recent literature, we highlight the spectrum of how and which SETS dimensions contribute to the production and delivery of ecosystem services (Figure 2) and examine challenges by providing case studies from traditional ecosystem service categories—provisioning, regulating, and cultural services—to illustrate the proportional nature of SETS interactions affecting management and production of ecosystem services (Figures 2 and 3). We suggest that applying the SETS framework to ecosystem services has the potential to improve the integration of ecosystem services into decision-making and management to improve outcomes that meet normative goals.

ADDRESSING MULTI-FUNCTIONAL ECOSYSTEM SERVICES

The SETS framework provides a way to consider potential trade-offs or synergies of service production supported by multiple SETS dimensions.[27] In particular, the SETS framework allows us to map the implications of these trade-offs more broadly, including for cultural ecosystem services, by adding social and technological considerations. We offer the example of urban farms and gardens here to illustrate trade-off considerations that emerge when applying the SETS framework. For example, provisioning in urban farms and gardens has been well studied in urban ecosystem services research.[102–104] Yet, we argue the SETS framework can bring a more holistic understanding of key social, ecological, and technological drivers of food supply and burdens and hazards associated with urban gardens as a nature-based solution to inequality in food access. Urban garden ecosystems provide food for local families and communities and offer co-benefits, such as habitat for pollinators, space for community gatherings, and cooler microclimates, often touted as a solution to “food deserts” and nutritional inequality.[95] However, urban gardens may also increase water, fertilizer, and pesticide use and exclude other uses and users of the land area they occupy. Examined through the full suite of SETS dimensions (Figure 3), urban food production, along with its many co-benefits, is dependent on sufficient land for cultivation,[105–107] pest regulation, pollination, safe, and nutrient rich soils.[108] Yet, at the same time, the social and institutional characteristics governing the stewardship and management of the garden are essential to food production.[102] For example, lack of local knowledge about community gardening programs and environmental benefits can lead to abandonment and failure of urban gardens, as was shown in Phoenix.[109] Governance, decision-making capacity, property rights, and division of labor are important indicators of food provisioning and the perceived value of services in urban gardens.[103,104,110] In Barcelona, Spain, for example, bottom-up

	SOCIAL SYSTEM	ECOLOGICAL SYSTEM	TECHNOLOGICAL SYSTEM
Ecosystem Service	Cultural-economic-governance dimensions	Ecological, climate, biophysical dimensions	Technological-engineered infrastructure dimensions
Food production	• Community stewardship, labor, & management • Local policies, property value, & property rights • Diverse knowledge systems • Local food markets • Local economy	• Land for cultivation • Pest regulation • Pollinators • Nutrient-rich soil • Water resources • Plant diversity	• Land for cultivation • Pest regulation • Pollinators • Nutrient-rich soil • Water resources • Plant diversity • Physical infrastructure in urban gardens: raised beds, compost bins, tool sheds, benches, & irrigation systems for production • Energy & transportation systems for distribution
Stormwater absorption & flood control	• Regulations • Incentives & funding • Management, maintenance, & stewardship of infrastructure	• Bioswales & vegetated retention basins • Soil characteristics • Green streets • Green space • Wetlands	• Engineered bioswales • Concrete storage facilities • Pipes • Curb cuts • Street sweeping • Impervious surface area
Climate regulation & cooling	• Stewardship, including watering & maintenance of vegetation • Individual's preferences & choices of species	• Type and amount of urban vegetation (street trees, urban forests, green roofs, & other urban vegetation) • Species • Water availability • Soil depth	• Physical attributes: tree pits, roof structure & stability • Water delivery through hoses & pipes • Roads & transportation resources for human mobility to urban green space for cooling
Recreation	• Access • Maintenance & stewardship • Public awareness promotion campaigns for physical activity & visitation • Sense of place	• Open area • Water features • Tree canopy cover • Diversity of vegetation & wildlife	• Physical amenities: paths, fitness equipment, bike racks, playgrounds, climbing structures, basketball courts, skate parks, BBQ areas • Lights • Dog parks • Public art • Wifi

Figure 3. SETS dimensions of four example ecosystem services

Four ecosystem services, food production, stormwater absroption, climate regulation, and recreation, are described with respect to their interacting social, ecological, and technological dimensions that drive the production of urban ecosystem services and, ultimately, human benefit.

social movements led to policy shifts to legalize allotment gardens during the economic downturn.[62] In addition to ecosystem stewardship and management, diverse forms of collective and traditional knowledge are important to choices of cultivars and the productivity of the harvest.[102,111]

Physical infrastructure, such as raised beds, compost bins, benches, bathrooms, tool sheds, and irrigation, are technological and infrastructure dimensions essential to productive food provisioning. While the physical infrastructure makes food provisioning feasible, features such as roads and paths provide accessibility that is important to a suite of co-benefits, including developing a shared sense of community and land stewardship.[105,112] Finally, the distribution and delivery of produce is necessary to ensure that people receive and have access to the benefits provided by food production from urban and peri-urban gardens.[107] The resulting synergies from considering all SETS dimensions in the management of food production can lead to more equitable distribution of ecosystem services, benefits, and co-benefits by linking decisions that, on the surface, belong to a given social, ecological, and technological component yet have interdependent consequences. For example, changes to zoning might seem like a technocratic question, but the outcomes of zoning can affect the ability of people to grow their own food and enjoy the associated benefits of gardening, such as social cohesion. Likewise, reuse of industrial brownfields may seem like an expedient solution for reclaiming vacant land but can expose gardeners to high concentrations of toxic chemicals.[113] An explicit SETS approach may allow managers to better maximize food production, along with bundled co-benefits, and identify potential trade-offs and burdens. Since there are inherent winners and losers in different infrastructure pathways, SETS also provides a way of illuminating who that might be.[30] We hypothesize that *the success of urban gardens will depend primarily on social dimensions, in terms of knowledge, relations, commitment, and land rights, and ecological dimensions like soil quality, floral and faunal communities, and adequate space, while less critical are technical dimensions, such as automated irrigation systems and fencing, that can enhance the provision of services but are not as essential, though this is likely to vary significantly in different urban contexts* (hypothesis visualized in Figure 2). Transdisciplinary research will be needed to elucidate the relative roles of such dimensions and processes across diverse SETS contexts in order to improve decisions on best management practices to restore and scale the production of ecosystem services from different urban ecosystems, such as urban gardens.[114]

ADDRESSING SUBSTITUTABILITY AND VALUATION

The concept of substitutability evaluates trade-offs between cost and efficacy across SETS dimensions that provide and deliver ecosystem services. Thus, an explicit SETS approach to the valuation of ecosystem services is needed to better understand the full suite of investment costs to maintain ecosystem services benefits, equity implications, and the critical role of people in long-term management and stewardship of ecosystem services.

For example, climate change exacerbates existing shortfalls in stormwater management in many cities.[115] The increasing intensity, frequency, and duration of precipitation in urban locations exacerbates pluvial and fluvial flooding.[116] Widespread adoption of mixed "gray" and "green" stormwater management practices by many cities also serve as critical sources of ecosystem services.[117] These include short- to long-term retention of surface water from precipitation. Rain gardens, bioswales, bioretention ponds, constructed wetlands, and green roofs are examples of engineered infrastructure in designed ecosystems as hybrid ecological-technological solutions in diverse cities.[91,118–122] UEI investments for stormwater management in the US are a result of social-institutional directives, including water quality and stormwater codes, US Environmental Protection Agency grants and memoranda,[123] advocacy by watershed management non-governmental organizations, and incentives for private landowners or developers.[124] These initiatives have resulted in the uneven distribution of UEI within some cities, leading to inequities and environmental injustice issues.[82,125] UEI also requires active human stewardship to realize the benefits.[125,] For example, the installation of bioswales in Baltimore (MD, USA) was not well received in some neighborhoods, where trash accumulated and reduced the designed ecosystem services and stormwater infiltration benefits.[125]

While using UEI is a complementary approach to gray infrastructure (e.g., piped sewer systems) that help cities manage stormwater and water quality, the services provided by, for example, green infrastructure are unlikely to fully substitute for the services provided by gray infrastructure even when the UEI is intentionally designed, especially under increasingly variable conditions. Bioswales, retention basins, and other hybrid types of UEI interventions should combine social, ecological, and technological approaches from initial design, to building and construction, to management and stewardship, since all affect the ecosystem service benefits and value of stormwater management. The SETS framework allows for articulating and testing hypotheses such as the following: in low- to medium-density urban neighborhoods, retention capacity of engineered infrastructure and ecological functioning of soils and vegetation are primary factors in maximizing stormwater management capacity in bioswales, while human management, maintenance, and local stewardship will have less impact on stormwater management benefits (hypothesis visualized in Figure 2). In more dense urban neighborhoods, we hypothesize that local stewardship and management will become indispensable in maximizing stormwater retention and infiltration benefits. We encourage testing of these hypotheses. We also suggest that the arguments discussed should be considered when assessing the substitutability and value of ecosystem services and when testing hypotheses generated by the SETS framework in different urban contexts.

ADDRESSING SCALE MISMATCHES OF ECOSYSTEM SERVICES

Systems approaches accounting for all SETS dimensions are needed to address the multiple temporal- and spatial-scale mismatches that can occur such as need mismatches, in which particular ecosystem service are not spatially produced where they are needed or where production is temporlly out of sync with demand.[97,126] Ensuring sustainable management and supply of ecosystem services requires further working across scales, aligning local-scale provisions with regional-scale production, transport, and delivery mechanisms all along the ecosystem service supply chain.

For example, addressing the multi-scalar nature of urban ecosystem services is essential when planning and managing the cooling impacts of urban vegetation and infrastructure to reduce urban heat island effects and heat stress in cities. Green infrastructure, as well as legislation and ecological-technological innovations, are required to address climate regulation at local and regional scales. Cities like Paris and New York have adopted regional legislation requiring new buildings to include solar or green roofs to meet climate mitigation, adaptation, and resilience goals for decreasing heat exposure. Retrofitting buildings to transform conventional roofs to green roofs has been shown to potentially lower mean surface temperatures in New York up to 0.8°C,[127] with even greater surface temperature reduction at the scale of individual buildings. Further, future climate models incorporating urban expansion show that wholesale adoption of green roofs could significantly reduce warming at regional scales in the 21st century.[128]

Green roofs are an example of hybrid green infrastructure where attention to the ecological and technological dimensions, as well as planning, policy, and management, are equally needed to realize cooling benefits. If green roofs are used for food production, then social dimensions are important. For example, not only human management and stewardship but also institutional capacity and commitments, potential markets, and business transactions that occur at different spatial and organization scales ensure that desired ecosystem services are provided to beneficiaries over time. Further, local policies that can incentivize construction, mobilization of finance to provide upfront implementation, and building or even larger community buy-in could all be essential to supply of services from this type of green infrastructure. Ecological dimensions operate at local scales, including the need for quality soil, adequate organic matter, healthy soil microbes, species assemblages that support healthy ecological communities, and species traits that are locally adapted to environmental conditions.

Beyond increasing local cooling through evapotranspiration, thermal insulation, and shading, green roofs can increase longevity of roof structures in temperate climates and reduce overall costs.[129,130] In addition, green roofs, such as the Brooklyn Grange rooftop farms in New York, provide multiple co-benefits like habitat and green-space connectivity to support biodiversity, as well as opportunities for recreation, education, and social events. Even if co-benefits are ignored, achieving maximum cooling by green roofs to reduce surface and ambient temperatures requires ongoing human intervention and infrastructure, such as irrigation during hot, dry summer periods. To reflect the importance of scale, the SETS framework allows for testing hypotheses, such as the following: *local cooling by a particular green roof is driven largely by ecological functioning of vegetation and soil ecosystems and the building morphology (e.g., height and organization of nearby buildings), whereas citywide cooling benefits by green roofs will rely not only on ecological functioning but also on citywide incentives and regulations to ensure broad adoption of this cooling strategy* (hypothesis visualized in Figure 2). The need to focus attention and energy on social, ecological, and/or technological dimensions will also change over time. Thus, we hypothesize that *technical infrastructure, such as engineering specifications of roofs and installation of irrigation systems, are important for initial green roof installation and establishment of cooling benefits, while social systems, such as stewardship and government incentives, become more important over time to maintain and maximize the cooling efficacy and ecological functioning of green roofs*. The SETS framework can help ensure multiple dimensions are taken into account, for example, acknowledging that strong government incentives and thus the role of governance can be critical to using green infrastructure as a nature-based solution for urban cooling and related urban climate change adaptation (Figure 3). Green roofs and other urban vegetation for cooling are not a silver-bullet solution to reducing heat risk for the whole city nor are they one-size-fits-all-cities solutions, but they can be important tools for addressing urban heat together with air conditioning, cooling centers, painting roofs white to improve reflectivity, and alternative shade structures.[128]

ADDRESSING INEQUITY AND INJUSTICE

Historical legacies of past planning and policies have created intersecting inequities and injustices[131,132] that create further barriers for equitable investment in nature-based solutions and the ecosystem services they provide. We suggest that the SETS framework can be a conceptual foundation to explicitly acknowledge and address existing structural barriers to fairer nature-based-solutions investments. The SETS framework can help to investigate questions and understand how investments in UEI and nature-based solutions contribute to gentrification, along with rezoning, new development, lack of affordable housing, and other challenges that marginalized communities face. It can also be an approach for investigating procedural justice issues and articulating more inclusive approaches that integrate diverse values, norms, knowledge systems, and traditions into planning and decision-making. For example, city residents do not value ecosystem services uniformly.[133,134] Tree-planting campaigns in New York City (NY, USA) revealed that some residents pursue and request trees, while others cut them down or otherwise block city tree-planting efforts.[38] With a SETS perspective, transdisciplinary scholars and practitioners can consider how human values, perceptions, and actions are as important as, or in some cases even more important than, ecological functioning to realizing ecosystem service benefits. Further research is still needed to explore the way technology and social norms interact to mediate the production of and access to ecosystem service benefits. Additionally, more research is needed to appreciate the role that human labor and stewardship play in the co-production of ecosystem services.[135,136] For example, understanding what actors, institutions, and actions are best relied on to improve a just and fair provision of ecosystem services is important and can provide a process for the inclusion of diverse voices in decision-making.

Recreation—a mixture of many cultural ecosystem services—relies on ecological structure but is significantly enhanced by the addition of social and technological dimensions to ensure equitable access (Figure 3).[54] For example, green roofs are often on private properties, limiting wider public and equitable access for recreation, or lack of building elevators for rooftop access for those with physical disabilities. UEI, including a broad array of urban parks, vegetated rooftops, canopy cover by trees, wetlands, natural areas, and a diversity of vegetation and wildlife, is key to creating a vibrant space for recreation, yet we suggest that this ecosystem service provisioning is driven by a comprehensive suite of social, ecological, and technological dimensions (Figure 2). Thus, we hypothesize that *the social, infrastructural, and technological amenities together are primary determinants of physical activity and frequency of use of urban ecosystems for recreation*.[137,138] In particular, public access designed for those with disabilities, park maintenance, free Wi-Fi, activity and event programming, and awareness campaigns improve the frequency of use and physical activities in outdoor urban green spaces.[139,140] Likewise, physical activity is improved with access to physical infrastructure within the green space, such as walking paths, recreation facilities, well-maintained fitness equipment, bike racks, barbeque areas, water amenities, and public art.[141–143] Improving equitable and fair access to recreation, like other ecosystem services, depends on planning, managing, and designing for the inclusion and interaction of social, ecological, and technological dimensions.

IMPROVING URBAN RESILIENCE WITH SETS

The SETS framework brings forward a systems perspective that considers the reality of cities as complex systems. Here, we provide a SETS framework for ecosystem services that highlights the diversity of innovative ecosystem- and technological-based infrastructure strategies to produce multiple urban services for incorporation into urban planning, management, and design. This framework moves beyond the traditional definition of ecosystem services production as a product of ecological phenomena, or even social-ecological system dynamics. The framework acknowledges that for ecosystem services to provide benefits to human well-being, they need technological and infrastructure support, as well as social institutions and governance systems, to ensure that benefits accrue to people and accrue equitably. Taking this approach will require future research to examine how individual ecosystem services vary in the individual contribution and interactions of SETS dimensions across contexts within and among cities. Though we emphasize the SETS conceptual framework applied to urban systems, we hypothesize that ecosystem services are produced and supplied by SETS in all landscapes. The primary differences may be how much social-, ecological-, and technological-system dimensions contribute proportionally to the supply of a given service or bundle of services.

In moving from concept to practice, a systems approach to the management and planning of ecosystem services in urban areas is critical to meet the multiple goals of achieving urban livability, justice, and resilience to stresses and shocks. Nature-based solutions and ecosystem services in cities, such as access to reliable clean water and local strategies to reduce flooding, are receiving increasing attention and investment as essential ecological infrastructure to build resilience in the face of increasingly intense extreme events and non-climatic chronic hazards.[37,116,144–146] Resilience of urban SETS may be improved by providing multiple ecosystem services, offering redundancy in multiple functions, and incorporating flexibility to address uncertain future conditions that solely gray (hard) infrastructure solutions do not allow.[60,147] To achieve these normative goals, the SETS approach can be a boundary object in a transdisciplinary engagement that will be critical to allow for the exchange of diverse knowledge perspectives among researchers, practitioners, and community members and to promote the development of new and shared solutions.[96,109,148] We argue that the SETS framework for understanding and managing ecosystem services will create opportunities for new innovations to improve urban resilience.

Still, active efforts to further develop the SETS application to ecosystem services are needed. For example, there is a wide range of disciplines and perspectives that can be included (or not) within each S, E, and T dimension, and they may not all be well represented within any given SETS analysis. We encourage developing opportunities to explore ecosystem services from multiple disciplinary perspectives such as within and across urban planning, urban ecology, urban design, landscape architecture, arts and humanities, climate adaptation, and more. The complexity of urban systems may make it difficult to isolate distinct drivers and impacts on ecosystem service provisioning. The SETS framework can help to ensure that multiple dimensions—and even multiple disciplines—are included in SETS research and practice, regardless of the disciplinary starting point. Although SETS literature is expanding,[149,150] more work is needed to integrate SETS with other integrative approaches, such as in sustainability science to explore synergies and trade-offs of maximizing benefits for people, the environment, and financial budgets. It will also be helpful to develop comparative research to examine the reliability and resilience of the social, ecological, and technological dimensions of ecosystem service provisioning to advance research on the resilience of ecosystem services. For example, while the reliability of engineered gray infrastructure is strictly quantified using transparent protocols, the reliability of ecological dimensions of green stormwater infrastructure and green roofs for producing services is not clearly defined, complicating analysis of substitutability. Further research is also needed to engage in transdisciplinary learning processes among practitioners, researchers, and community members to co-develop new knowledge and management strategies for ecosystem services to better address equity and justice issues. This integration is an important component of efforts to improve the delivery of ecosystem services in cities across the world.

Finally, the ability to continue to produce services over time in complex urban environments depends on answers to diverse questions. For example, how are ecosystem services co-produced by the combination of social, ecological, and technological processes? How are the benefits of ecosystem services distributed across neighborhood, city, and regional scales? Are ecosystem services produced and supplied at the location and scale at which they are needed? Who benefits from urban ecosystem services? What key drivers in cities maintain, or hinder, our ability to benefit from ecosystem services in the long run? How important are management and stewardship for ecosystem services production? Are ecosystem services resilient over time to multiple types of disturbances and extreme events? These and other questions may determine the ability to manage SETS in ways that can continue to produce services over time and underline the need to better understand how multiple interacting social, ecological, and technological dimensions shape the production, distribution, and consumption of urban ecosystem services. Given the inherent complexity of these interacting dimensions in urban systems, an interdisciplinary, and even transdisciplinary, systems approach, in which researchers work closely with urban planners and diverse community members, is key to understanding *what*, *how*, and *for whom* ecosystem services are produced. The SETS framing of ecosystem services is thus argued as necessary to understand how the interactions of multiple dimensions of urban systems across spatial and temporal scales can together advance resilience agendas.

Given the urgency of issues we collectively face to address climate challenges and improve social equity in access to urban services in ways that improve livability, sustainability, and resilience, taking the SETS nature of ecosystem services into account must move from concept to practice with explicit engagement of diverse urban stakeholders. The SETS framing can open up innovative planning, design, and implementation of nature-based solutions through SETS analysis and management of UEI to address current and future resilience challenges more comprehensively.

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AUTHOR CONTRIBUTIONS

T.M. and E.M.C. contributed equally to the manuscript, and M.B.-B., C.C., and N.B.G. co-led the conceptual framing with T.M. and E.M.C. T.M. and E.M.C. contributed equally to lead the literature review and writing, with equal contributions to the writing and synthesis from all authors through UREx SRN meetings and writing workshops.

DECLARATIONS OF INTERESTS

The authors declare no competing interests.

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