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REVIEW

Urban Ecological Infrastructure: An inclusive concept for the non-built urban environment

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It is likely that half of the urban areas that will exist in 2050 have not yet been designed and built. This provides tremendous opportunities for enhancing urban sustainability, and using "nature in cities" is critical to more resilient solutions to urban challenges. Terms for "urban nature" include Green Infrastructure (GI), Green-Blue Infrastructure (GBI), Urban Green Space (UGS), and Nature-Based Solutions (NBS). These terms, and the concepts they represent, are incomplete because they tend to reduce the importance of non-terrestrial ecological features in cities. We argue that the concept of Urban Ecological Infrastructure (UEI), which came from a 2013 forum held in Beijing and from several subsequent 2017 publications, is a more inclusive alternative. In this paper we refine the 2013 definition of UEI and link the concept more directly to urban ecosystem services.

In our refined definition, UEI comprises all parts of a city that support ecological structures and functions, as well as the ecosystem services provided by UEI that directly affect human outcomes and wellbeing. UEI often includes aspects of the built environment, and we discuss examples of this "hybrid infrastructure". We distinguish terrestrial, aquatic, and wetland UEI because each type provides different ecosystem services. We present several examples of both "accidental" UEI and UEI that was explicitly designed and managed, with an emphasis on wetland UEI because these ecotonal ecosystems are uniquely both terrestrial and aquatic. We show how both accidental and planned UEI produces unexpected ecosystem services, which justifies recognizing and maintaining both purposeful and serendipitous types of UEI in cities. Finally, we posit that by incorporating both "ecological" and "infrastructure", UEI also helps to bridge urban scientists and urban practitioners in a more transdisciplinary partnership to build more resilient and sustainable cities.

Keywords: Urban Ecological Infrastructure; Ecosystem services; Hybrid infrastructure; Urban sustainability; Urban resilience

Infrastructure and nature in cities

Homo sapiens is becoming an increasingly urban species (Wigginton et al. 2016; Elmqvist et al. 2018; NSF AC-ERE 2018), a global shift that underscores the profound importance of understanding urban ecosystems. Cities, as concentrated consumers of energy and resources, are producers of various wastes, but they are also centers of innovation, efficiency, social networks, and solutions (David 1995; Grimm et al. 2008; Bettencourt et al. 2009; Pickett et al. 2013; Grimm and Schindler 2018). Cities are designed and built to be human habitats, and the result is urban infrastructure. Infrastructure is typically defined as the physical components of interrelated systems that provide commodities and services essential to enable, sustain, or enhance societal living conditions (*sensu* Neuman and Smith 2010). In its classical definition, infrastructure is generally restricted to the built [and otherwise human-constructed] environment; this is the way architects, engineers, and city planners and managers often think of it. In contrast, our focus here is on non-built "nature in cities" infrastructure and the broader adoption of a more inclusive term and concept for it: Urban Ecological Infrastructure (UEI).

The traditional concept of infrastructure likely began to expand to include nature in cities with the designs

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of Frederick Olmstead, then later with the work of Ian McHarg (1969) and, more recently, Frederick Steiner (2006). Awareness of nature in cities began to mature and become more widespread during the environmental movement of the 1960s and 70s. Since then, the importance and value of nature in cities has strengthened with the growth of urban ecology as both a discipline and an approach to understanding urban systems dynamics. With this strengthening has come the prevalence of several terms by European and U.S. urban scientists and practitioners to refer to nature in cities. Green Infrastructure (GI) is one (Tzoulas et al. 2006; Keeley 2011; Andersson et al. 2014; Larsen 2015; Koc et al. 2017); it is typically defined as the interconnected network of natural and semi-natural elements capable of providing multiple functions and ecosystem services encompassing positive ecological, economic, and social benefits for humans and other species (Benedict and McMahon, 2006; Koc et al. 2017). The GI concept has recently been expanded to Green-Blue Infrastructure (GBI), in order to include urban aquatic features (*sensu* Barbosa et al. 2019). Another more recently used term is Urban Green Space (UGS), defined as the natural, semi-natural, and artificial ecological systems within and around a city that comprise a range of habitats (Niemela et al. 2010; Cilliers et al. 2013; Aronson et al. 2017). Additionally, the term Nature-Based Solutions (NBS) has gained considerable traction, particularly in Europe (Eggermont et al. 2015; Cohen-Shacham et al. 2016; Maes and Jacob 2017; Kabisch et al. 2017; Frantzeskaki et al. 2019; Keeler et al. 2019), although this concept seems to be more focused on goal-oriented engineering rather than on the natural infrastructure itself (Nesshover et al. 2017, WWAP/UN-Water 2018). The definitions of GI, GBI, UGS, and NBS overlap considerably, and all are routinely coupled with the ecosystem services concept (e.g., Gomez-Baggethun et al. 2013; Andersson et al. 2015; Locke and McPhearson 2018; Keeler et al. 2019). GI and UGS are more strongly focused on terrestrial ecological features in cities; notably, a recent review and typology of GI by Koc et al. (2017) included no aquatic features, while a review of the GI literature by Haase et al. (2014), that was focused on ecosystem services, did not include urban wetlands. Similarly, applications of the GBI and NBS terms and concepts rarely discuss or include urban wetlands.

The concept of Ecological Infrastructure first appeared in a 1984 report by the United Nations Educational, Scientific, and Cultural Organization's (UNESCO) Man and Biosphere Program. It was several decades before the concept of UEI emerged in the literature, as a product of the 2013 International Ecopolis Forum on "Urban Ecological Infrastructure for New Urbanization" that was held in Beijing, China (Li et al. 2017a). This forum defined UEI as the organic integration of blue, green, and gray landscapes, combined with "exits" (outflows and recycling) and "arteries" (corridors; Li et al. 2017b). This definition included the built urban environment, and thus seems to include all urban infrastructure. The Li et al. (2017b) definition was also complicated by the inclusion of processes both within and between patches of UEI in the urban matrix. Perhaps because this definition was so expansive, the UEI concept has not become known by, let alone resonated with, the larger communities of urban systems scientists or practitioners in Europe, the U.S., or elsewhere beyond China.

Our objectives for this paper include:

1. The presentation of a simplified and more concise definition of UEI that directly connects UEI to the ecosystem services it provides, eliminating the need to include the ecological processes that produce those services explicitly in the definition.
2. A desire to make urban researchers and practitioners from Europe, the U.S., and elsewhere more broadly aware of the UEI concept, in hopes that it will be adopted as a more inclusive concept for nature in cities.
3. Justification for the idea that use of both "ecological" and "infrastructure" in the UEI concept forms a key bridge between urban ecologists and urban practitioners–UEI elevates urban ecological features to the same consideration by the latter as urban built features.
4. Demonstration that terrestrial, aquatic, and wetland types of UEI provide unique ecosystem services, and that a more refined focus on these ecosystem-specific processes may produce "surprise" ecosystem services.

A simplified definition of UEI

Our simplified and more concise definition of UEI encompasses all parts of a city that include ecological structures and functions. Ecological structure is the physical components that make up ecosystems (e.g. species, soils, waterways) while ecological function is the processes that result from interactions among the structural components (e.g. primary production, nutrient cycling, decomposition). UEI forms a critical bridge between nature in cities and the people that live in cities via its purveyance of urban ecosystem services (**Figure 1**). These ecosystem services are, by definition, the benefits that people gain from UEI and the resulting effects on human outcomes. Many of these ecosystem services result from the ecological function of UEI (the arrows in **Figure 1** that connect function to ecosystem services to outcomes), but some are purely structural (the arrow in **Figure 1** that connects UEI with outcomes). For example, urban trees are known for providing a number of function-derived ecosystem services, such as transpirational cooling and soil retention and development. But urban trees also provide services that are strictly tied to their ecological structure, including shade and habitat for wildlife.

Notably, infrastructure must possess ecological structure and function to be considered UEI. For example, swimming pools provide key services such as exercise, recreation, and cooling, but [by design] pools do not have ecological structure or function so they are not UEI. In our broadest of definitions, UEI is effectively all of the physical components of a city *except* the built environment. A building roof that is painted white (or even green) and called a "green roof" because of energy savings is not

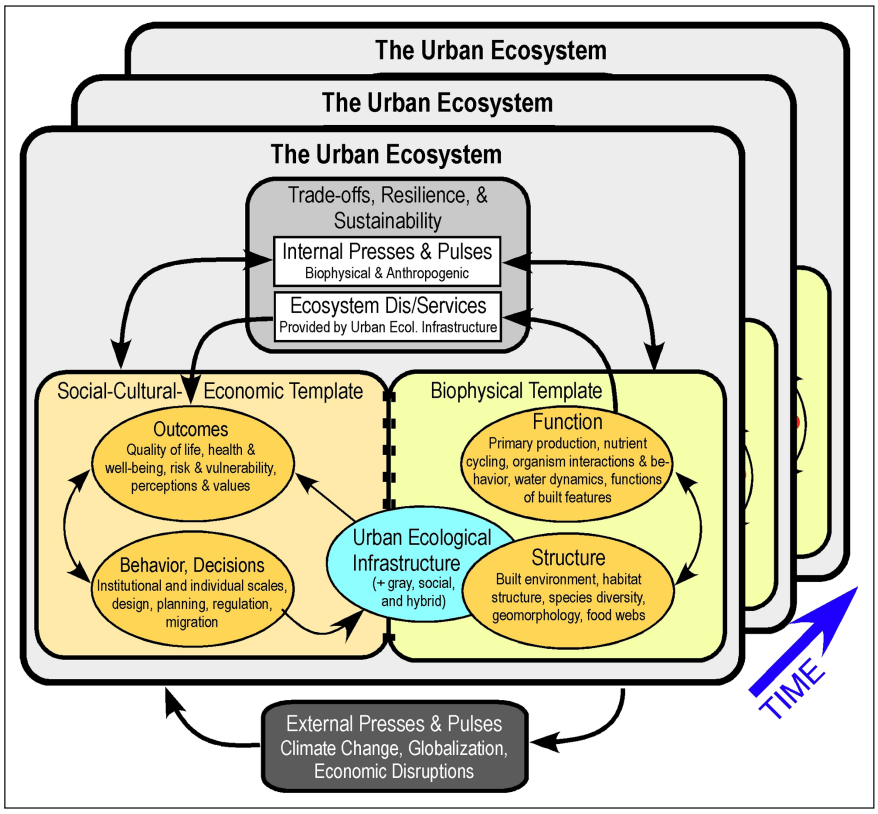

Figure 1: Conceptual framework of the CAP LTER Program. The conceptual framework being used by the Central Arizona-Phoenix Long-Term Ecological Research Program (CAP LTER) to structure and guide its urban ecological research. Note the blue oval in the center that demonstrates how UEI bridges the biophysical and human realms of the urban ecosystem. DOI: https://doi.org/10.1525/elementa.385.f1

UEI, but a green roof that includes soil and plants and is designed and managed for stormwater and heat abatement has ecological structure and function, and thus is UEI. Other examples of UEI include parks, streams, street trees, residential yards, riparian areas, lakes, urban agriculture, vacant lots, and constructed treatment wetlands. To the extent that a planted front porch flowerpot provides aesthetic benefits and food for pollinators, it is also UEI. Thus, UEI occurs at all scales. Finally, UEI is typically designed and managed to varying degrees, but not always. Examples of unplanned and/or unmanaged UEI include "accidental wetlands" (*sensu* Suchy 2016; Palta et al. 2016, 2017), vacant lots (McPhearson et al. 2013), and [seemingly] neglected areas.

Our ecologically inclusive UEI concept [of course] includes all terrestrial ecological features in cities, which we refer to as Green UEI. Bare soil is a particular terrestrial ecological feature that is present in all cities and is often a separate land cover class. Bare soils are sites of important ecological functions, including a host of biogeochemical processes and water infiltration (Herrmann et al. 2016). Thus, we distinguish bare soil from green UEI because it is not vegetated and is generally overlooked in research on GI/UGS and ecosystem services. For example, many vacant lots in Phoenix—a hot, dry desert city—are bare soil because without irrigation few if any plants can survive. Interestingly, vacant lots make up a large fraction of total urban land area, averaging 15% or more (Kremer et al. 2013). For these reasons, we include this unvegetated Brown UEI in our terrestrial ecological categorization.

All cities also have various types of aquatic ecological features, including lakes, streams, rivers, canals, and coastal oceans. We refer to this as Blue UEI. Notably, in their analysis of cultural ecosystem services in cities, Andersson et al. (2014) explicitly discussed both green and blue infrastructure, as do other recent publications (Ioja et al. 2018). In addition, because of the ways that water moves across landscapes, aquatic and wetland UEI features are often highly connected in urban ecosystems, even when those connections are not readily visible (e.g. buried urban streams). Yet urban wetlands are the ecological components that are either left out of discussions, studies, and reviews of nature in cities or are designated as either terrestrial or aquatic. All cities have wetlands of some form—undisturbed or degraded, constructed or restored, or simply accidental (*sensu* Palta et al. 2017). But wetlands have structural and functional characteristics that are both terrestrial and aquatic—they are effectively ecotone systems (Mitsch and Gosselink 2015). This means that wetlands combine the ecological characteristics of both Green and Blue UEI, yet wetlands are uniquely neither terrestrial or aquatic. For this reason we categorize urban wetlands separately, as Turquoise UEI (as first defined in Childers et al. 2015), because when one combines the colors green and blue the result is the color turquoise.

Our four-color approach to defining the UEI concept distinguishes Green, Brown, Blue, and Turquoise UEI because

each type provides a unique set of ecosystem services, and each type has its own management trade-offs because of potential disservices (in **Table 1** we present examples of Blue, Turquoise, and Brown UEI; the literature is rich with examples of Green UEI). Still, having these four categories reunited under the common banner of UEI allows for the connectivity among them (e.g., the same water may flow through Brown, Green, and/or Turquoise UEI before it reaches Blue UEI) to be more readily highlighted and to be managed in more integrated ways.

Why UEI is more inclusive than currently used terms for nature in cities

We argue that UEI as both a term and a concept, is necessary because of the terrestrial-centric nature of GI and UGS. Both GI and UGS seem to downplay or even ignore the importance of aquatic and wetland ecosystems in cities, yet all cities have streams, rivers, canals, lakes, shorelines or coastlines, and various types of wetlands. This emphasis on the terrestrial makes some sense, given that *Homo sapiens* is a land-bound species. Regardless, a focus on only terrestrial ecological features is an incomplete representation of nature in cities. The recent expansion of GI to GBI, so as to include aquatic features, still fails to acknowledge the ecological uniqueness of wetlands and their important contributions to UEI-based urban ecosystem services. While NBS does include aquatic features and wetlands (WWAP/UN-Water 2018), it is a goal-oriented and engineering-based concept that tends to focus on single-service delivery. We know this is insufficient because nature in cities provides multiple, and sometimes conflicting, benefits and these vary because of the social, technological, and ecological context of individual cities (Keeler et al. 2019). Our definition of UEI, detailed above, is considerably less abridged in its inclusion of urban ecological systems.

Another complication with GI is that this same term has a number of enviro-political connotations. Green infrastructure is routinely used to describe environmentally friendly, or "green" policies (e.g., recycling) or technologies (e.g., solar panels). This confusion over what GI actually means may lead to miscommunication or misunderstanding when urban ecologists are working with decision makers or with the public. One person's conception of nature in cities may be another person's idea of environmentally-supportive policies. As urban ecologists are striving to work more with urban designers, engineers, planners, other practitioners, and urban residents, it is important to ensure that we are all talking about the same things.

UEI as a bridge between urban scientists and practitioners

We posit that UEI, as both a term and a concept, will resonate with designers, planners, and managers, strengthening this ecologist-practitioner bridge and thus advancing our ability to move knowledge to action in support of more sustainable urban futures (per Childers et al. 2015; Pickett et al. 2016). An example of this comes from recent work by two authors of this paper (DLC and CAS) on a UEI stormwater management project on the campus of Arizona State University, Tempe AZ USA. A newly-constructed LEED Platinum Student Pavilion building included bioswales and other UEI features in the surrounding landscape to manage stormwater. The university administration also wanted to apply for SITES certification for the site (SITES

Table 1: Select examples of Blue, Brown, and Turquoise UEI, including associated ecosystem services and potential or perceived disservices. Ecosystem service abbreviations: P = provisioning services; R/S = regulating or supporting services; A/C = aesthetic or cultural services. DOI: https://doi.org/10.1525/elementa.385.t1

UEI Type	UEI Color	Ecosystem Services	Potential Ecosystem Disservices
Residential and park lakes	Blue	Enhanced property values (R/S), recreation (A/C), local cooling (R/S), fishing (P)	Disease vectors (e.g. mosquitoes), undesirable algal blooms
Urban streams and rivers	Blue	Flood control (R/S), recreation (A/C), local cooling (R/S), fishing (P), transportation (R/S)	Flooding, disease vectors, undesirable water quality
Riparian areas	Turquoise	Flood control (R/S), water quality enhancement (R/S), local cooling (R/S), wildlife habitat (A/C), recreation (A/C)	Flooding, disease vectors, undesirable wildlife
Water delivery canals	Blue	Water supply (P), local cooling (R/S), recreation (A/C), fishing (P)	Disease vectors, undesirable wildlife
Constructed treatment wetlands	Turquoise	Water quality enhancement (R/S), local cooling (R/S), wildlife habitat (A/C)	Disease vectors, undesirable wildlife
Accidental wetlands	Turquoise	Water quality enhancement (R/S), local cooling (R/S), wildlife habitat (A/C), human habitat (P)	Disease vectors, undesirable wildlife, undesirable people
Vacant lots	Brown	Stormwater regulation (R/S), groundwater recharge (R/S), soil development (R/S), wildlife habitat (A/C)	Sources of blowing dust, aesthetically undesirable
Construction sites	Brown	Stormwater regulation (R/S), groundwater recharge (R/S)	Sources of blowing dust
Fallow urban agricultural plots	Brown	Stormwater regulation (R/S), groundwater recharge (R/S), soil development (R/S), wildlife habitat (A/C)	Sources of blowing dust, aesthetically undesirable

is a certification program similar to LEED that focuses on the ecological efficacy of a building's surrounding landscape). The SITES certification process requires that the applicant empirically demonstrate effective outcomes of UEI solutions, which thus requires monitoring of UEI processes. These practitioners had little to no experience with environmental monitoring, but they did know about our long-term research on stormwater management using UEI through the Central Arizona-Phoenix Long-Term Ecological Research Program (CAP LTER; Hale et al. 2014, 2015).

The subsequent practitioner-researcher collaboration on the Student Pavilion's UEI involved several meetings, workshops, and field trips and resulted in a fully co-produced monitoring design for the site. Our research on this stormwater management UEI not only produced ecohydrological and biogeochemical data, but also included survey data derived from interviews of all practitioners and scientists involved in the monitoring design process (Sanchez 2019).

The architects and engineers involved in the project came into the co-production design process referring to their stormwater management features as GI. When asked to define GI, practitioner definitions of GI were remarkably similar to UEI. Further, it was clear they were aware of the many different perceptions of what GI means, including its enviro-political connotations, and they readily acknowledged the confusion this may produce. When introduced to the UEI concept, it was clear they had never heard of it before but they were quickly receptive to it as a better, more inclusive, and less confusing alternative. We posit that as the UEI concept becomes more prevalent in these design co-production activities, its value as a bridge between urban research and practice will become clearer.

Ecosystem services, and "surprise" services, provided by UEI

The UEI concept, and UEI itself, also forms a critical bridge between nature in cities and the people that live in cities (**Figure 1**). The most important link between these two realms is the ecosystem services provided by UEI. Most of these services derive from the ecological functions of UEI, as shown in **Figure 1**, but some of the benefits people derive from UEI are structural and more direct. For example, trees in a city park provide a number of functionally-based ecosystem services, including cooling via evapotranspiration, soil development, carbon and nutrient sequestration, and stormwater management. But the same trees also provide shade for people and habitat for birds, insects, and other wildlife—these are purely structural ecosystem services. UEI is also an important component of hybrid urban infrastructure, which Grimm et al. (2016) define as components of the urban fabric that are a mix of built and environmental structures in cities. As such, hybrid infrastructures provide benefits via both ecological structure and function (e.g., ecosystem services) and built structures (e.g., services; Depietri and McPhearson 2017).

In this section we present case study examples of ecosystem services provided by UEI. The literature is rich with examples of terrestrial UEI—also known as GI, UGS, or NBS—and the ecosystem services it provides (e.g., **Figure 4** in Haase et al. 2014). For this reason, there is no need to expand on these here. Rather, we focus our UEI case studies on Blue and Turquoise UEI because: 1) these systems have been neglected in GI, UGS, and NBS research and in the urban ecosystem services literature; 2) it is important to demonstrate that urban wetlands provide services that are unique from those of terrestrial or aquatic UEI and; 3) Blue and Turquoise UEI often provides unexpected, or "surprise", ecosystem services. Our point here is that by focusing on the terrestrially-based UEI in our cities, we are often surprised by the additional benefits that people derive from other "wetter" forms of UEI. The following examples document the value of Blue and Turquoise UEI to urban residents, via both the ecosystem services these systems were designed and managed to produce as well as via serendipitous ecosystem services.

1. Blue UEI in Phoenix AZ USA

Tempe Town Lake is a man-made lake that was built in the heart of downtown Tempe AZ in 1999 (**Figure 2A, B**). It was built by constructing dams across the bed of the Salt River, which has been effectively a dry river since the late 1930s. Tempe Town Lake was built to promote economic development, to provide recreational opportunities, and to manage stormwater and flooding. The lake provides effective flood control because the dams can be lowered, allowing the lake to accommodate significant flows during storm events or upstream dam releases. High flow events (>1000 cubic feet per second over a period of days to weeks) have necessitated opening the dams on five occasions since 2005. According to the City of Tempe, the economic impacts of the lake have exceeded $1.5 Billion. More than 2.4 million people spend time at the lake and the associated Tempe Beach Park every year, making it Arizona's second most popular public attraction—after the Grand Canyon (https://www.tempe.gov/city-hall/community-development/tempe-town-lake). Clearly, Tempe Town Lake has provided the three main ecosystem services of design.

In 2012, 68 users of Tempe Town Lake and park were surveyed about their perceptions and attitudes towards six ecosystem services: habitat provisioning, aesthetics, microclimate and stormwater regulation, and recreational and educational opportunities (Wilson 2012). Attitudes towards all of these ecosystem services were positive, and not surprisingly water was the central interest for most park users. Microclimate regulation, aesthetics, and recreational opportunities ranked highest in user preferences, and user attitudes and perceptions aligned reasonably well with the City's design and management goals for the lake and park.

We have monitored water quality in Tempe Town Lake since 2005 as part of the CAP LTER Program. One outcome of this long-term monitoring effort is our discovery of an unexpected ecosystem service: Because the lake is highly productive, it takes up significant amounts of atmospheric CO_2 over most of the year. The primary evidence for high primary production is the consistently alkaline pH (>8.5; **Figure 3A**) due to the uptake of CO_2—which is an acid when dissolved in water—by phytoplankton. Corroborating evidence is found in the consistently high

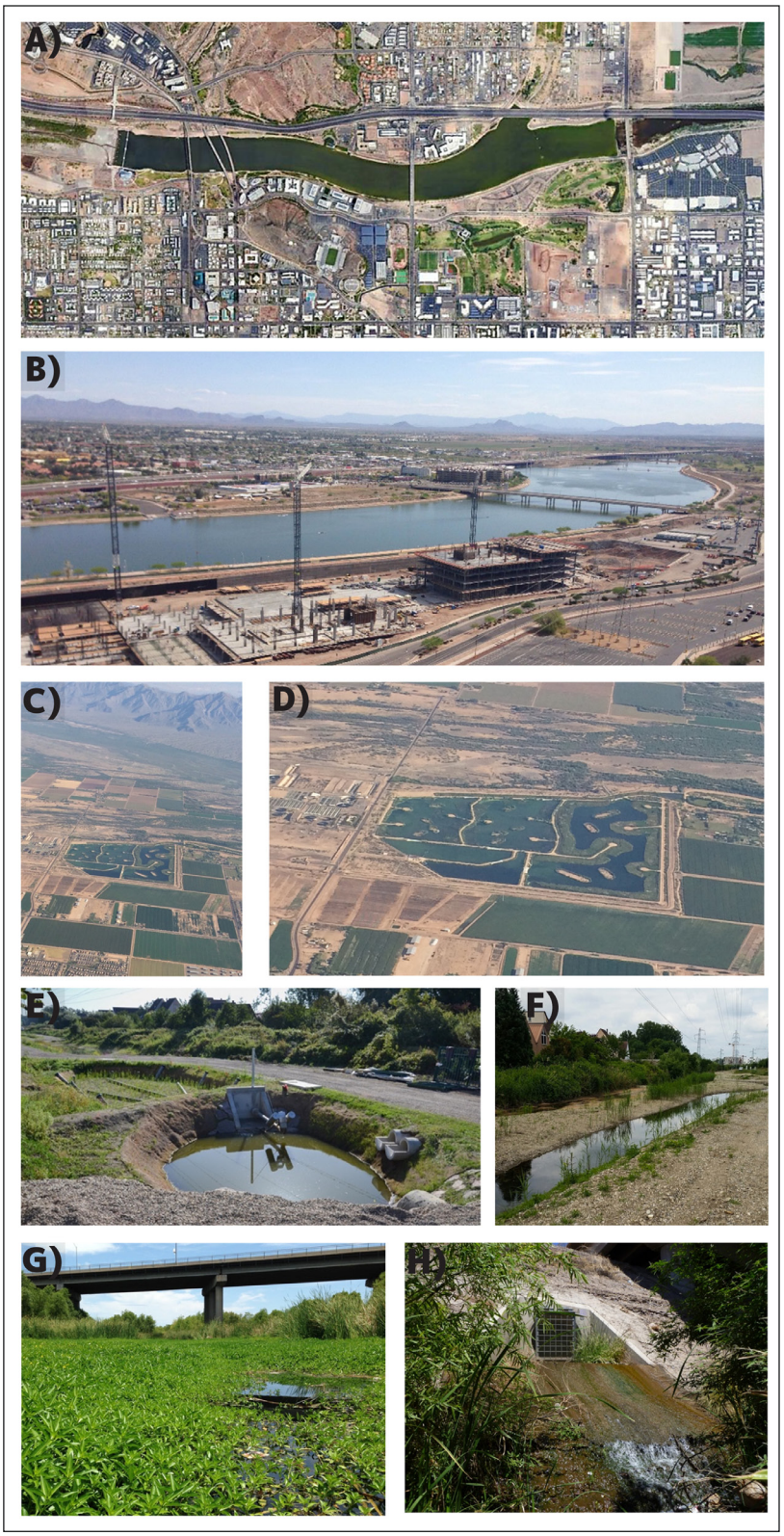

Figure 2: Photographs of the UEI systems described in the case studies. (A) Tempe Town Lake, Tempe AZ. The lake is directly north of downtown Tempe and the ASU campus; **(B)** There has been substantial economic development along the south shore of the lake (Photos A and B: Google Earth images); **(C)** The Tres Rios CTW (center). **(D)** Long-term monitoring and research have been carried out in the L-shaped 42 ha wetland cell on the right, which includes 21 ha of vegetated marsh. The wastewater treatment plant is on the far left of both photos, and the Salt River is immediately above the CTW (Photos by D. Childers); **(E)** The stormwater management UEI at the Ostwaldergraben system in Strasbourg, France shortly after installation. **(F)** The nearby stream shortly after restoration (Photos by P. Bois); **(G)** Accidental wetlands in the Salt River bed, downtown Phoenix AZ USA; **(H)** A stormwater outfall into the river bed with a large enough stormwatershed, or pipeshed, that it produces perennial flow (Photos by A. Suchy). DOI: https://doi.org/10.1525/elementa.385.f2

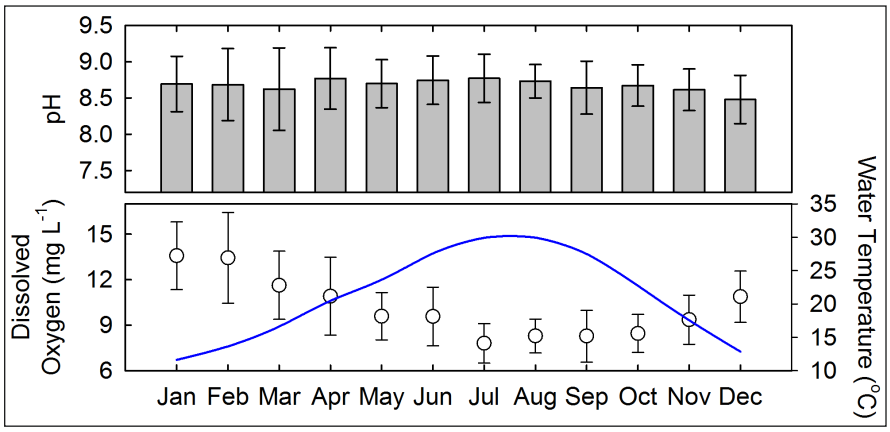

Figure 3: Tempe Town Lake water quality data. Tempe Town Lake monthly average data for pH (top), dissolved oxygen (bottom, open symbols), and water temperature (bottom, blue line). Data are taken from the City of Tempe water quality database; weekly data are grouped by month and monthly averages are calculated for the period 2005 to 2017 (n = ~50 for each month). Error bars are ±1 S.D. of the monthly mean (CAP LTER dataset DOI:10.6073/pasta/59d2e20260ad78d887e9bf3dd8987db4). DOI: https://doi.org/10.1525/elementa.385.f3

dissolved O_2 concentrations (7.8 to 13 mg L^{-1}; **Figure 3B**); on average, the lake is ~12% supersaturated with respect to O_2 throughout the year. The lake has very low nitrogen concentrations (<2 mg NO_3^- L^{-1}; <0.2 mg NH_4^+ L^{-1}) because of high algal productivity. While this carbon sink cannot come close to offsetting the atmospheric carbon sources of Tempe, most of which are associated with transportation, this is a valuable and little-known service of this Blue UEI.

2. Deliberate Turquoise UEI in Phoenix AZ USA

In 2010, the City of Phoenix began using a large constructed treatment wetland (CTW) to provide final tertiary treatment to effluent from its 91st Avenue wastewater treatment plant—the largest in the Phoenix Metro Area (**Figure 2C**). This CTW, known locally as Tres Rios, includes three wetland treatment cells that total roughly 100 ha and the system is capable of treating up to 400,000 m^3 day^{-1} of wastewater effluent. Since 2011, the CAP LTER Program has been quantifying wetland ecosystem processes in the largest of the three wetland cells (**Figure 2D**; Weller et al. 2016). Tres Rios was designed to provide the ecosystem service of surface water treatment in the form of nutrient reduction, and our data confirm that it is meeting this goal quite well (Sanchez et al. 2016). In fact, we have found that if nitrogen makes its way into the vegetated wetland component of this system, it is nearly completely expunged from the water (**Figure 4**).

As part of our long-term research in the Tres Rios CTW, we have also been quantifying and estimating the whole-system water budget. This includes water loss via plant transpiration, which is remarkably high during the hot, dry Sonoran Desert summers (Sanchez et al. 2016). As we analyzed these data, we realized the large volumes of water being lost to the atmosphere from the vegetated marsh must be replaced, and the only possibility for this was via a gradual but persistent flow of surface water into the marsh from the adjacent open water areas. We call this phenomenon the "Biological Tide". It has been verified in the field and represents the first time that anyone has ever documented plant-mediated control of surface hydrology in a wetland (Bois et al. 2017). In addition, the biological tide brings additional nitrogen and pollutants into the vegetated marsh for treatment, enhancing the ecosystem service for which it was designed. This enhanced efficacy of the CTW was an unexpected ecosystem service of this Turquoise UEI. Another surprising ecosystem service is that Tres Rios quickly became a significant habitat for wetland and aquatic wildlife, including being a mecca for birds. This CTW is a seasonal or permanent home to dozens of species of wetland and aquatic birds, including protected species.

3. Deliberate Blue-Turquoise UEI in Strasbourg France

Strasbourg, in NE France, is characterized by a dense network of waterways within the city boundaries. One of them, the Ostwaldergraben, is a small stream fed mostly by groundwater. As the city grew it was strongly channelized and enlarged. It also once received wastewater discharge from former tanneries. The City of Strasbourg launched a program in 2010 to restore the stream and recover it from its "mediocre" ecological state, as assessed by the European Water Framework Directive (EC 2000). The restoration process highlighted that the stream could be morphologically and chemically degraded by stormwater being discharged from the nearby urban residential watershed. Given this information, stormwater inflows were equipped with ponds (Blue UEI) and constructed wetlands (Turquoise UEI; Bois et al. 2019). This UEI was designed to improve water quality and mitigate stormwater flows (**Figure 2E, F**). After six years of operation, we have confirmed that the system is providing the ecosystem services that it was designed to provide: Fewer than 20% of storm events discharge into the stream and the UEI effectively removed suspended sediment, organic matter, nitrogen, phosphorus from the water (**Figure 5**; Schmitt et al. 2015, Walaszek et al. 2018).

A key goal of the stream and associated riparian zone restoration was to help bring back a pioneer and endangered species: The green toad (*Bufotes viridis*). Surprisingly, the artificial ponds, which were initially only designed for stormwater management, have been colonized by this

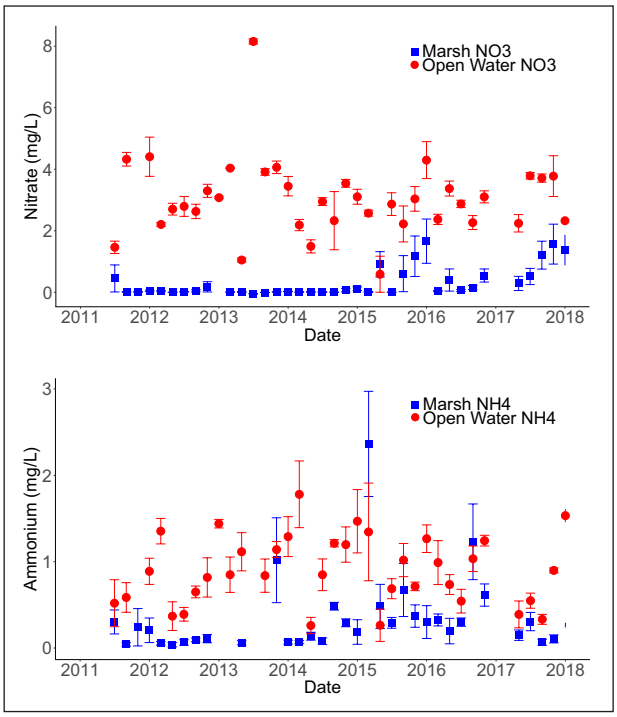

Figure 4: Tres Rios constructed treatment wetland water quality data. Nitrate (top) and ammonium (bottom) concentration data from the Tres Rios CTW. Data are collected bimonthly along three transects within the vegetated marsh; the red circles represent triplicate samples collected at the marsh-water interface and the blue squares are samples collected near the shore. Not that in nearly all samples, nitrate is in very low concentrations near the shore, relative to near the open water. The pattern for ammonium is similar, but not as dramatic. See Sanchez et al. (2016) for methodological details (CAP LTER dataset DOI:10.6073/pasta/3eb1f02c8db033f63a144a6f9d778fa7). DOI: https://doi.org/10.1525/elementa.385.f4

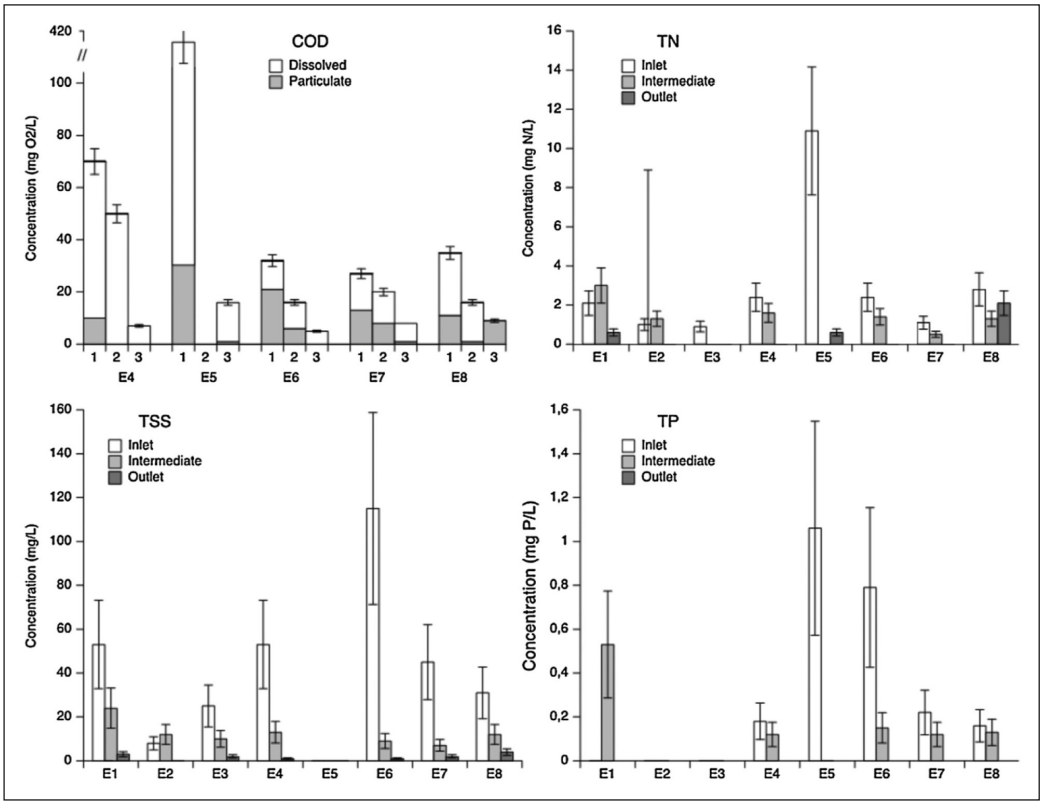

Figure 5: Ostwaldergraben stormwater treatment wetland water quality data. Change in pollutant concentration from the inlet to between the pond and the constructed treatment wetland (intermediate) to the outflow in the Ostwaldergraben system shown in Figure 2E, F (from Schmitt et al. 2015). COD = chemical oxygen demand; TN = total nitrogen; TSS = total suspended solids; TP = total phosphorus. DOI: https://doi.org/10.1525/elementa.385.f5

endangered toad as well as by other amphibians, thus providing an unexpected ecosystem service. The results of questionnaires from our semi-structured interviews of nearby residents have shown that they recognize and value this new habitat for amphibians (Bois et al. 2019) as well as the aesthetic enhancements provided by the restored stream and associated stormwater management UEI. Interestingly, the water quality and quantity regulating services provided by this UEI are still poorly perceived by local communities. This suggests an opportunity for scientists working in the system to expand their education and outreach activities in these neighboring communities.

4. Accidental Turquoise UEI in Phoenix AZ USA

The Salt River that runs through central Phoenix was once a perennial river. In prehistoric times its flow supported the agricultural and cultural productivity of the Hohokam people for nearly 1000 years (Murphy 2012). With the arrival of European settlers about 150 years ago, though, a lack of resilience to, and tolerance for, flooding became a major issue. By the late 1930s, the last of seven dams and reservoirs had been built upstream of Phoenix, on the Salt and Verde Rivers, sequestering 100% of the flow of both rivers for urban and agricultural use in the Phoenix metropolitan area. The Salt River has effectively not been a river since that time, except in extreme but rare events.

A lack of water in an urban riverbed does not necessarily preclude the possibility of wetlands, even in the arid southwestern U.S. As it turns out, Phoenix is a rather "leaky" city; storm drains that empty into the Salt River flow frequently, predictably, and even continuously, depending on the size of their urban pipe-sheds (Palta et al. 2017). The result is an array of "accidental" wetlands in the riverbed itself that provide unmanaged and unexpected ecosystem services, including nitrogen processing and removal and wildlife habitat (**Figure 2G, H**; Suchy 2016; Palta et al. 2017; Suchy et al. in press.). But an even more surprising collection of ecosystem services provided by these accidental wetlands was discovered when we began conducting field research in these systems. These perennial stormwater outflows and their associated Turquoise UEI are regularly used by homeless or indigent people throughout the Phoenix Metro area and provide many benefits, including cooling, bathing, and even food. These transient populations often prefer the wetlands to local shelters or cooling centers and have developed local knowledge of which outfalls have "good" (i.e., high quality) water and which do not (Palta et al. 2016). These accidental wetlands in the Salt River, that are not designed or managed, thus provide an array of unexpected ecosystem services to a diversity of city residents.

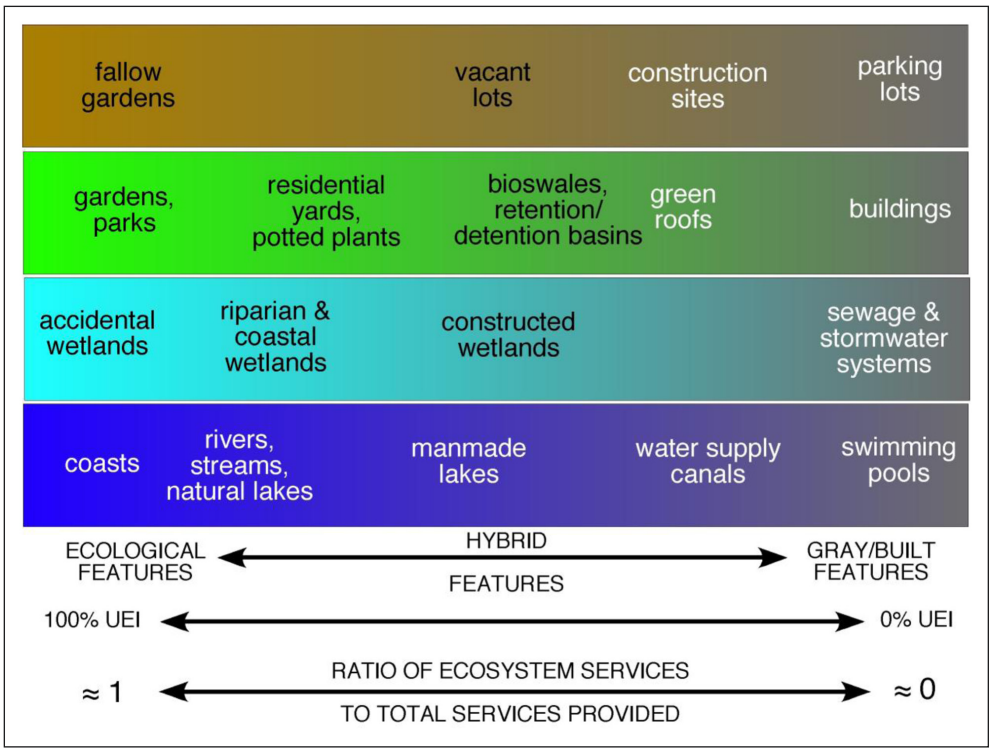

Figure 6: Schematic of the infrastructure hybridity gradient from 100% UEI to 100% built. Conceptual depiction of a gradient from ecological to hybrid to built features for the four colors of UEI. Note that while cities contain a great deal of purely gray/built infrastructure which does not include UEI (far right), they often contain few examples of pure UEI (far left); most UEI is actually hybrid infrastructure. For each UEI color, several examples and their approximate location on the ecological ←→ built gradient are shown. The gradient in the ratio of total services provided to those that result from ecological structure and function is also shown; ≈1 is where virtually all are ecosystem services from UEI, ≈0 is virtually none of the services are ecosystem services. The infrastructure types from the four case studies are also shown (stormwater retention/detention basins, accidental wetlands, constructed wetlands, and manmade lakes). DOI: https://doi.org/10.1525/elementa.385.f6

Synthesis and Conclusions

In this paper we present a more inclusive and simpler definition of Urban Ecological Infrastructure, refined from the earlier use of the concept by Li et al. (2017), that explicitly addresses all urban ecological components, including aquatic and wetland systems. We argue that UEI, as both a term and a concept, is preferable because the many existing terms for this idea are focused on goals and outcomes rather than on the ecological components themselves. For example, concepts such as ES and NBS merge functions and benefits and have required myriad papers to disentangle them. Additionally, existing related concepts (e.g., GI and UGS) are terrestrial-centric and thus downplay the importance of aquatic and wetland ecosystems in cities. In fact, all cities have aquatic components, including streams, rivers, canals, lakes, shorelines or coastlines, and all cities have various types of wetlands. A focus on mainly terrestrial ecological features is therefore an incomplete representation of nature in cities. Our refined definition of UEI is unabridged and includes all types of urban ecological systems. We use metaphorical colors to distinguish the different characteristics of, and services that come from, terrestrial, aquatic, and wetland ecosystems: Green, Blue, and Turquoise UEI, respectively. We include Brown UEI as a fourth type because non-vegetated terrestrial features are also common in all cities and urban soils as UEI provide important ecosystem functions and services.

But cities also contain a wide array of hybrid infrastructure types that span a full gradient from completely UEI to completely human-made (**Figure 6**; Grimm et al. 2016; Depietri and McPhearson 2017). As hybrid infrastructure incorporates more ecological characteristics and fewer built characteristics, a larger fraction of total benefits derived from it will be ecosystem services (**Figure 6**). Additionally, focusing on one single targeted service, as is often the case with NBS approaches, might prevent managers and stakeholders from recognizing, managing for, and benefitting from other ecosystem services that may be provided by UEI. It is this concept of hybridity in urban infrastructure, from mostly UEI to all built, that makes the UEI concept both fully inclusive and powerful. None of the other terms for nature in cities captures this fusion of the built and ecological features that we find throughout all cities.

An important advantage of the UEI concept is that the term itself includes both "ecological" and "infrastructure". Thus, the concept forms a key bridge between urban researchers and urban practitioners, and we anticipate that it will elevate urban ecological features to the same consideration by those practitioners as urban built features. This is key as cities expand their use of UEI in diverse biophysical and social contexts. At present, even without considering unintended benefits or consequences, UEI can deliver mixed outcomes. For example, although the use of bioretention swales is supposed to mitigate stormwater runoff and aid in pollutant removal, storm size and frequency alter the effectiveness of the swales (Norton et al. 2017). It is thus imperative that we continue to incorporate scientific knowledge into designs and management practices.

UEI may also allow practitioners from different sectors to account for synergies and tradeoffs among the services for which each sector is responsible. For example, vacant land may be managed as wildlife habitat, as a productive food landscape, or for storm water management (Kremer et al. 2013; McPhearson et al. 2013), depending on who takes leadership in management. But not all transformations from Brown to Green UEI result in the same ecosystem services. For example, although urban agriculture may provide food and pollinator habitat (Clinton et al. 2018), the over-application of fertilizers and other soil amendments by hobby gardeners (Metson et al. 2015; Lewis et al. 2018) may result in downstream water degradation rather than increasing water quality through stormwater retention. The UEI concept should allow diverse stakeholders (e.g., food policy councils, local water quality authorities, and zoning authorities in the example above) to talk to one another about how a parcel might be used to maximize benefits while avoiding damaging trade-offs. This is an advantage of the fact that UEI, as both a term and a concept, should resonate with designers, planners, and managers, strengthening the ecologist-practitioner bridge while advancing our ability to move knowledge to action in support of more sustainable and resilient urban futures. Our experience with co-producing a stormwater UEI monitoring design demonstrated this bridging effect. And this is already happening in our Strasbourg case study: The city's Urban Ecology and Water Department worked with both scientists and local communities to define, design, and implement the restoration of the Ostwaldergraben (Bois et al. 2019).

The UEI concept has important implications for the future of cities. For example, there are projections that by 2050 four in five people will live in cities. This means that as much as half of the areas that will be urban in the future have yet to be built—a huge opportunity for not just "thinking out of the box", but for "thinking of a whole new box" in terms of what urban development looks like and how it behaves (McPhearson et al. 2016; Alberti et al. 2018). With multiple social and environmental pressures, operating at myriad scales (e.g., climate change as an existential threat through extreme events, especially in coastal cities), the UEI concept provides a critical entry point for rethinking urban development so that it meets both sustainability and resilience goals. We argue that a key to this new vision of urban development is the transdisciplinary fusion of ecology and design, *sensu* Childers et al. (2015). Urban planners and designers, including architects, engineers, and landscape architects, need to be coaxed into thinking beyond a single project and urban scientists need to be coaxed into using their knowledge about urban ecosystems to make cities better places to live. The UEI concept inherently includes ecological connectivity, via a variety of hybrid UEI-built infrastructure types, as well as the spatial heterogeneity that characterizes all cities.

The literature is replete with analyses that demonstrate how UEI-based solutions are more adaptive and flexible than hard-engineered solutions, such that "safe to fail" infrastructure can impart resilience to urban systems

while "fail-safe" infrastructure often does not (Chester and Allenby 2018). There is also copious evidence that the co-production of knowledge, designs, and solutions by urban practitioners and researchers is a key to more sustainable future pathways for cities—those that exist today and those yet to be built (Elmqvist et al. 2018). We argue that UEI is the best term and concept for nature in cities because it conceptually, and perhaps literally, bridges the worlds of knowledge generation and action. It should thus be a critical conduit for enhancing the co-production of urban sustainability solutions that will lead to more resilience cities.

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Competing interests

The authors have no competing interests to declare.

Author contributions

The authors of this paper contributed equally to the conception and refining of the ideas, to the case study examples and related data, and to the writing of the manuscript. All authors approved the final version for publication.

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