PROJECT SUMMARY

Overview:

Phase V of the Central Arizona–Phoenix LTER Program (CAP) will focus on the central question: ***How are human-environment interactions mediated by urban ecological infrastructure (UEI) to shape the social-ecological urban ecosystem—past, present, and future—and how can we use knowledge of these relationships to inform more just, transformative, and sustainable futures?*** The overarching goal is to foster social-ecological urban research aimed at understanding urban ecosystems using a holistic, ecology *of* cities perspective while contributing to an ecology *for* cities approach to enhance urban sustainability. This goal will be met through six programmatic objectives to answer the research question: 1) use ecological and social data to answer new questions requiring long-term perspectives; 2) develop and use models and scenarios through participatory, community-based strategies; 3) advance urban ecological theory while contributing new theory derived from transdisciplinary research; 4) promote and strengthen environmental justice using broadly inclusive approaches to CAP science and outreach; 5) build and use transdisciplinary partnerships to foster resilience and enhance sustainability in urban ecosystems while contributing to the education and well-being of urban dwellers of all types, ages, and experiences; and 6) adaptively manage CAP research and how work with communities of practice is framed. CAP V research will be organized around five interdisciplinary questions that will build on 19 long-term datasets and experiments in a fully integrated and synthetic research platform.

Intellectual Merit:

Homo sapiens is becoming an increasingly urban species, pointing to the profound importance of understanding urban ecosystems. The urgency of this research imperative has motivated CAP since 1997 and will continue to inspire CAP V. CAP researchers view urban ecological infrastructure (UEI) as a critical bridge between the biophysical and human/social domains. CAP's central question articulates how human-environment interactions mediate the reciprocal relationships that connect human perceptions, motivations, and behaviors associated with UEI to urban ecosystem structure and function. Heterogeneity in both ecological and social components of human-environment interactions will be a major focus to advance how diverse UEI differentially affects ecosystem services and disservices across people and places. The CAP V conceptual framework envisions a form of heterogeneity called UEI hybridity—a gradient from purely ecological to primarily built—to address: 1) human-environment feedbacks associated with key UEI features; 2) adaptive and eco-evolutionary responses of organisms to human activities; 3) UEI feedbacks to urban heat, air quality, and water; 4) how interactions with nature affect the perceptions, decisions, and wellbeing of urban residents; and 5) how governance and institutions impact and are shaped by human-environment interactions.

Broader Impacts:

Intellectual merit and broader impacts are intentionally integrated in CAP V research. Much of the research proposed here will have broader impacts on science, communities, and cities, and many CAP V activities will involve explicit partnerships with practitioners and communities. CAP's Schoolyard LTER—Ecology Explorers—will continue to connect K-12 teachers and students with CAP research, including by continuing to host summer professional development programs for K-12 teachers and by expanded outreach to other focal neighborhoods. CAP will continue its community science projects around Phoenix through collaborations with partners such as the McDowell Sonoran Conservancy, the Central Arizona Conservation Alliance, and numerous municipal agencies. CAP V will expand community-led opportunities by strengthening partnerships with organizations and community entities in South Phoenix and other focal neighborhoods. The successful CAP REU Program will continue to use various mechanisms to recruit underrepresented students. CAP will support graduate students through the Grad Grants program and through extensive research infrastructure, long-term data, and mentoring. The CAP JEDI Committee will promote and implement JEDI principles and practices that are focused on more equitable and just futures for the CAP community and across the CAP region. Finally, CAP's large, diverse database with its 236 datasets is a valuable and growing resource for LTER scientists and students, urban researchers worldwide, urban practitioners, teachers, and the general public.

PROJECT DESCRIPTION

I. Intellectual Merit: Introduction

A. Preamble: Urban ecology has had a strong interdisciplinary, social-ecological focus for several decades (e.g., Grimm et al. 2000). Many of the differences between urban ecology and ecology in general result from the fact that urban ecosystems are not only intentionally created (Pataki 2015), albeit often with unintentional effects, they constitute foundational transformations of nature. Thus, when studying cities as ecosystems there is a need to consider the linkages among the built and biotic components of cities (Pickett and Cadenasso 2008; Markolf et al. 2018). The concept of urban ecological infrastructure (UEI, see Text Box 1; Childers et al. 2019) is central to our research at the Central Arizona-Phoenix LTER Program (hereafter CAP), and we propose to organize the CAP V research around a hybridity gradient of UEI from completely ecological features to primarily built features.

Urban ecology also has strong roots in transdisciplinary convergence research. The translational (*sensu* NSF AC-ERE 2018) impact of urban ecosystem science is enhanced when urban ecologists not only engage in integrated science--through the development and testing of shared research questions, robust models, and place-based ecological data--but are also involved in planning, design, and management processes (e.g., James et al. 2009; Lovell and Taylor 2013; Cook et al. 2021). This is precisely what the urban sites in the U.S. LTER Network have been doing for nearly 25 years. We propose to strengthen these connections intellectually and through co-production activities with planners, designers, managers, policymakers, and residents in CAP V. As an example of co-production with decision-makers in the cities we study, a CAP scientist was recently named director of the nation's first publicly funded Department of Heat Response and Mitigation in the City of Phoenix. We are particularly excited about our CAP V plans to deepen our collaborative work with the communities we study.

CAP is one of two urban sites in the U.S. LTER Network. Our research has always had, and will continue to have, a broadly interdisciplinary social-ecological foundation. One cannot study an urban ecosystem without also studying its ecosystem engineer: *Homo sapiens*. Human perceptions, actions, and decisions will continue to be centered in our research, with increased attention to the wellbeing of diverse residents in the CAP region. These attributes and outcomes are influenced by environmental justice, racial equity, and social transformation in response to pressing changes in climate, human migration, increasing wealth disparities, and worldwide changes in urbanization itself. These issues are central to interdisciplinary social-ecological science and to urban ecology. Our conceptual focus in CAP V will be on both ecological and social heterogeneity, as well as on a form of heterogeneity that we refer to as UEI hybridity—a hybridity gradient from primarily ecological to primarily built (Childers et al. 2019; Andersson et al. 2022). To answer our central question, our five specific research questions--organized under a new central conceptual framework--encompass the totality of these concepts.

B. CAP V Central Research Question: To say that *Homo sapiens* is becoming an increasingly urban species is so evident that it no longer needs citation. Understanding urban ecosystems has motivated CAP since its inception in 1997 and will continue to inspire CAP V. As we advance and expand our urban social-ecological investigations in exciting new directions, the central question that will guide CAP V research is:

> ***How are human-environment interactions mediated by urban ecological infrastructure (UEI) to shape the social-ecological urban ecosystem—past, present, and future—and how can we use knowledge of these relationships to inform more just, transformative, and sustainable futures?***

This question articulates how human-environment interactions control the reciprocal relationships that connect human perceptions, motivations, and behaviors associated with UEI to urban ecosystem structure and function. Our focus on these human←→environment interactions will be on spatial heterogeneity in ecological and social components, and on the ecosystem services and ecosystem disservices (hereafter ES/EDS) provided by a diverse array of UEI. Heterogeneity is fundamental to urban ecology (Pickett et al. 2017; Zhou et al. 2017), and it was a major focus of CAP research in the early years. We are excited to return to this focus in CAP V. Diverse human actions at multiple scales create ecological and social heterogeneity that transforms the city, but these connections are very much bidirectional. Human→environment interactions include the design, construction, and management of the city as our habitat. Environment→human interactions include the myriad ways people respond to ES/EDS as they perceive and experience them, and the resultant decisions that they make. These dimensions create constant human←→environment feedbacks, which is a central tenet of social-ecological systems theory and of urban ecological theory. Ultimately our aim is to move towards desired futures, from a normative perspective, that are more just, transformative, and sustainable.

TB 1: What Do We Mean by UEI?

Cities are designed human habitats, and urban infrastructure is the result. Neuman & Smith (2010) define infrastructure as the physical components of interrelated systems that provide commodities and services essential to enable, sustain, or enhance living conditions. UEI is an inclusive concept defined as any element of an urban ecosystem that supports ecological structure and function (Childers et al. 2019). Conspicuous examples include parks, lakes and streams, street trees, and gardens. Less obvious examples include yards, vacant lots, accidental wetlands, green roofs and walls, even flowerpots with blooming plants. As such, most UEI is designed or managed to some degree (Steiner 2006), and most UEI is a hybrid of ecological and built features (Fig. 1.2).

Our **overarching goal** for CAP V is to foster interdisciplinary social-ecological urban research aimed at understanding these complex systems using a holistic, ecology *of* cities perspective (Grimm et al. 2000), while contributing to an ecology *for* cities to enhance urban sustainability (Childers et al. 2014, 2015) through transdisciplinary partnerships with city practitioners and residents (*sensu* the NSF ACERE 2018 convergence report). We will **meet this goal** through six objectives--We will: 1) use our long-term observations and experiments to answer new questions requiring long-term perspectives; 2) develop and use models and scenarios to address our research questions; 3) broadly apply existing urban ecological theory while contributing new theory derived from our research; 4) promote and strengthen the environmental justice and equity component of CAP using broadly inclusive approaches in our science and worldviews through our partnerships and actions; 5) build and use transdisciplinary partnerships to foster resilience and enhance sustainability in urban ecosystems while contributing to the education and well-being of urban dwellers of all ages and experiences; and 6) use these experiences to adaptively manage our research and how we frame our work with communities of practice.

C. CAP V Central Conceptual Framework: The CAP V conceptual framework (Fig. 1.1) is considerably different from, and a significant advance from, our CAP IV framework (as depicted in Childers et al. 2019). Our new conceptualization of the urban ecosystem reflects: 1) an enhanced focus on urban heterogeneity--both ecological and social--across various spatial scales in the urban landscape (from the parcel scale to the entire central Arizona region, including Tribal Nations); 2) a more coordinated and interdisciplinary focus on our 12 key study neighborhoods and the people and parcels that comprise them; 3) enhanced partnerships and collaborations with our study neighborhoods and decision-makers in several municipalities in the metro area--which we call communities of practice; 4) a focus on human←→environment interactions and feedbacks; and 5) our continued focus on UEI as a construct to connect social and ecological dynamics, but now with emphasis on a UEI hybridity gradient from the purely ecological to the largely built (Fig. 1.1). This UEI hybridity gradient is informed by a similar gradient presented in Childers et al. (2019; Fig. 1.2).

Our conceptual framework depicts the heterogeneity domains in which our research will operate to answer our five specific research questions (Fig. 1.1, right panel). We detail these questions in Section II.C but will overview them here relative to Fig. 1.1. Research question #1 (RQ1) focuses on the human←→environment feedbacks of UEI features related to many of our long-term experiments and projects; it has a strong ecosystem ecology focus with a social-ecological component and answering it will involve work at all spatial scales. RQ2 will explore organismal life-history traits and eco-evolutionary dynamics in response to human activities. While this question has clear human→environment interactions, answering it will largely entail ecophysiology, population ecology,

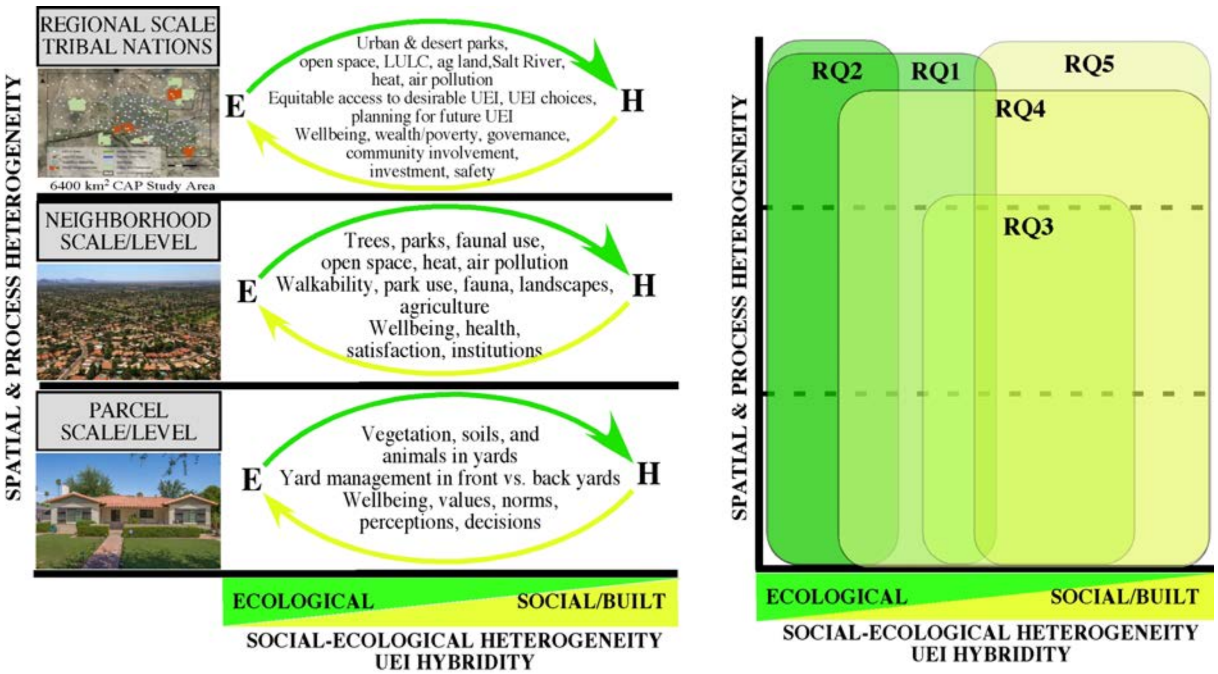

Figure 1.1: CAP V central conceptual framework. In both panels the horizontal axis represents the gradients of social-ecological heterogeneity and UEI hybridity; the vertical axis is spatial heterogeneity, with the three primary scales/levels at which we operate: parcels, neighborhoods, and the region, which includes the local Tribal Nations and regional municipalities. **Left panel**: The human (H)←→environment (E) feedbacks are shown with green and yellow arrows. Environment→human interactions are primarily ecosystem services/disservices at all levels. Human→environment interactions at the parcel scale include yard management decisions and drivers of those decisions and changes in yard structure and function. These interactions at the neighborhood scale include UEI preferences, legacies, access to UEI, and inequities in UEI access. Regional scale human→environment interactions include governance, institutions, and differences in land use/land cover (LULC) and associated UEI. Within the arrow ovals we show the various ways we will quantify heterogeneity at each scale/level. **Right panel**: The approximate domains in the CAP V heterogeneity space where each specific research question (RQ) will operate. The largely ecological questions (RQ1 and RQ2) are shown in green while the largely social questions (RQ5) are shown in yellow. The overlap in RQ domains demonstrates the overlap among them, the activities we will undertake to answer them, and overall programmatic integration.

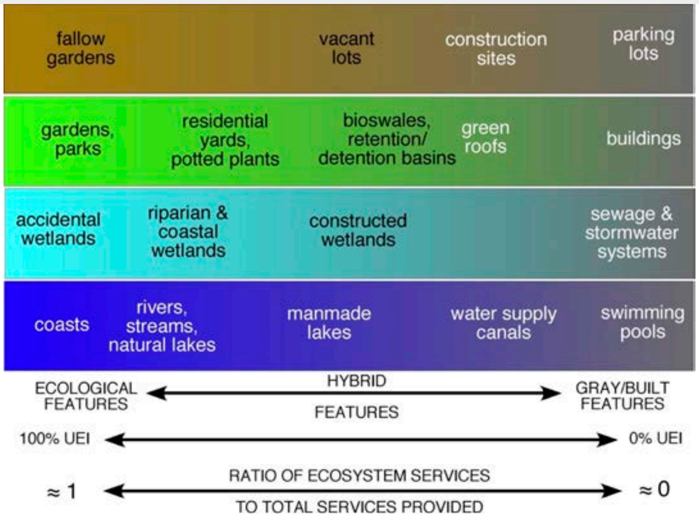

Figure 1.2: UEI hybridity gradient from purely ecological (left) to built infrastructure (right). The contribution of ecosystem services to total services delivered by the infrastructure is shown at the bottom. The four colors represent types of UEI: terrestrial vegetated (green) and unvegetated (brown), aquatic (blue), and wetland (turquoise). Examples of different types of infrastructure are shown to demonstrate the hybridity gradient (from Childers et al. 2019).

and evolutionary ecology. Our third question (RQ3) will address how UEI hybridity controls human←→environment feedbacks associated with urban heat, air quality, and water. Research to answer RQ3 will include exciting new initiatives on urban air quality and environmental justice. This work will be broadly social-ecological and focused on scales at which people experience their immediate environment. RQ4 uses a focus on human←→environment feedbacks to understand how interactions with nature affect the perceptions, management decisions, and wellbeing of urban residents. This RQ will operate in a broadly social-ecological domain, also at the scales where people live and work, and our research here will include an expansion of our community-based work. Finally, RQ5 will have a predominantly social science focus on how governance and institutions impact and are affected by human←→environment feedbacks associated with air quality, water, and food, including those that operate across spatial scales (Fig. 1.1). We will continue our successful scenarios work as part of this research, and this future-looking work will build transformational capacities to help our communities overcome legacies of neglect, inequity, disinvestment, and injustice.

II. Intellectual Merit: Results of Prior Support

Brief History of CAP LTER: CAP, one of the two urban LTER sites, has been the hub for studies of complex social-ecological systems in the Phoenix metro area (Fig. 2.1) since 1997. From CAP I (1997-2004) and II (2004-2010), we learned that land-use legacies explain ecological heterogeneity (e.g., past agriculture increased soil nitrogen and carbon; Lewis et al. 2006; Zhu et al. 2006) and that other social factors also explain ecological patterns (e.g., the "luxury effect," whereby biodiversity is higher in wealthier neighborhoods; Hope et al. 2003; Kinzig et al. 2005; Walker et al. 2009). Our regional-scale research showed a high degree of heterogeneity in atmospheric deposition (Lohse et al. 2008), soil nutrients (Kaye et al. 2008), the nitrogen budget (Baker et al. 2001), exposure to toxic hazards (Bolin et al. 2000), and landscape pattern (Luck and Wu 2002). We conducted historical analyses of land use/land cover change (LULCC; Li et al. 2014) to document the development and impact of the urban heat island (UHI) effect and how it disproportionately affects lower-income neighborhoods and communities of color (Baker et al. 2002; Harlan et al. 2006; Brazel et al. 2007; Li et al. 2016). In CAP III (2010–2016), we addressed feedbacks between social and ecological systems more explicitly, as mediated through ecosystem services (defined as the benefits that people derive from ecosystems; Jenerette et al. 2011; Cook et al. 2012; Hale et al. 2015; Larson et al. 2016; Palta et al. 2016). CAP research has always adopted a long-term perspective to understand how urbanization and associated heterogeneity (e.g., changes in population, demographics, land, and infrastructure) interact with external forces (e.g., global climate change, economic change, human movements) to determine urban social-ecological system structure and function (Grimm et al. 2008). The central conceptual frameworks of CAP III (Grimm et al. 2013) and CAP IV (2016-present; Childers et al. 2019) were based on ecological disturbance theory, but with human/social elements representing both drivers and responders (Grimm et al. 2017).

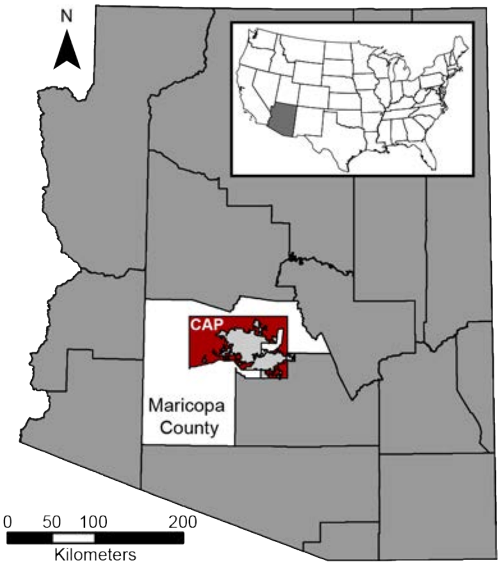

Figure 2.1: The 6400 km^2 CAP IV study area in central Arizona (red) that includes the Phoenix Metro Area (light gray within the red). Dark lines are county boundaries.

During CAP IV we used the results of our longitudinal social survey to delve more deeply into integrated social-ecological analyses (Andrade et al. 2019; Warren et al. 2019; Larson et al. 2020; Wheeler et al. 2020; Brown et al. 2021) and expanded our framing of ES to include bio-cultural services (Larson et al. 2019; Brown et al. 2020). We also unraveled complex patterns in residential land change and a decline in bird diversity coupled with human satisfaction, finding that residents of more bird-diverse neighborhoods are more satisfied with their local biodiversity (Warren et al. 2019; Stuhlmacher et al. 2020; Wheeler et al. 2020). We remain committed to studying urban ecosystems using an ecology *in*, *of*, and *for* cities framework (Grimm et al. 2000; Childers et al. 2015; McPhearson et al. 2016; Pickett et al. 2016); that is, to understand the city as a complex, adaptive social-ecological system and to bring our knowledge to action in the transition of cities to a more sustainable trajectory--for example, through future scenarios work (Iwaniec et al. 2020a). During CAP IV we also intensified our microclimatological investigations of urban heat using both empirical data (Kamarianakis et al. 2017; Li et al. 2017; Middel et al. 2019; Zhang et al. 2019; Middel et al. 2020; Wright et al. 2021), modeling (Middel et al. 2014, 2015), and management (Hondula et al. 2019). We initiated several new design-based collaborative projects focused on understanding how UEI may be best used to mitigate heat and enhance the wellbeing of residents (Guardaro et al. 2020). Finally, we also began a new urban air quality and environmental justice initiative during CAP IV, and we are excited to be significantly ramping up these efforts during CAP V.

B. Ten representative publications from CAP IV: Given that CAP researchers have produced more than 160 publications since 2017, this was a challenging exercise. Rather than use quantitative analytics (e.g., number of citations, journal impact factor) to make our choices, we focused on assessing the impact of publications and their analyses on the direction of CAP research, the use of long-term data, representation of both ecological and social-ecological approaches, cross-site findings, and important theoretical or conceptual contributions. In alphabetical order, the ten most representative CAP IV publications are:

Andrade, R., J. Franklin, K.L. Larson, C.M. Swan, S.B. Lerman, H.L. Bateman, P.S. Warren and A. York. 2020. Predicting the assembly of novel communities in urban ecosystems. Landscape Ecology. DOI: 10.1007/s10980-020-01142-1. This collaboration with colleagues from the BES LTER program used a metacommunity perspective to address how human activities influence the processes by which ecological communities are structured in urban ecosystems. The authors presented a framework that links social-ecological dynamics to ecological communities in order to understand multi-scalar biodiversity patterns and the assembly of novel communities in urban ecosystems. The first author was a CAP graduate student.

Banville, M.J., H.L. Bateman, S.R. Earl and P.S. Warren. 2017. Decadal declines in bird abundance and diversity in urban riparian zones. Landscape and Urban Planning. DOI: 10.1016/j.landurbplan.2016.09.026. This paper used CAP's long-term bird community data to examine long-term changes in bird assemblages at 12 riparian sites in Phoenix and the nearby Sonoran Desert. Engineered riparian sites supported more broadly distributed generalists while non-urban riparian sites supported more specialists. The authors found that bird species richness, diversity, and abundance declined across riparian types during the last two decades, even for common species. The first author was a member of the CAP staff.

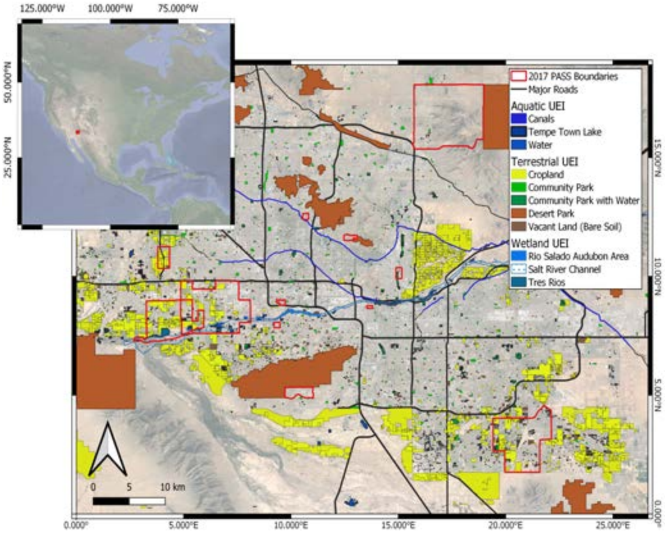

Figure 2.2: Distribution of various types of UEI (color coded per Childers et al. 2019) and their proximity to the 12 PASS neighborhoods (outlined in red). From Brown et al. 2020.

Brown, J.A., K.L. Larson, S.B. Lerman, D.L. Childers, R. Andrade, H.L. Bateman, S.J. Hall, P.S. Warren, and A.M. York. 2020. Influences of environmental and social factors on perceived bio-cultural services and disservices. Frontiers in Ecology and Evolution. DOI: 10.3389/fevo.2020.569730. This paper used CAP's long-term social survey data to investigate residents' perceptions of the coupled value of aesthetic and biological qualities as related to diverse UEI and other environmental and social factors. The results demonstrated the influence of place identity, neighborhood cohesion, and income on both biocultural services and disservices and underscored the added value of considering both the form of UEI and perceptions among people who live near it when designing and implementing infrastructure. Fig. 2.2 is from this publication. The first author was a CAP postdoc.

Childers, D.L., P. Bois, H.E. Hartnett, P.T. McPhearson, G.S. Metson and C.A. Sanchez. 2019. Urban ecological infrastructure: An inclusive concept for the non-built urban environment. Elementa: Science of the Anthropocene. DOI: 10.1525/elementa.385. This paper presented the concept of UEI as broadly inclusive of all nature in cities. It discussed why the UEI concept is more useful than other similar terms, such as green infrastructure or nature-based solutions. It presented several demonstrative case studies, including two from CAP, as well as the UEI hybridity gradient shown in Fig. 1.2.

Groffman, P.M., M.L. Cadenasso, J. Cavender-Bares, D.L. Childers, N.B. Grimm, J.M. Grove, S.E. Hobbie, L.R. Hutyra, G.D. Jenerette, P.T. McPhearson, D.E. Pataki, S.T.A. Pickett, R.V. Pouyat, E. Rosi-Marshall and B.L. Ruddell. 2016. Moving towards a new urban systems science. Ecosystems. DOI: 10.1007/s10021-016-0053-4. This theoretical paper was produced by a number of well-respected urban ecologists. It presented two critical challenges for ecosystem science that are rooted in urban ecosystems: 1) predicting or explaining the assembly and function of novel communities and ecosystems in cities; and 2) refining our understanding of humans as components of ecosystems. The authors argued that addressing these challenges is critical to the further development of sustainability science. They pointed to the need for a new initiative in urban systems science to catalyze the next wave of fundamental advances in ecosystem science and interdisciplinary science.

Iwaniec, D.M., E.M. Cook, M.J. Davidson, M. Berbés-Blázquez, M. Georgescu, E.S. Krayenhoff, A. Middel, D.A. Sampson and N.B. Grimm. 2020a. The co-production of sustainable future scenarios. Landscape and Urban Planning. DOI: 10.1016/j.landurbplan.2020.103744. This paper presented findings from CAP's scenarios and futures work that used an approach focused on the co-development of positive and long-term alternative future visions. Through practitioner and academic stakeholder collaborations, this research integrated participatory scenario development, modeling, and qualitative scenario assessments. This work creates opportunities to bridge science and policy by building anticipatory and systems-based decision-making and research capacity for long-term sustainability planning.

Larson, K.L., E.A. Corley, R. Andrade, S.J. Hall, A.M. York, S.A. Meerow, P.J. Coseo, D.L. Childers and D.M. Hondula. 2019. Subjective evaluations of ecosystem services and disservices: an approach to creating and analyzing robust survey scales. Ecology and Society. DOI: 10.5751/ES10888-240207. This paper focused on public perceptions of ES/EDS, noting that ecosystem properties and functions can produce beneficial or detrimental outcomes for human wellbeing. It used a robust approach to measure beliefs about ecosystem services and disservices using CAP's long-term social survey data. The analysis found distinctive patterns in resident views of desirable and undesirable biota, benefits and risks pertaining to heat and stormwater, recreational and aesthetic value, and societal nuisances and problems.

Ripplinger, J., S.L. Collins, A.M. York and J. Franklin. 2017. Boom-bust economics and vegetation dynamics in a desert city: How strong is the link? Ecosphere. DOI: 10.1002/ecs2.1826. This analysis used a key long-term CAP dataset to explore how The Great Recession affected the dynamics of residential vegetation diversity. The authors found that the housing market boom–bust episode acted as a socioeconomic driver of overall plant community composition. Many neighborhoods in Phoenix were hit hard by foreclosures and home abandonment. Once lawn management stopped, the plant communities reverted to a more "weedy" composition. The first author was a CAP graduate student.

Warren, P.S., S.B. Lerman, R. Andrade, K.L. Larson, and H.L. Bateman. 2019. The more things change: Species losses detected in Phoenix despite stability in bird–socioeconomic relationships. Ecosphere. DOI: 10.1002/ecs2.2624. This analysis used CAP's long-term bird community data and long-term social survey data to measure changes in residential bird communities, species–habitat relationships, and human perceptions of bird species diversity. The analysis found that desert specialist species were associated with neighborhoods with high per capita income rates and lower percentages of renters and Hispanic/Latinx residents. Non-native species were positively associated with neighborhoods with water-intensive vegetation. Habitat–species relationships did not change, but a significant loss of bird species was observed and resident satisfaction also declined, suggested that people perceived this environmental degradation.

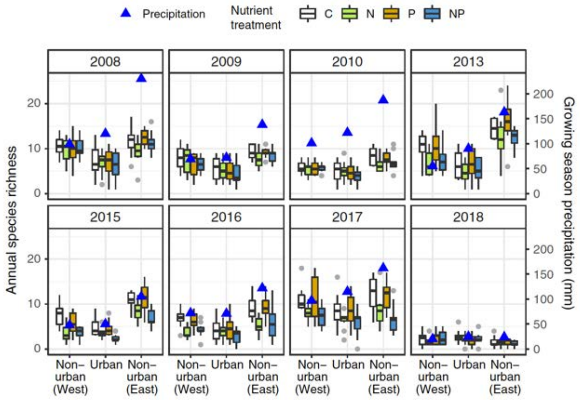

Figure 2.3: Annual plant species richness and precipitation (blue triangles) for control (C) and N, P and N+P additions. Diversity was lower in N-enriched and urban plots and water availability in both current and previous growing season led to increased diversity (Wheeler et al. 2021).

Wheeler, M.M., S.L. Collins, N.B. Grimm, E.M. Cook, C. Clark, R.A. Sponseller, and S.J. Hall. 2021. Water and nitrogen shape winter annual plant diversity and community composition in near-urban Sonoran Desert preserves. Ecological Monographs. DOI: 10.1002/ecm.1450. This paper used data from CAP's long-term N and P fertilization experiment in urban and Sonoran Desert parks and preserves to test how nutrient availability interacts with growing season precipitation, urban location, and microhabitat to affect winter annual plant diversity. The analysis found reduced taxonomic diversity of annual plants in N-enriched and urban plots and that water availability in both current and previous growing seasons was a primary control on annual plant diversity. Fig. 2.3 is from this publication and the first author was a CAP graduate student.

C. Data Availability: Information Management (IM) is an integral component of CAP. Our IM goals include supporting data acquisition, archiving well-structured and well-documented long-term research data in data repositories for the benefit of the scientific community, decision-makers, and public, enabling and promoting dataset discovery and access and providing leadership and education on sound data-management practices. CAP IM adheres to LTER Network data access policies. We have adopted the Creative Commons CC0 data-use agreement for most datasets, and we strive to make data available in a timely manner. Most CAP data are housed in the Environmental Data Initiative (EDI) data repository, where 236 CAP LTER datasets are currently available. We detail these datasets in our Data Table (Supplementary Documents). In this table we highlight datasets related to publications of note and cross-reference key datasets to Table 3.1 (Section III.B). The CAP IM team continually strives to improve the quality and scope of its services, as detailed in our Data Management Plan (Supplemental Documents).

D. Results of Broader Impacts: The broader impacts of CAP IV include: 1) developing and maintaining a comprehensive, spatially explicit, long-term database on social-ecological variables (see Section II.C for details); 2) expanding awareness of cities as social-ecological platforms for solving sustainability challenges; 3) co-producing knowledge and future scenarios with decision-makers (*sensu* Ostrom 1996; Grove et al. 2016; Iwaniec et al. 2020a); 4) integrating education and outreach into our work; and 5) growing the diversity and breadth of the CAP community both substantially and substantively. Our information management (IM) program is well-developed; datasets are archived, documented, up to date, and accessible. We have communities of practice with regional NGOs, community-based organizations, local and regional governments, school districts, and individual schools to promote appreciation and understanding of urban challenges and solutions (see Section IV.B & C). We have leveraged major new grants in support of decision-making on water and heat challenges, resilience to extreme events under climate change, and the convergence of social, ecological, and technological approaches to enhance urban resilience (Section III. D). The co-production of knowledge is a major success of our scenarios and futures work, and the co-production of innovative designs incorporating UEI into new projects is a major success of our urban design work. The motivation behind the new Phoenix Office of Heat Response and Mitigation draws from extensive CAP research at the intersection of people, climate, and ES, including foundational studies from CAP I and II (Harlan et al. 2006; Brazel et al. 2007). We have continued to support education at all levels: K-12 education with our award-winning Ecology Explorers program; 39 undergraduate students supported through our REU program; 58 students funded since 2010 through our novel Grad Grants program; and funding of several postdocs.

E. Results of Supplemental Support: In 2019 CAP was awarded a RET supplement to support research experiences by two teachers from the Roosevelt School District of Phoenix, which includes the predominantly Hispanic/Latinx and underserved South Phoenix neighborhood where we focus much of our community-based work. The teachers spent the summer working in Kevin McGraw's lab learning urban bird ecology and ecophysiology. In 2020 CAP was awarded a larger RET supplement that supported two teachers from the Sunland Elementary School, which is also in the Roosevelt School District. They spent Summer 2020, the 2020-21 school year, and Summer 2021 working with Jenni Vanos on air quality research. The supplement supported the installation of three sophisticated air quality sensors on their school campus that continue to provide the teachers and the school with access to real-time data. They have been using these sensor data in their classes and to inform administrators about the air quality issues being faced by students at their school. Finally, in 2020 CAP was awarded an equipment supplement to purchase a new field vehicle. This request was justified on safety grounds because at the time two of the vehicles in CAP's feet were nearly 20 years old and had logged more than 150,000 miles.

F. Response to Previous Review (October 2020 site review): Our virtual midterm site review was held in mid-October 2020, and we received the review report and NSF's summary of key points on March 3, 2021. Here we briefly summarize the main points from this external review and our responses to each:

- Integration: Programmatic integration is an ongoing challenge for all LTER programs, and the review team noted that we need to work on this. Our eight Interdisciplinary Research Teams (IRTs) have served us well as organizational and coordination tools, but we acknowledge that this structure does not lend itself to communicating how CAP science is integrated. To that end, we re-organized ourselves for our CAP V planning by forming four larger and far more interdisciplinary research *themes*. Throughout CAP V we will use these themes to guide our integration and synthesis efforts. Also, during CAP IV we restructured many of our long-term observational efforts to co-locate sampling sites as much as possible; we discuss these changes in Sections III.B and III.C.
- Use and analysis of long-term data: The review team suggested that we were not adequately using or informing our long-term data. To explore how widespread the use of our long-term data is, we analyzed all CAP IV publications and tracked how many of them analyzed or relied on our long-term data. The count ranged from 22% to nearly 50%. We then isolated all publications in which a student was first author. The rationale here was that student projects are often short-term research. After doing that, the percentage of publications that explicitly analyzed CAP long-term data rose to 40% - 65%. The papers that did not report long-term data mostly focused on species-specific research (e.g., physiology, distribution), on spatial comparisons (e.g., of soil characteristics), or were theoretical or conceptual papers. This analysis makes clear the use and value of our long-term data for CAP research, as has been the case for many of our 822 papers published since CAP I was funded in 1997.

  The review team also suggested that CAP’s portfolio of long-term experiments is modest. This conclusion is somewhat true, because of the difficulties of conducting traditional, controlled ecological experiments in a city. In CAP V we propose a greatly expanded focus on long-term social-ecological research in our 12 Phoenix Area Social Survey (PASS) neighborhoods, where the residents themselves are the experimental drivers as they make decisions about how to design and manage their yards. The research questions presented here are informed by our long-term data and will require continued collection of those data; we will also propose new long-term data collection initiatives here.

- Social-ecological research: The review team suggested that CAP is starting to "lag behind the leading edge" of social-ecological integration. We argue that CAP researchers and science continue to lead the discipline of urban ecology—empirically, theoretically, and conceptually. Interdisciplinary and integrated social-ecological research has always been a hallmark of CAP, and this proposal richly cites these contributions in blue. To ensure we will continue to do so, during early years of CAP V we will transition our leadership to having two co-directors: An ecosystem ecologist and a cultural geographer. This was notably lauded in our site review report. Our CAP V organizational structure (Section III.A and Project Management Plan) will continue to be deeply interdisciplinary and social-ecological. We understand that LTER sites must be "first and foremost centers of ecological research", and CAP will continue to be a leader in basic urban ecological research. But this should not diminish the value of our interdisciplinary social-ecological focus, nor our transdisciplinary convergence focus.
- Diversity, equity, and inclusion: The review team was disappointed in the diversity of the CAP community. We took this criticism to heart and began addressing it immediately. Early in 2021, before receiving our site review report, we recruited new scientists to contribute to CAP and we now have 13 new BIPOC colleagues (nine are Black, three are Indigenous, one is Latino, and eight are women). The expertise these scholars bring to CAP includes urban wildlife ecology, urban air quality, food security, and tribal community development. Four of these new members are in key leadership positions in CAP V (Project Management Plan) and our Environmental Justice and Equity thematic group was one of four that led development of this proposal (Section III.A). The review team did praise us for our Justice Equity Diversity and Inclusion (JEDI) Committee. That committee has been very active, and among the activities they sponsor is a monthly Equity Circle. We highlighted their work, and JEDI in general, in a strong way at our 2021 and 2022 All Scientists Meetings. We also have a strong JEDI Action Plan that includes mechanisms for enhancing JEDI in CAP and assessing progress toward meeting these goals. We are proud of our progress on this front to date and will continue to grow CAP in important, inclusive, and diverse ways (see Section IV. A for more details).

III. Intellectual Merit: Proposed Research – CAP V Integrated Research Plan

A. Study Area and CAP V Organization: The CAP study area includes 6400 km^2 of rapidly urbanizing central Arizona—effectively the entire Phoenix metro area (Figs. 2.1 and 3.1). The region is home to nearly five million residents. The CAP study area includes 26 independent urban municipalities, agricultural areas, and undeveloped Sonoran Desert. It surrounds and is bordered by three Indigenous tribal reservations that are home to Akimel O'otham, PiiPaash, and Yavapai peoples. The CAP enterprise is structured around the six objectives we presented in Section I. B. Supporting these are five Interdisciplinary Research Teams (IRTs) that are centered on our five specific research questions. Each IRT has three or more co-leads, identified in Section III.C and in our Project Management Plan, and everyone in the CAP community is a member of at least one of these IRTs. Our research questions, and the justification and methods behind them, were developed by four thematic groups that we formed to plan and develop CAP V: human-environment interactions (coleads: Bateman, McGraw, Schell); urban hydroclimate (coleads: Fuller, Meerow, Hondula); environmental justice and equity (co-leads: Berbés, Hale, Vanos); and temporal change (coleads: Coseo, Iwaniec, Jackson). These themes will continue to structure our cross-program integration and synthesis throughout CAP V.

B. Long-Term Datasets and Experiments: The foundation for all CAP research remains our long-term observational datasets and experiments, many of which began with CAP I (Table 3.1; Fig. 3.1). The original intent of many of these long-term datasets was to document the dynamic heterogeneity of our 6400 km^2 study area. In many cases we have met this goal, so early in CAP IV we re-designed some of our observational data collection to enhance spatial and temporal coordination among long-term datasets and to more clearly integrate the long-term data with the research activities of our IRTs and with our

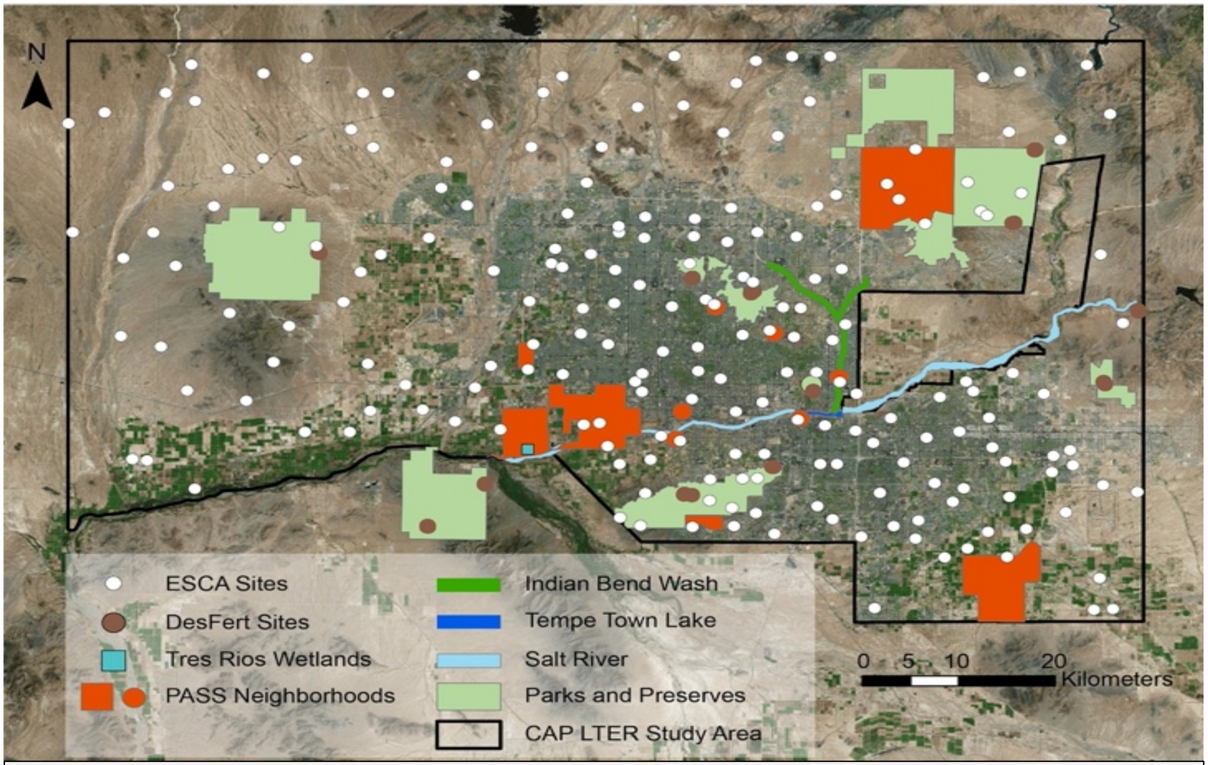

Figure 3.1: CAP study area (also shown in red in Fig. 2.1) showing the specific locations of many of our core long-term observational and experimental sites and where much of the CAP V place-based research will be carried out.

central conceptual framework (Fig. 1.1). These redesigns freed up critical resources (technician time, driving time, supplies, sample analysis costs), enhancing our ability to explore new research questions in CAP V while taking full advantage of our long-term data to answer them. Most importantly, where we rethought our long-term data collection, our re-designed sampling schemes *maintained the long-term integrity of our existing datasets*.

We organize our long-term observational datasets and experiments around an ecology *in*, *of*, and *for* and *with* cities structure (Table 3.1; *sensu* Grimm et al. 2000; Childers et al. 2015; Pickett et al. 2016; Pickett et al. 2021). The ecology *in*, *of*, and *for* cities construct represents a “prepositional journey” that urban ecology has made in the last 25 years as it has expanded from the early study of ecological pattern and process in urban environments (*in* cities) to the interdisciplinary recognition that humans are a critical part of urban ecosystems (*of* cities), then to the realization that a transdisciplinary convergence approach to urban ecology, focused on “knowledge to action”, is needed to make cities sustainable and resilient in the future (*for* and *with* cities). The summary of our long-term datasets and experiments in Table 3.1 includes the scientific lead(s), the year data collection began, the LTER core areas being addressed, and the research questions that will use those data. We will highlight each of these datasets in the Research Plan below using text boxes located [to the extent possible] where a dataset is first mentioned.

C. <u>CAP V Research Plan and Specific Research Questions</u>: CAP research has long made numerous contributions to urban ecology. We will continue our investigations into the relationships urban dwellers have with their environment by quantifying how human activities affect the structure, function, and heterogeneity of UEI and, in turn, how ES/EDS provided by UEI affect people (**Research Question 1**). The urban environment affects the life history traits of non-human organisms in myriad ways, and we will continue to explore the eco-evolutionary dynamics and evolutionary responses that result from these interactions (**Research Question 2**). CAP has always had a major focus on urban hydroclimate, and our work on heat and microclimate expanded considerably in CAP IV. We will continue to expand this

Table 3.1: Long-term datasets & experiments (ecology *in/of/for/with* distinctions per Childers et al. 2015; Pickett et al 2021), including the responsible researcher, year started, LTER core areas involved, and research questions (RQ) that will use the data. Core area abbreviations: PP=primary production, PC=population/community dynamics, ND=nutrient dynamics, OM=organic matter dynamics, D=disturbance, LU=land use/land cover change, and SES=social-ecological systems dynamics.

L-T dataset or experiment	Lead(s)	Started	Core areas	Research Questions
I. Ecology in cities datasets/exp's				
Bird communities, residential bird surveys	Lerman & Warren	2000	PC, LC, SES	RQ2,4
Health & coloration in urban & rural birds	McGraw	2010	PC, D, SES	RQ2
Herpetofaunal communities	Bateman	2012	PC, LU, D, SES	RQ2,4
Ground-dwelling arthropods	McCluney	1998	PC, LU, D, SES	RQ2
Wildlife, Salt River corridor	Lewis	birds: 2013 cameras 2018	PC, LU, SES	RQ2,4
Wildlife, urban parks	Hall	2020	PC, LU, SES	RQ2,4
Ecology, behavior, and evolution of black widow spiders	Johnson	2006	PC, LU, D, SES	RQ2
Tres Rios constructed treatment wetlands	Childers	2011	ND, OM, SES	RQ1,3
Tempe Town Lake	Hartnett	2005	ND, OM, D, SES	RQ1,3
II. Ecology of cities datasets/exp's				
Land Use-Land Cover Change (LULCC)	Frazer & Turner	2000	LU, SES	RQ1,2,3,4,5
Phoenix Area Social Survey (PASS)	Larson	2005	D, SES	RQ1,2,4,5
Ecological Survey of Central Arizona (ESCA)	Earl	2000	PP, ND, OM, LU, SES	RQ1,2,4
DesFert - plant & soil dynamics	Ball	2007	PP, ND, OM, D	RQ1
DesFert - atmospheric deposition	Stewart	2007	ND, D, SES	RQ1
DesFert-precip. mod. (DroughtNet)	Collins	2018	PP, ND, OM, D	RQ1
Urban stormwater dynamics	Grimm	2009	ND, OM, D, SES	RQ1,3
Regional drinking water quality	Fox	1998	ND, OM, D, SES	RQ3,5
Socioeconomics, urban agriculture	Aggarwal	2005	D, LU, SES	RQ4,5
Urban microclimate & heat	Middel	2015	D, LU, SES	RQ3,4
III. Ecology for and with cities datasets/exp's				
Scenarios & futures	Iwaniec	2015	D, LU, SES	RQ5
Edison Eastlake neighborhood redevelopment & microclimate	Hondula	2019	D, LU, SES	RQ3,4,5
Urban air quality & environmental justice	Vanos	2018	SES	RQ3,4,5

research in CAP V to include a new focus on urban air quality and its effects on city residents (**Research Question 3**). Urban heat, air quality, and water have many influences on people, plants, and animals, and the distribution of UEI often controls these influences. In CAP V we will explore how heterogeneity in the distribution of UEI and its benefits affects both people and non-human organisms. To do so, we will expand our community-based work in marginalized and neglected neighborhoods and [for the first time] include work with local Tribal Nations and Indigenous communities, centering residents in the search for UEI-based solutions that will improve their immediate environments and wellbeing (**Research Question 4**). In doing so, we will explore how different theories of change and worldviews shape key actors as well as cultural and policy changes that lead to more just, sustainable, and resilient futures. In CAP IV we introduced a novel and highly acclaimed research focus on participatory scenario building. This line of research featured prominently in the UREx SRN program (2015 - 2022) and other more recently funded convergence-based research (Section III.D). In CAP V we will expand our scenarios and futures work into the realm of urban transitions while investigating how governance structures operating at the various scales shown in our central conceptual framework (Fig. 1.1) affect the urban environment today and into the future (**Research Question 5**). The first necessary step in pursuit of many of our research questions will be to educate and inform CAP researchers about how successful community-based work should be done, and our JEDI Committee has already begun this process in preparation for these exciting CAP V endeavors.

Research Question 1 (RQ1): **How do the collective activities of a heterogeneous urban population influence the structure and function of ecosystems at local to regional scales, including benefits and feedbacks to those people?** *Co-leads: Ball, Grimm, Throop*

RQ1 Rationale: The structure and function of ecosystems and ecological dynamics within and adjacent to cities are strongly affected by human activities, including continued urbanization and land use change (Text Box 2; Fig. 3.2). Although several global-change drivers interact at various scales to drive urban ecosystem structure and function, compounding impacts to ecosystems and people, it is unclear whether in the future the suite of interacting changes at local (urban) scales will continue to have a greater influence than environmental changes at regional to global scale (Grimm et al. 2008; Fig. 3.3). For example, global climate change resulting in intensified and prolonged drought may interact with N deposition from vehicle emissions at the regional scale to change soil nutrient availability, trajectories of plant growth, and community structure in desert parks and preserves. Similarly, LULCC and associated management may alter plant communities at local scales, changing habitat and faunal species diversity, and rising temperature may shift species distributions. In turn, long-term ecosystem change in the CAP study area at both local and regional scales affects critical and implicit ES/EDS to city residents, such as recreational amenities, access to nature, and amelioration of extreme heat. *We expect accelerating change in these environmental drivers to result in continued detectable ecosystem responses in our existing long-term experiments at the regional scale (DesFert, DroughtNet) and at local scales (ESCA, urban stormwater dynamics, Tempe Town Lake, and Tres Rios).*

In the DesFert experimental sites (Text Box 3), we have demonstrated the influence of N deposition on annual plant communities (Wheeler et al. 2021), biocrust abundance and stoichiometry (Ball and Alvarez Guevara 2015), and soil biogeochemical fluxes (Hall et al. 2011, Ball et al. 2019, Bilderback et al. 2021). As DesFert constitutes the longest spatially and temporally explicit dataset of N deposition in drylands, we were able to document a dramatic decline in N deposition during the pandemic "Anthropause", particularly in parks within the urban matrix. Whether this pulse change in deposition will be detected in changes in soil nutrients, plant growth, or biomass of desert annuals is to be seen. Similarly, *we expect to see a press effect of declining N deposition over the next decade as a concerted societal shift to electric vehicles takes hold*. Two DesFert sites are home to DroughtNet experimental rainout shelters, in collaboration with the SEV LTER. These experiments are simulating the long-term effects of declining precipitation that we expect over the next several decades, allowing us to test the *effect of anticipated*

TB 2: Land-use land-cover change (LULCC)

Documenting the spatial heterogeneity of changes in urban land cover is arguably our most fundamental endeavor. We generate time series of LULCC products at spatial resolutions of 1m, 30m, and 250m. The CAP data portal currently holds: 1) 1m resolution land-cover classifications for 2010 using NAIP (National Agricultural Imagery Program) data based on 12 land classes (Li et al. 2014); 2) 30m resolution Landsat-based land-cover classifications for 1985, 1990, 1995, 2000, 2005, 2010, 2015 and 2020 based on 11 classes (Fig. 3.2). Continuing in CAP V, we are reworking our 2015 and 2020 NAIP-based land-cover classifications and hierarchically integrating these data with the 30m and 250m data. In addition, we have completed: 1) a 1m resolution "open" or "vacant" land cover for 2010 and 2015 (Smith et al. 2017; Smith et al. 2020); 2) a 1985-2020 (5-year intervals) time series of land-surface temperature at 30 m resolution; and 3) are developing alignments of the 1m resolution coverage to address CAP V research questions (Fan et al. 2015; X. Li et al. 2016).

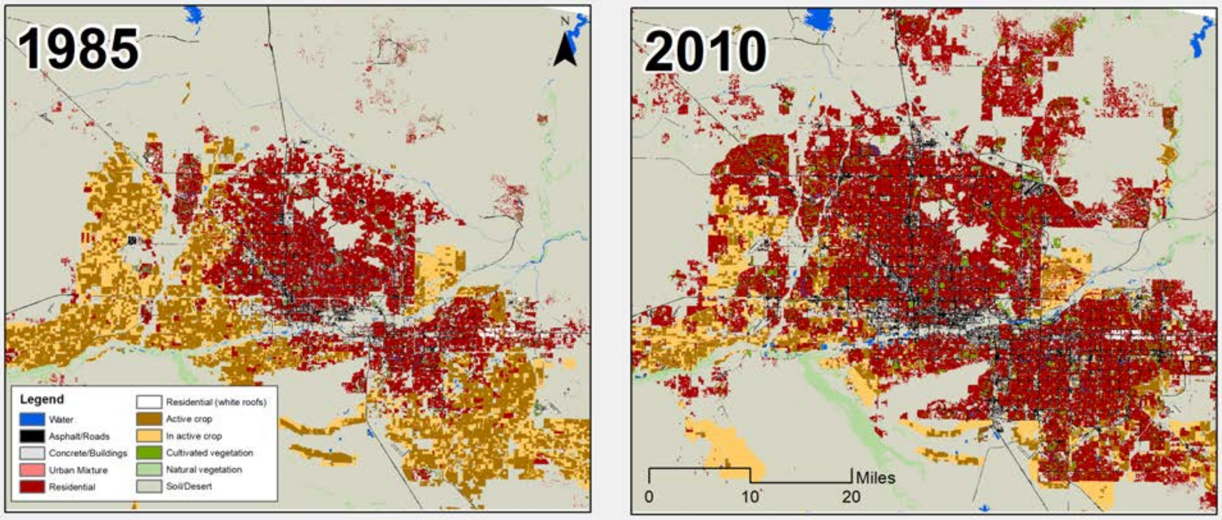

Figure 3.2: Land use classifications that include roughly the first half of CAP funding. Created using 30m Landsat imagery and an updating-backcasting classification method that creates continuity in the land cover classes across the multiple time periods (Zhang and Li, 2017).

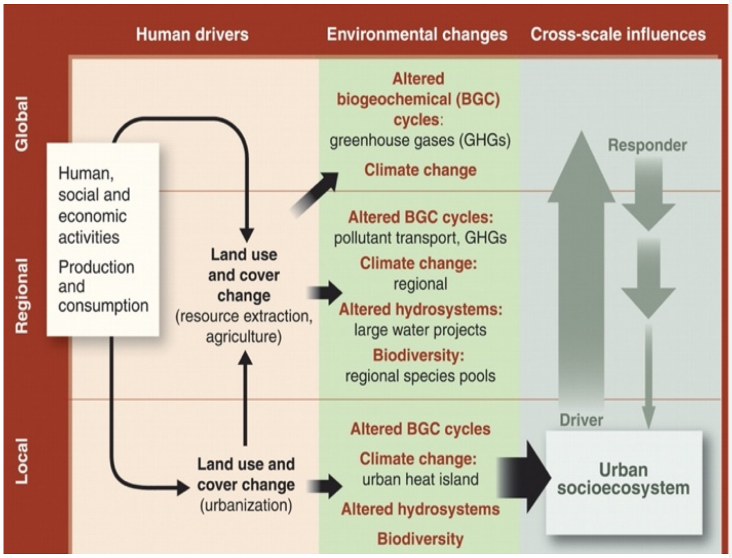

Figure 3.3: Framework showing urban social-ecological system (lower right) as a driver of (upward arrows) and responder to (downward and horizontal arrows) environmental change. Land use and cover change is a master driver at all scales of biogeochemical cycles, climate, hydrosystems, and biodiversity. Although at present large local environmental changes (horizontal black arrow) are greater than those that filter down from the global scale (small downward gray arrow), it is unknown whether (or when) the relative dominance of global and local drivers will shift. Not all possible interactions and drivers are shown. From Grimm et al. (2008).

increased drought severity on plant communities and ecosystem properties in these popular desert parks and preserves.

TB 3: Desert Fertilization Experiment (DesFert)

Since 2006, the DesFert experiment has simulated how atmospheric enrichment from the city affects nearby native desert ecosystems using a fully factorial nitrogen and phosphorus fertilization design at 15 sites in desert parks and preserves. DesFert doubles as an urban-rural gradient experiment in which we explore the impacts of the urban environment and nutrient enrichment on biotic and abiotic ecosystem properties in protected desert areas (Hall et al. 2011; Kaye et al. 2011; Sponseller et al. 2012; Ball and Guevara 2015; Davis et al. 2015; Cook et al. 2018; Ball et al. 2019; Bilderback et al. 2021; Wheeler et al. 2021). Parameters include plant community composition (Wheeler et al. 2021; Fig. 2.3), primary production, soil biogeochemistry, and atmospheric deposition. We complement these dry deposition measurements with an urban site located on ASU's campus. These measurements of ambient N deposition comprise the longest spatially and temporally explicit dataset of N deposition in drylands (Cook et al. 2018). In 2018, colleagues from the SEV LTER Program installed rainout shelters at two DesFert sites, with seven rainout shelter plots and seven control plots each. Thanks to this collaboration, CAP is now part of the global DroughtNet network.

We will continue to use our LULCC data at a 1-m resolution to test hypotheses about human activity and ecosystem response. For example, *we expect that the continued transition from grass lawn-dominated to xeriscaped landscapes to translate into lower N loads to aquatic recipient systems*. Spatially intensive sampling every six years through ESCA (Text Box 4) documents the ecological effects of dramatic changes in land use at local scales, lending support to the primacy of local drivers in controlling structure and function (Fig. 3.3). Since we began this sampling more than 20 years ago, more than a third of our sites have transitioned from agriculture or desert to urban or suburban land use, and we can now evaluate the impact of that transition; for example, in terms of soil nutrient storage (Hope et al. 2005) or vegetation cover and carbon storage (McHale et al. 2017) at the whole-system level, and in terms of human decisions at the parcel scale. All of these changes also alter habitat for fauna, and we track changes in animal communities— birds, mammals, herpetofauna, ground-dwelling arthropods—in both space and time. Notably, many of these ecological communities include charismatic animals that people directly associate with their environment and that affect their perceptions of nature in the city (see also RQ2).

Long-term change in biogeochemical signals of urban aquatic recipient systems reflect LULCC, changes in stormwater management practices, and climate variability. Based on past work (Hale et al.

TB 4: Ecological Survey of Central Arizona (ESCA)

With ESCA, we have documented environmental heterogeneity in both space and time at 204 re-visit sampling sites every five years since 2000. With these data we have documented the ecological effects of converting agricultural and desert to urban land covers, and now roughly two-thirds of our 204 sites are urbanized. We have used these data to quantify spatial variation in soil black carbon (Hamilton and Hartnett 2013), soil microbial communities (Cousins et al. 2003; Rainey et al. 2005), biogeochemistry (Hope et al. 2005; Oleson et al. 2006; Zhu et al. 2006; Zhuo et al. 2012), and various flora (Hope et al. 2003, 2006; Stuart et al. 2006; Dugan et al. 2007; Walker et al. 2009) and fauna (Bang and Faeth 2011). We have also developed innovative statistical approaches to assess biophysical and social controls on spatial patterns of biophysical variables (Kaye et al. 2008; Majumdar and Gries 2010; Majumdar et al. 2008, 2010, 2011). The regular 2021 ESCA sampling had to be postponed until 2022 because of the pandemic. Hereafter we will conduct ESCA sampling on a 6-year rotation to more logically match our funding cycles. For the 2027 sampling we will relocate 60 already-developed sites to the 12 PASS neighborhoods in order to routinely sample the ecological and biogeochemical characteristics of five parcels in each neighborhood. We will sample these 60 residential parcels every three years, beginning in 2024, allowing us to document ecological and social heterogeneity both within and across these neighborhoods.

TB 5: Urban stormwater dynamics

Our long-term stormwater quality and hydrology research focuses on urban watersheds with different types of infrastructure (Hale et al. 2015). We study how LULCC, type and configuration of storm-water infrastructure, and climate variability control hydrological and biogeochemical retention and stormwater transport (Grimm et al. 2005; Larson et al. 2013; Hale et al. 2015). Our study site, Scottsdale's Indian Bend Wash (IBW), is a ≈240 km^2 catchment that is almost completely urbanized. It follows a gradient of development age from its southern confluence with the Salt River and Tempe Town Lake (TTL) to its northern headwaters in the McDowell Mountains (Roach et al. 2008). Concurrent with this oldest-to-newest development gradient, stormwater infrastructure includes infrastructure types with varying effectiveness at retaining water and nutrients (Hale et al. 2015). We sample chemical constituents of stormwater during all runoff-producing storms. Using these data we found that urban streams in Arizona are less "flashy" than their non-urban counterparts (McPhillips et al. 2019), in direct contrast to prevailing theory of the urban stream syndrome (e.g., Walsh et al. 2005).

TB 6: Tempe Town Lake (TTL)

Since 2005, we have measured temperature, pH, conductivity, dissolved oxygen, total nitrogen, and dissolved organic carbon concentrations and quality in TTL (Fig. 3.4). The lake is unique in that it is occasionally emptied and refilled after river-flow events, or once after a dam failure. These major disturbances are opportunities to study dynamic evolution of the lake to new limnological states. Early in CAP IV we installed an *in situ* datasonde to measure water quality, including optical dissolved organic carbon characteristics, at high temporal resolution. Initially, we supplemented the sensor data with twice-weekly samples. We are developing calibrations that relate optical characteristics to bulk organic carbon concentrations and have developed statistical models that allowed us to reduce the number of discrete samples needed over time.

TB 7: Tres Rios constructed treatment wetlands

We have been conducting research, mostly with student volunteers, at Tres Rios since 2011. This 42 ha "working" wetland (21 ha of vegetated marsh, 21 ha of open water) was built in 2010 to remove nutrients from effluent being discharged into the Salt River by the largest wastewater treatment plant in Phoenix. Water leaving the Tres Rios wetlands flows into a new riparian restoration city park, and the roughly 10km reach of the Salt River downstream of the outfall is the only place in the entire valley where the river is perennial and functions ecologically and hydrologically as a river ecosystem. By combining our plant productivity and nutrient budgets we have shown near-complete uptake of nitrogen by the marsh (Weller et al. 2016; Treese et al. 2020; Childers 2020), and we have demonstrated, for the first time, plant mediation of surface water hydrodynamics in this wetland (Fig. 3.5; Sanchez et al. 2016; Bois et al. 2017; Childers 2020). We regularly host research charrettes with the City of Phoenix Water Services Department to communicate findings to their managers and staff.

TB 8: Phoenix Area Social Survey (PASS)

The PASS has been conducted approximately every 5 years since 2006. The sampling design is a random sample of residents in neighborhoods stratified by income, race/ethnicity, and location in central to fringe areas. Previous research incorporating PASS data has demonstrated social and spatial heterogeneity of environmental dynamics, including heat stress and vulnerability (Harlan et al. 2012), landscape preferences and practices (Larson et al. 2009a; 2010; 2017; Wheeler et al. 2020), and perceived ecosystem dis/services associated with local environmental features (Larson et al. 2019; Brown et al. 2020; Meerow et al. 2021). In recent years (2017 and 2021), PASS research underscored integrated social-ecological analysis based on proximity to various forms of UEI (Fig. 2.2) where other CAP research is occurring (Andrade et al. 2020; Brown et al. 2021). In CAP V we will move PASS implementation to a 6-year cycle.

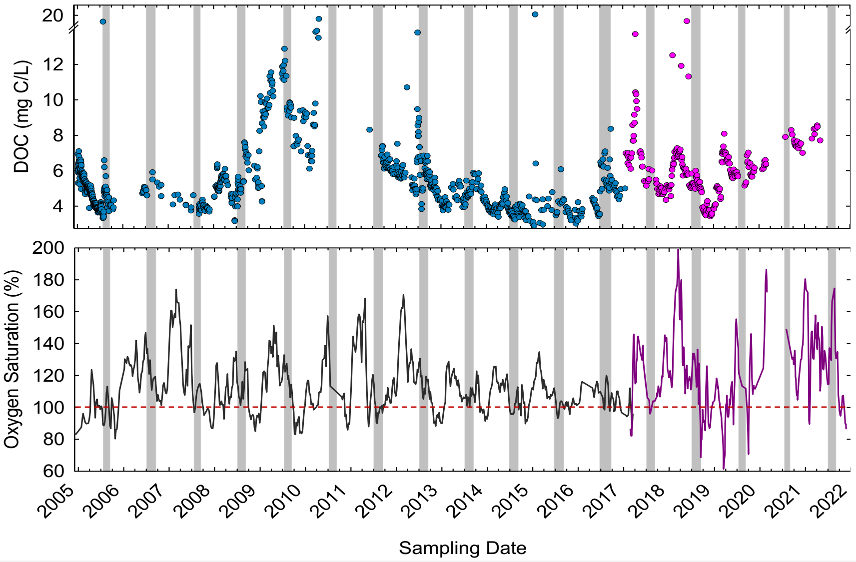

Figure 3.4: Dissolved organic carbon (DOC; top) and oxygen saturation (bottom) for Tempe Town Lake from 2005 to 2022; data from CAP IV are indicated in pink. The gray vertical bars indicate summer monsoon periods when there can be significant rainfall. DOC varies significantly from year to year and reflects inputs from rainfall/run-off, human management, and primary production. Oxygen saturation state is presented as a 3-week moving average and is nearly always super saturated (note the red line at 100%) during the spring and summer, when phytoplankton production and seasonal warming contribute to the saturation state.

2015) *we expect that both land cover (and land management, i.e., fertilization) and stormwater management (i.e., infrastructure such as retention basins) will most strongly influence nutrient exports from urban catchments.* Our stormwater research focuses on the hydrologic and biogeochemical dynamics in a popular park known as the Scottsdale Greenway (IBW from Text Box 5). This award-winning example of UEI protects Scottsdale residents from flooding while providing the valuable service of mediating the quality and quantity of stormwater that flows into Tempe Town Lake (Text Box 6). The iconic TTL, located in the Salt River channel, provides valuable recreational services and an economic stimulus to the City of Tempe. The shoreline of the lake continues to be developed at a rapid pace. Management of the lake, including the episodic flood-induced draining of the lake, is a strong driver of its structure and function. Our long-term data have demonstrated that the lake moderates local climate and is a significant sink for atmospheric carbon. *We expect that local shoreline development will begin to have a stronger effect on lake chemistry than watershed contributions from IBW.* Finally, the Tres Rios constructed wetland receives inputs from a large wastewater treatment plant (Text Box 7). We have documented the structure and function of this "working ecosystem" in partnership with the City of Phoenix Water Services Department since 2011. Tres Rios cleans the water that flows through a riparian restoration public park immediately downstream, and the roughly 10 km stretch

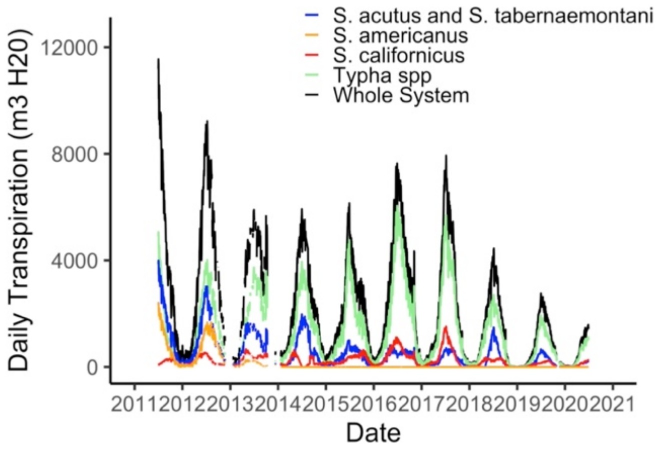

Figure 3.5: Daily transpiration volumes by plant species groups from the 21 ha of marsh in the 42 ha system. This water loss drives the "biological tide" (Bois et al. 2017). When we combined our water and N budgets, we found that, over a decade of study, on average the biological tide was responsible for half of the N uptake by the marsh (Treese et al. 2020; Childers et al. 2020).

of the Salt River that is below Tres Rios is the only segment of the river in the valley that is perennial and living. Tres Rios is a habitat oasis for a wide variety of birds, mammals, and other animals for both the park and the river, providing both expected and implicit ES/EDS to residents near and far.

RQ1 Approach: We will continue the DesFert experiment with the embedded Drought-Net rainfall reduction experiment through CAP V to evaluate the ecological consequences of *increased drought owing to climate change* coupled with a predicted *press decline in N deposition* resulting from human decisions and actions (i.e., shift to electric vehicles). We will continue to produce our 1-m resolution LULCC analysis every five years, allowing us to quantify LULCC for the city as a whole and for the ESCA sampling sites (the next 6-year sampling is scheduled for 2027). We will modify ESCA protocols in CAP V to reflect our increased emphasis on social-ecological research in the 12 PASS neighborhoods (Text Box 8), allowing us to more closely *link these long-term ecological data with residents' perceptions, values, and behaviors.* We will strategically relocate a subset of ESCA sites with residential land use to yards in those neighborhoods, with five ESCA yards per neighborhood, and we will sample these yards every three years following standard ESCA protocols in order to capture more rapid ecological changes in these places where we also quantify resident perceptions, values, motivations, and decisions

We will continue our IBW stormwater research as well as our long-term efforts in Tempe Town Lake and the Tres Rios wetlands through CAP V. Continued LULCC, development along the shore of Tempe Town Lake, and population growth (and associated wastewater loads) will be quantified and compared with our long-term data on stormwater chemistry from IBW, Tempe Town Lake biogeochemical dynamics and metabolism, and efficacy of the Tres Rios wetlands in removing N. Through this coupling of ecological and social data, we will analyze perceptions of air, water, and environmental quality, as well as attitudes toward local wildlife in our study neighborhoods. We will bolster the PASS data with semi-structured interviews of PASS survey respondents and people using IBW, Tempe Town Lake, and Tres Rios--each of which has a PASS neighborhood nearby--to assess perceived ES/EDS being provided by distinct UEI. Finally, we will assess the equitable distribution of ecosystem functions and benefits by considering how perceived and measured ES/EDS are distributed across the study neighborhoods, in relation to nearby UEI, as well as socio-demographics from PASS and from our socio-economic analyses.

Research Question 2 (RQ2): **How do differences in organismal life-history traits, over short- and long-time scales, respond to and shape eco-evolutionary dynamics and evolutionary responses (e.g. via plasticity, adaptation) to human-induced changes in climate, resources, and niche availability in urban environments?** *Co-leads: Meerow, McGraw, Schell*

RQ2 Rationale: Phoenix is one of the hottest major cities in the United States, and temperature is increasing due to both climate change and the urban heat island effect. Metropolitan Phoenix is also undergoing a period of rapid population growth. In fact, in the last decade Phoenix grew faster than any major U.S. city (11.2%; U.S. Census Bureau 2021). Population growth has fueled rapid urban development and expansion across the desert region, resulting in major changes in land cover and consequently availability of habitat and resources (Wentz et al. 2007). From 1970 to 2018, average temperatures in Phoenix rose more than 4° Fahrenheit (2.2° Celsius; Climate Central, 2019). As an extreme example of climatic change and urbanization, the CAP study area provides an opportunity to examine how different organisms adapt to anthropogenic change.

A growing literature across an array of taxa has highlighted widespread, complex, and varied organismal responses that facilitate survival in cities (Miles et al. 2021; Ouyang et al. 2018). For instance, certain species shift their activity patterns to avoid peak human activity (Gaynor et al. 2018), while others increase their dietary breadth to exploit novel urban niches (Pagani-Nunez et al. 2019). Remarkably, several emerging studies provide compelling evidence to suggest that species are rapidly evolving to withstand anthropogenic challenges (Alberti et al. 2017, 2020; Szulkin et al. 2020), including intensifying urban heat islands (Angilletta et al. 2007; Diamond et al. 2018), nutritionally deficient food subsidies (Harris and Munchi 2017), and reduced water availability (Brans et al. 2018). Biodiversity is an essential

TB 9: Bird communities, including those in PASS neighborhoods

We have learned a great deal about the influence of human activities and behaviors on urban biodiversity (Shochat et al. 2004, Shochat et al. 2006, Shochat et al. 2010, Lerman et al. 2012a,b) and, in turn, how biodiversity links to human perceptions, values, and actions (Lerman and Warren 2011; Andrade et al. in press a,b), and how patterns change over time (Warren et al. 2019). Habitat–species relationships remained unchanged, but with significant losses of species over time (Fig. 3.6; Allen et al. 2019; Warren et al. 2019). These losses parallel declines in human satisfaction of the bird communities (Warren et al. 2019). In CAP V we will continue to quantify species abundance/distribution for birds (Banville et al. 2017). Our residential bird sampling is focused on the 12 PASS neighborhoods and other bird sampling sites are co-located with the DesFert sites, with other desert parks/preserves where we are pursuing question-driven research, and along the Salt River, where we are also sampling herpetofauna and other wildlife.

component bolstering our ability to withstand the global climate crisis (Grimm et al. 2008); *it is imperative that we investigate how organismal traits respond to environmental challenges over both short and long timescales, as well as how those changes scale to impact community-level processes.*

In parallel, an emerging consensus has underscored the urgency of articulating how heterogeneity in human social drivers of cities affect nonhuman organisms (Avolio et al. 2021; Schell et al. 2020b), as well as how future landscape changes may facilitate or impede adaptive responses to those changes (Des Roches et al. 2021). This growing narrative captures our collective anxiety around accelerating environmental crises induced by anthropogenic climate change. Hence, to fully predict overall species resilience to impending landscape transformations, *we are necessarily required to uncover the substantive links between societal function and species responses*. CAP was principally built on, and has been a major architect in, the establishment of the social-ecological frameworks motivating a new wave of research linking organismal and ecological change to human social dynamics (Des Roches et al. 2021; Leong et al. 2018; Magle et al. 2021; Ouyang et al. 2018; Sepp et al. 2018; Schell et al. 2020a). As such, *we are uniquely positioned to build substantive links between urban ecology and evolution, human social systems, and overall ecosystem resilience* (Fig. 3.7).

RQ2 Approach: We will capitalize on three primary long-term data sources to address our question about organismal change in response to human←→environment feedbacks: 1) species occurrences; 2) organismal phenotypic and life-history traits; and 3) urban social-ecological factors. To track the abundance and distribution of plant and animal species over space and time in Phoenix, we will use our long-term census data on birds (Text Box 9), ground-dwelling arthropods (Text Box 10), and plants from ESCA, but also complement with other more restricted datasets on taxa including herpetofauna (Text Box 11: Banville and Bateman 2012), black widow spiders (Text Box 12), and mammals (Text Box 13; Magle et al. 2021). However, key to studying directions and rates of population- and community-level changes in species is *the monitoring of specific targets and indicators of selection* (i.e., which environmental pressures map onto specific trait changes in organisms; Text Box 14). Such organismal traits include direct indicators such as body size but also fitness proxies for success (e.g., lifespan, generation time, reproductive

TB 10: Ground-dwelling arthropods

Our 20-year dataset has been important in early studies of effects of cities on arthropod communities (e.g. McIntyre et al. 2001; Cook and Faeth 2006; Bang and Faeth 2011), as well as recent high-profile findings of global declines in terrestrial insects (van Klink et al. 2020) and in improving our understanding of drivers of community stability across landscapes and systems (Patrick et al. 2021). Sampling has occurred quarterly since 1998 (Fig. 3.8) across subsets of 57 total locations. We will continue to sample 12 sites that are co-located with long-term bird community sampling locations, maintaining our ability to examine long-term trends at desert and residential locations. Eight additional sites in the McDowell Sonoran Preserve are monitored by citizen scientists.

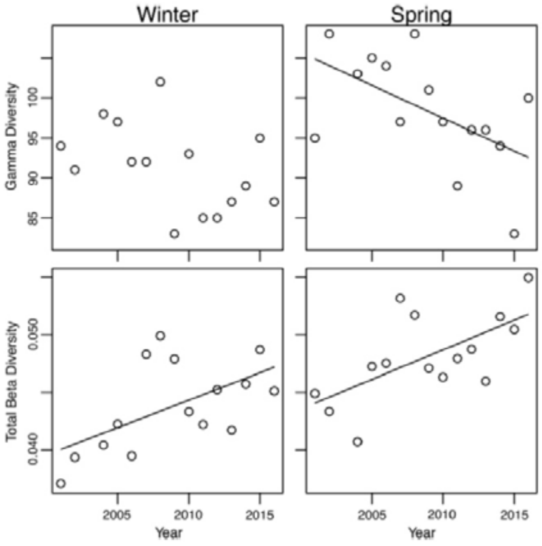

Figure 3.6: Bird community response variables at regional and landscape scales. Gamma diversity = # species observed; Beta diversity = community uniqueness (from Allen et al. 2019).

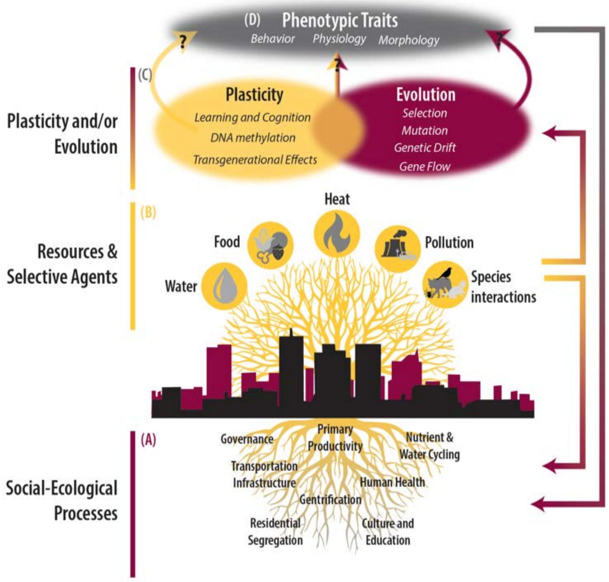

Figure 3.7: Conceptual framework being used to guide the evolution and adaptation research proposed for RQ2.

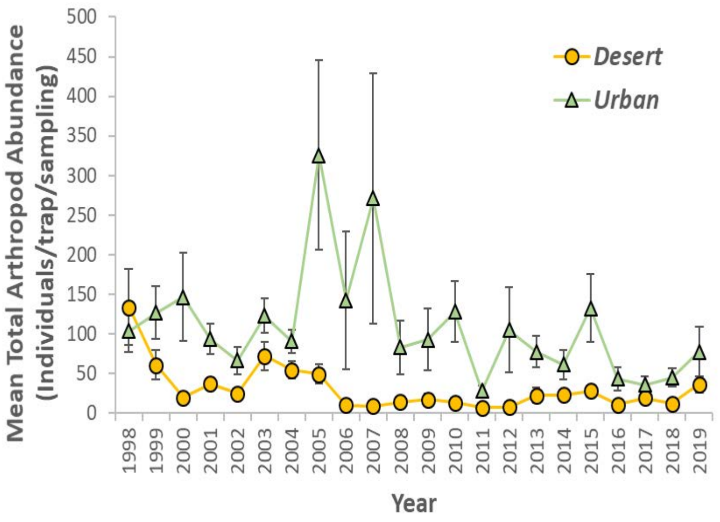

Figure 3.8: Ground-dwelling arthropod abundance across the CAP study area, aggregated by urban vs. non-urban Sonoran desert sites. Abundances are consistently higher in urban environments (see Bang and Faeth 2011 for site locations and methodological details).

TB 11: Herpetofauna communities

Since 2012 we have quantified the reptile and amphibian communities that inhabit the Salt River corridor along a sampling gradient from upstream rural environments in the Tonto National Forest to and through the urban matrix. We sample herpetofauna communities at seven sites three times a year in seven permanent 10m X 20m plots at each site. Some locations are near accidental urban wetlands in the Salt River bed (*sensu* Palta et al. 2017). Reptile and amphibian communities tend to have greater species richness in restored urban reaches and non-urban reaches compared to dry urban reaches (Fig. 3.9; Banville and Bateman 2012; Bateman et al. 2015).

TB 12: Ecology, behavior, and evolution of black widow spiders

For more than 10 years we have been studying this urban arthropod pest to disentangle the urban variables that shape its phenotype. We have found that family of origin as an important variable in determining many life history traits (Johnson et al. 2010; 2014) and found few phenotypic differences between urban and desert spiders (e.g. Gburek and Johnson 2018), suggesting a great deal of plasticity in black widow phenotype (Halpin and Johnson 2014). Recent work suggests dramatic genetic divergence between urban and desert spiders (Miles et al. 2018). The Urban Heat Island affects black widows: Their refuges are up to 6°C hotter than surrounding areas during extreme summer months (Johnson et al. 2019), and this dramatically slows development, compromises body mass, reduces web building in adults, and heightens levels of spiderling aggression towards prey, including conspecifics (Johnson et al. 2020; deTranaltes et al. 2021).

TB 13: Wildlife use of urban environments

During CAP IV we implemented three studies across an urbanization gradient using remote wildlife cameras to evaluate the trade-offs for wildlife between obtaining limited resources (e.g., food and water) and avoiding anthropogenic risks. From 2018-2020 we used a stratified random sampling design to deploy 50 wildlife cameras across urbanization gradients. In 2020 we deployed 43 wildlife cameras along the Salt River corridor to understand how the interactions among water, riparian vegetation, and urbanization influence wildlife populations. We collaborate with partners across the United States to understand how wildlife populations responded to the pandemic shutdown (Zellmer et al. 2020; Bates et al. 2021), how human disturbance influences wildlife populations (Suraci et al. 2021), and how socio-economic factors affect wildlife communities across the US (Magle et al. 2021). Notably, this research has allowed us to recruit two new urban wildlife scientists to CAP in early 2021: Nyeema Harris (Yale Univ.) and Chris Schell (Univ. California-Berkeley). Finally, we have deployed 40 wildlife cameras in open space parks to better understand how income and ethnic demographics of neighborhoods correlate with wildlife populations.

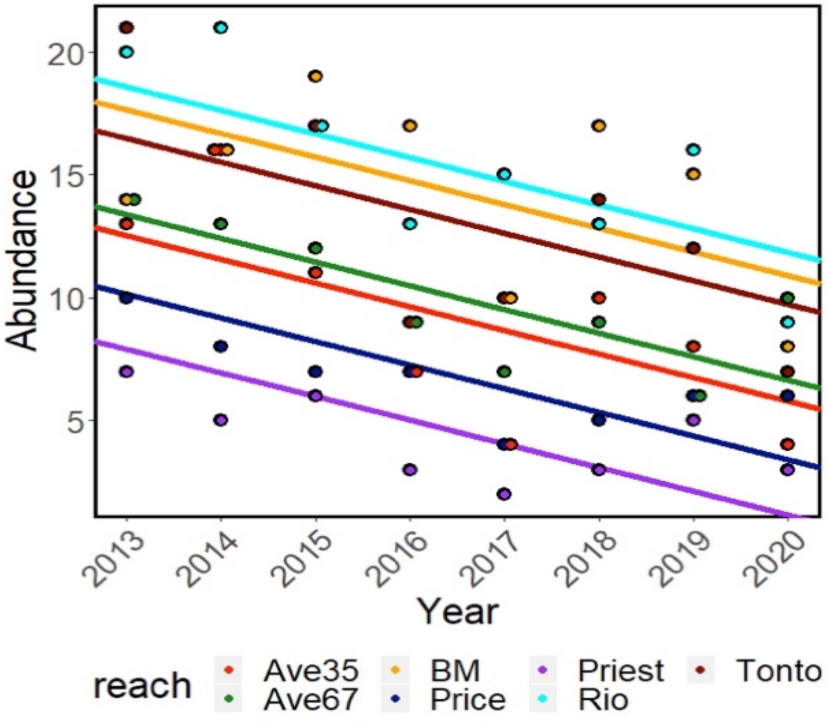

Figure 3.9: Herpetofauna abundances at seven urban and non-urban sites along the Salt River. Abundances have been consistently declining at all locations for the last 10 years (see Banville and Bateman 2012 for site locations and methodological details). We sample herpetofauna communities at seven sites three times a year in seven permanent 10m X 20m plots at each site. These sites include both urban locations and sites in the upstream Tonto National Forest. Some locations are near accidental urban wetlands (*sensu* Palta et al. 2017).

rate) or components of gene flow (e.g., dispersal/migration patterns, habitat connectivity, home range size). Thus, we will layer this trait-based approach to studying organisms and species, coupled with life-history comparative data across species from the literature, onto both the species distributional and the environmental/resource databases. These trait-based organismal datasets include: 1) new morphological measurements on CAP's archived ground-dwelling arthropod (e.g. body size, allometry) and plant samples (e.g. leaf/plant size); 2) long-term phenotypic and physiological investigations of emblematic individual species (spiders: Johnson et al. 2019; birds: Giraudeau et al. 2018); and 3) literature compilation of data on key life-history features of local species, including home range size, reproductive rate, generation time, lifespan, and body size (e.g., Minias 2016, Santini et al. 2018, Hantak et al. 2021). Last, we will map our census/sampling locations of plants and animals in the Phoenix area to our long-term social-ecological datasets, including urban climate, LULCC and how it relates spatially to specific types of UEI, and PASS. The PASS data in particular provide unique insights into human attitudes and behaviors related to diverse wildlife taxa and resource provisioning (e.g., native plantings, bird feeding) at an individual parcel scale. We will use these data to investigate how differences in organismal evolutionary changes across the city are perceived (or not) and may reflect recent alterations to human and urban activities at the parcel, neighborhood, and regional scales. At broader scales, we will link predicted habitat occupancy from camera traps to public perceptions and attitudes in PASS neighborhoods, to local microclimate, and to nearby UEI features that offer varying levels of habitat and other ES/EDS.

TB 14: Health and coloration in urban and rural birds

For the past decade, we have monitored several metrics of individual quality—notably, indices of health state and expression of condition-dependent plumage coloration—in a widespread bird species (the house finch, *Haemorhous mexicanus*) at several urban, suburban, and rural sites in the CAP study area. We have captured and measured nearly 5000 finches across nine sites since 2011 and have shown that urban finches harbor greater parasite burdens (Giraudeau et al. 2014; Sykes et al. 2021) and exhibit less colorful plumage (Hasegawa et al. 2014; Giraudeau et al. 2015, 2018; Sykes et al. 2021) than finches from rural areas. Recently, we also detected the first historical disappearance of avian poxvirus infection from our finch populations (i.e. at all capture sites), which overlapped with the pandemic-driven societal shutdown (i.e. the "Anthropause") in 2020. This disease returned in our populations in May 2021, and more rapidly in urban areas, providing evidence from a natural experiment that relaxation of human activities may significantly reduce stress and health challenges of native urban wildlife.

***Research Question 3 (RQ3):* What are the spatial and temporal relationships between heterogeneous UEI and urban heat, air, and water, and how do UEI influences on these parameters affect people, plants, and animals?** *Co-leads: Fuller, Hartnett, Hondula*

RQ3 Rationale: The deployment and management of UEI to achieve desired societal outcomes is prominently featured in many city strategic plans, including in the CAP domain. UEI also appears in the recently passed federal Infrastructure Investment and Jobs Act, including through a $500 million Healthy Streets Program. Implicit in the logic driving these investments is the expectation that UEI will effectively mitigate contemporary societal challenges, including urban heat, air pollution, and flooding, and thus have positive outcomes related to human health and wellbeing, ecosystem function, and urban infrastructure and economies (e.g., Brown et al. 2015; Li et al. 2017; Kim and Coseo 2018; Hobbie and Grimm 2020). Previous CAP research has illuminated some of these relationships, including links between landscape composition/configuration and land surface and air temperatures (Myint et al. 2015, Jenerette et al. 2016, Li et al. 2016, Zhang et al. 2019) and how landscape configuration relates to biometeorological indices that more comprehensively reflect the human energy balance (Zhao et al. 2018, Middel et al. 2019, Wright et al. 2021). We have also used cross-sectional approaches with physical, social, and health data to demonstrate how landscape characteristics are associated with inequitable spatial patterns in human health and wellbeing (Harlan et al. 2013, Jenerette et al. 2016; Palta et al. 2016). CAP researchers have recently produced a comprehensive evaluation of how more than 50 different types of urban infrastructure (including many different types of UEI, such as a wide range of tree species) affect environmental factors that influence the human energy balance and human thermal comfort (Text Box 15; Middel et al. 2021). We will continue to evaluate the tradeoffs among shade provisioning by different tree species, transpiration-driven cooling, and water consumption. Yet the shade-cooling-water nexus represents only a fraction of the factors necessary to consider as municipalities set and implement tree canopy-cover goals with a variety of ES in mind (Hondula et al. 2018;

TB 15: Urban microclimate and heat

We have been investigating the impact of urban form, design, and landscaping on microclimate since CAP III. Early studies quantified the cooling benefits of increased tree canopy cover, various landscaping styles, and "cool roofs" on near-ground air temperature (Middel et al. 2014, 2015). We also use our LULCC data to quantify the effects of urban configuration and composition on surface temperatures (Li et al. 2016; Wang et al. 2018; Zhang et al. 2019). During CAP IV, we have expanded our heat research to include observational transects with the biometeorological cart "MaRTy" (Fig. 3.10; Middel et al. 2019; Middel et al. 2020). Thermal exposure assessments have been conducted in PASS neighborhoods (Wright et al. 2021), in the Edison Eastlake neighborhood (Text Box 18), and at the Phoenix Zoo. In addition, annual long-term monitoring of trees in Tempe's Rio Salado Arts Park began in 2017 to track shade benefits over time. During CAP V, we will also continue to collect standard microclimate data at two existing meteorological stations—one in an urban park and one in a desert preserve. Lastly, we will continue to monitor urban meteorological conditions with our rooftop Earth Networks station on ASU's campus. This station monitors CO_2 and CH_4 and transmits data in real time to the network's website and a local news station.

TB 16: Urban air quality and environmental justice

During CAP IV we began an exciting new initiative focused on urban air quality and environmental justice in two historically segregated and neglected regions of Phoenix--South Phoenix and West Phoenix. We have installed 22 solar-powered air quality sensors (Clarity Nodes) that track $PM_{2.5}$ and NO_2 concentrations in these neighborhoods. Data from these sensors are transmitted to campus and are available in near-real time, providing an accessible, unrestricted data platform. Some of these sensors are located on school campuses in South Phoenix, including at the school of our two RET teachers, and at Paideia Academies, a Title I charter school that serves a student population that is 85% underrepresented minority and lower income. Notably, our relatively new research in this arena has allowed us to expand our environmental justice work into the realm of human health and to recruit two new urban air quality scientists to CAP in early 2021: Christina Fuller (Georgia State Univ.) and Vernon Morris (ASU).

Figure 3.10: The portable MaRTy cart used for collecting microclimate data along urban transects (see Middel et al. 2019 for details).

Jennings et al. 2021; Roman et al. 2021). Other factors we will evaluate include plant and tree species selection, siting, and maintenance needs including irrigation.

A fundamental necessity for rigorous assessment of spatial and temporal relationships between UEI and urban heat, air, and water, and people is the availability of data that quantify the distribution and function of UEI. Continuing to map the locations of a variety of UEI features, which we have already begun (Fig. 2.1; Brown et al. 2020), will be critical in advancing CAP research while also informing future planning and scenario development. As one example, the most recent publicly available data concerning tree cover in the CAP domain consist of our high-resolution 2015 LULCC data and point estimates for tree locations derived from 2014 United States Geological Survey LiDAR flights. Our ability to model future UEI impacts and support regional decision-making will be enhanced with more spatially explicit information about sites that are suitable for UEI deployment and more realistic representations of future UEI configurations beyond the “all” or “none” frameworks that have characterized previous efforts (e.g., Georgescu et al. 2014). It is also important to be cognizant of the fact that not all UEI is viewed positively as providing local benefits (Larson et al. 2019; Brown et al. 2020).

RQ3 Approach: In CAP V, we will examine spatial and temporal heterogeneity in UEI and urban climate, including urban heat, air quality (Text Box 16), and water quality and quantity (Text Box 17), as well as the relationships among these variables. This will include a focus on how heterogeneity in UEI, in both space and time, and urban climate affect human health and wellbeing, as well as perceptions about the environment (using PASS data from 2017, 2021, and 2027) and who benefits from heterogeneous UEI. We will also advance our ongoing work measuring heat and air quality disparities at different scales from single schools, such as Paideia Academy, to neighborhoods, such as Edison Eastlake (Text Box 18) and South Phoenix, to the metropolitan region. We will use these data and models to evaluate how effectively various UEI interventions mitigate these locations and the region more broadly. Our ecohydrological research will build on our long-term research on urban stormwater (IBW), water supply, water as designed and managed UEI (Tempe Town Lake), and water being returned to the environment (the Tres Rios constructed wetland). Much of this urban hydroclimate research is being co-produced through innovative partnership models (see Section III.D), which we will also evaluate.

We will expand our inventories of UEI in the CAP study area, which will include comparisons of different assessment techniques. We will build partnerships with third-party data providers (e.g., Planet Labs, with whom ASU is an official learning partner, with free data access) who are collecting data at increasingly higher spatial and temporal resolution. We will use our ESCA data and UEI mapping from our LULCC products (per Brown et al. 2020) to calibrate models built from newer and higher-resolution platforms and to create more detailed historical estimates of the legacies of UEI in the CAP study area (e.g., tree counts or canopy cover at monthly to annual cycles). This will facilitate more rapid and robust estimates of UEI at critical CAP sites (e.g., PASS neighborhoods) in the future. New LiDAR data that will be available from the USGS in Summer 2022 will be an important component of this effort.

Our methodological approaches to understanding the relationships among UEI, urban heat, air, water, and people will continue to include spatial regression models/geographically weighted regression, time

TB 17: Regional drinking water quality

Fifty percent of the water used by humans in Phoenix is taken from the Salt and Verde Rivers upstream of the city. Since 1998 we have sampled water quality monthly in this system at 20 lake, river, urban canal, and finished drinking water sites. We analyze samples for an array of constituents, and we leverage these datasets with cooperation from local and federal agencies. Our long-term data on water quality have improved the understanding of taste and odor occurrence, control, and treatment (Fig. 3.11; Bruce et al. 2002; Hu et al. 2003; Westerhoff et al. 2005), DOC and algal dynamics (Westerhoff and Anning 2000; Nguyen et al 2002; Baker et al. 2006; Westerhoff and Abbaszadegan 2007), and disinfection byproducts (McKnight et al. 2001; Yang et al. 2008; Hanigan et al. 2015). We support an online forum to discuss regional water quality issues and our monthly water quality reports provide timely input to water providers for process control, reservoir and canal management, and drinking-water treatment.

series analysis, physical models, and machine learning approaches for classification (e.g., Zhao et al. 2018; Middel et al. 2019; Zhang et al. 2019). We will expand our use of structural equation models (e.g., Chakalian et al. 2019) to explore complex multi-scale, multi-factor associations between UEI and a wide range of outcomes, and we will add new tools including atmospheric chemistry and dispersion models to evaluate air pollution concentrations.

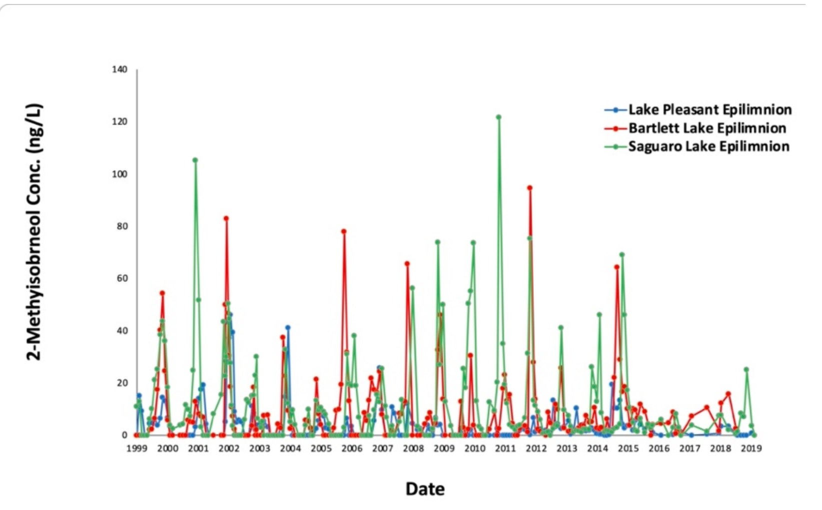

Figure 3.11: Monthly methyl-isoborneol (MIB) concentrations in surface water of three reservoirs that supply the Phoenix region with water. MIB is an algal metabolite occurring mainly in winter that humans can smell at concentrations as low as 10 ng L^{-1}. That people can detect this compound at such low concentrations means that it strongly links ecosystem processes (algal primary production) with human perceptions of water quality (odor).

Our air quality work began recently, during CAP IV, and we will strengthen it considerably in CAP V, motivated by continued concern about the effects of air pollution on people and ecosystems, by the environmental injustices associated with inequitable air pollution burdens and by long-term regional challenges in meeting federal air quality guidelines. In CAP V, we will enhance the spatial coverage of our air quality instruments with more real-time sensors to monitor particulate matter, NO_2, O_3, and volatile organic carbon. This expanded network of air quality monitoring will fill two major gaps: 1) most of these pollutants are not measured by the state regulatory monitoring network, so our work will capture baseline measures of their levels while tracking concentrations for long-term assessment of impacts and interactions; and 2) previously these pollutants were measured at only a few state regulatory sites, preventing any spatial quantification of environmental injustices related to air quality at the neighborhood scale. We will fill these gaps by growing our network of sensors that will characterize air pollutants at a fine, and more equitably accurate, resolution while also analyzing perceptions (from PASS data) about air quality and related ES/EDS.

TB 18: Edison Eastlake redevelopment and microclimate

In 2017, CAP researchers partnered with several NGOs and community groups to create a community-city-university partnership model called the Nature's Cooling System Partnership (Guardaro et al. 2020). The partnership developed a research-to-practice urban ES/EDS justice model. The City of Phoenix received a $30 million HUD urban redevelopment grant to redesign and rebuild an affordable housing project in the Edison Eastlake neighborhood. As partners on this project, CAP scientists are studying how the microclimate characteristics of the new development will compare to the pre-demolition conditions, and how to best design the new housing and associated landscapes to optimize resident comfort and wellbeing. An array of microclimate monitoring stations located throughout the neighborhood collected pre-intervention data and used ENVI-met modeling to explore new neighborhood designs (Crank et al., 2019). We combined a variety of social data, including satisfaction surveys, "heat walks" with MaRTy (Fig. 3.10; Dzyuban et al., 2020), and design workshops to collect resident input on their preferred future neighborhood design (Guardaro et al., 2020).

Research Question 4 (RQ4): **How can co-production with communities of practice integrate the multiple ways people experience nature--expressed through perceptions, management decisions,**

and wellbeing--as it is shaped by the distribution of UEI and associated ES/EDS? *Co-leads: Bateman, Coseo, Hale*

RQ4 Rationale: Broadly defined, nature consists of green space, open space, or undeveloped landscapes and biotic components that are not cultivated for commercial purposes (Ellen 1996; Simberloff 2014; Ducarme and Couvet 2020), although this explicit separation of nature from humans has been challenged (Mace 2014). Experience with nature and wildlife influences human wellbeing (Pyle 1993; Chamberlain et al. 2019). Cities are considered more "livable" when they provide equitable access to nature through parks, open spaces, and habitat for urban wildlife (Houck and Cody 2000; Lafortezza et al. 2009; Aronson et al. 2017). Yet, in modern cities, access to nature and positive outcomes for human wellbeing and health are often inequitably distributed. For example, people living in predominantly White and wealthier areas tend to have more positive experiences with desirable nature (Hope et al. 2008; Larson et al. 2019; Bateman et al. 2021). Declining interactions with nature diminish wellbeing and may create negative attitudes or fear towards nature (Soga and Gaston 2016). A major focus of this RQ will be on how we can achieve more equitable access to nature and just outcomes for human wellbeing. We will draw on theories from CAP IV of co-production (Watson 2014; Childers et al. 2015) and design experiments (Felson & Pickett 2005; Childers et al. 2015) while addressing theoretical gaps such as concepts of belonging (Barry & Agyeman 2020) and repairing community relationships (Jackson 2021). In CAP V we will grow critical partnerships with local, Indigenous, and traditional knowledge holders for a more diverse and complete understanding of UEI design and stewardship of human←→environment interactions. We define equitable UEI as an availability of nature that provides quality ES in the places where people live, work, and learn, and where ES quality is self-defined by those communities. Equitable access includes convenient and welcoming contact with recreational places such as urban parks, desert preserves, and other open spaces.

Views about nature vary based on local UEI features, personal and community values, lifestyles, and experiences (Andrade et al. 2019; Brown et al. 2020; Wheeler et al. 2020). In Phoenix, residential yards connect people to nature through the presence of trees (Hope et al. 2003), birds (Lerman and Warren 2011), reptiles (Ackley et al. 2015; Bateman et al. 2021), and black widow spiders (Trubl et al. 2011). These experiences can translate into attitudes and perceptions of nature, both positive and negative, that may feed back to actions that influence UEI. For example, vegetation cover and plant types influence environmental attitudes and actions (Fernandes et al. 2019; Brown et al. 2020) and people who prefer colorful birds tend to provide resources for birds (Cox and Gaston 2015; Andrade et al. in press). Similarly, negative attitudes (disgust, fear) towards nature may lead people to avoid or remove organisms that are deemed undesirable (Bixler and Floyd 1997; Bateman et al. 2021). Moreover, people do not share common views about nature (Davey et al. 1998; Larson et al. 2019; Brown et al. 2020; Andrade et al. in press) and how people design and manage their yards affects biodiversity, water use, and other ES/EDS (Larson et al. 2016; Warren et al. 2019; Wheeler et al. 2020).

At broader scales, municipal, regional, and Tribal Nation governance decisions about the provisioning and management of UEI amenities form important human←→nature feedbacks across the urban ecosystem (Brown et al. 2021; Larson et al. 2020). We have shown that greater ES, such as bird diversity, are available to wealthier communities and those near desert preserves (Lerman and Warren 2011; Larson et al. 2019; Andrade et al. in press) while lower-income and Hispanic/Latinx communities are often near types of UEI that engender negative perceptions of nature (ephemeral river channels, vacant lands, and agricultural areas; Brown et al. 2020). During CAP IV we strengthened connections to an emerging community of UEI practitioners and communities to better integrate and broaden our research. We linked knowledge of peoples' experiences with nature to more equitable UEI design and management. The Edison Eastlake redevelopment project is an example of such community of practice (Coseo 2019; Gaurdaro et al. 2020; Hamstead et al. 2020; Dyzuban et al. 2021; Middel et al. 2021). As part of that work we developed a community engagement process that we will use in CAP V to engage additional groups with distinct perspectives and governances of nature (Fig. 3.12; Guardaro et al. 2020).

Indigenous worldviews comprise one such example of distinct perspectives that vary among and within Tribal Nations. They are situated in intergenerational relationships and reflect responsibilities to nature and cultural roles such as caretakers of land, plants, animals, and water (Nelson et al. 2018; Wildcat 2009; Hausdoerffer et al. 2021). Global concerns about climate change and responsible management of energy, paired with regional issues of a dwindling water supply, long-term viability of desert farming, and access to food, all shine a light on the millenia-old knowledge and practice of Indigenous peoples who learned how to survive and thrive in harsh environmental conditions (Cajete 1999; Nelson 2008; Gilbert 2021). In areas where Indigenous communities co-manage landscapes in the U.S. and Canada, the impact of collaborative partnerships across jurisdictions often results in innovative, sustainable, and responsible stewardship of the environment (Charnley et al. 2007). Arizona is home to 22 federally recognized Tribal Nations, three of which are in or adjacent to the CAP study area. Much of our RQ4 research will focus on co-production of knowledge, and Indigenous consideration, participation, and perspectives will be a critical component of our discussions of resilience, sustainability, and transformative change.

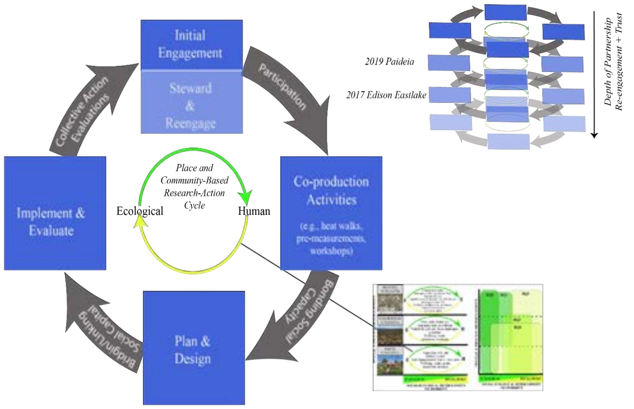

Figure 3.12: Conceptual diagram depicting the community engagement process that will be used to build a community of practice for equitable urban ecological research-to-action (adapted from Guardaro et al. 2020).

Our approach will integrate the rich perspectives of researchers, practitioners, and community members for a more effective transfer of research outcomes to practice (Campbell et al. 2016). This collaborative approach will: 1) make our research more equitable to under-resourced, under-invested communities and more relevant to all communities; 2) shorten the time that research becomes actionable; 3) provide more transparency and accountability to our non-academic partners; and 4) build a more ethical foundation of reciprocity into our collaborations (Fig. 3.12; Gaurdaro et al. 2020; Hamstead et al. 2020).

RQ4 Approach: Our approach will integrate the perspectives of CAP researchers, practitioners, and community members in co-productive community of practice partnerships (Campbell et al. 2016). The partnerships will use PASS data to analyze perceptions of ES/EDS, yard management practices, nature experiences, human wellbeing, and varied socio-demographics including race and ethnicity, income, and lifestyle factors (Text Box 19). We will combine these data with our long-term data on bird and herpetofauna community composition and mammal activity to examine who has access to nature (e.g., based on proximity to UEI, wildlife), who actively seeks nature experiences (e.g., outdoor recreation, gardening), and what are the associated outcomes (perceived biocultural dis/services, wellbeing). A

TB 19: Socioeconomics

The interconnections between people and UEI are heterogeneous and encompass a variety of ecological, economic, and social benefits. The US Decadal Census offers fundamental social science data to assess the heterogeneity in distribution of these benefits. We have matched the spatial dimension of these records to parcel-level records of housing sales and to past census and PASS data to understand how changes in UEI and associated ES/EDS impact household locational choices (Fishman and Smith 2017; Klaiber et al. 2017). CAP V will include a new initiative on urban agriculture and food deserts (Grewal & Grewal, 2012; Burns, 2015; USDA, 2017; Aggarwal et al. 2020), and publicly owned vacant lots provide real opportunities. During CAP IV, Smith et al. (2017) combined remote sensing and cadastral data to distinguish different forms of vacant land in the CAP study area. We will build on this work and our past collaborations with local stakeholders to: 1) co-develop a mapping tool to assess the current state of urban agriculture (*sensu* Myint et al. 2021); 2) assess how access to food is distributed; and 3) combine socio-economic, water use and emergy (i.e., embodied energy) analyses to assess the potential of urban agriculture to produce food efficiently and sustainably while improving food justice.

critical aspect of these analyses will be identifying experiences and outcomes that are inequitably distributed across diverse people and places. Wellbeing is quantified in PASS data using perceived quality of life and personal life satisfaction, and self-reported physical and mental health issues. *We expect that this community of practice approach will: 1) co-create more equitable processes for university-community reconciliation and innovative mutual knowledge co-production with previously excluded communities, or communities that lacked adequate information to determine where and how they might participate; 2) shorten the time research becomes actionable; 3) provide more transparency and accountability to our non-academic partners; and 4) build a more ethical foundation of repair, belonging, and reciprocity into our knowledge co-production partnerships* (Gaurdaro et al. 2020; Hamstead et al. 2020).

By accessing community-collected data from sources such as iNaturalist and our recent partnerships with wildlife removal companies, we will evaluate where human-wildlife interactions occur throughout the CAP study area. Combining landscape-level data on UEI with records of wildlife encounters will provide insight into where more opportunities to interact with nature occur. Additionally, knowing where individuals log observations across the landscape will provide insight into the effort put into experiencing nature. By understanding the distances individuals travel when recording wildlife observations, we will highlight potential inequalities in the distribution of and access to UEI. Finally, focusing on individual patterns in human-wildlife interactions may reveal potential preferences for specific wildlife that may in turn relate to increases in wellbeing.

We will address questions about how human beliefs, perceptions, and experiences relate to human←→environment interactions and to wellbeing. We will use long-term CAP data from the parcel, neighborhood, and regional (including Tribal Nations) scales (per Fig. 1.1). Because humans respond to nature based upon specific faunal traits (*sensu* RQ2) or beliefs held, we will compare two groups of taxa that vary widely in appearance and acceptance but which are native to the desert Southwest: birds and snakes. These analyses will continue our recent research relating neighborhood demographic data to bird rescues and snake removals (Andrade et al. 2021; Bateman et al. 2021). We will use PASS data to evaluate if the participants view these interactions as acts of nature stewardship and how these actions are related to beliefs held about nature. We will relate PASS data on household and community perceptions of benefits and risk regarding heat (Larson et al. 2019) to our data on microclimate and heat and our findings from the Edison Eastlake neighborhood redevelopment project. We will extend these comparisons to perceptions of air quality and data from our growing urban air quality work to better understand the equitable distribution of ES/EDS that mitigates both heat and air quality (RQ3). Finally, RQ4 will contribute to RQ5 by providing better insight for targeted community-oriented scenario planning.

Because we propose to form reciprocal partnerships with communities that are not PASS neighborhoods, our work will establish the groundwork to build communities of practice with partners from new neighborhoods, Tribal Nations, and NGOs. Our approach will include lessons learned from engagement in CAP IV with the Edison Eastlake and South Phoenix communities, and ultimately this work will translate into a more equitable long-term PASS dataset. Our work building these communities of practice will coordinate closely with CAP education and outreach activities, incorporating undergraduate and graduate student projects, and educating researchers with relevant training workshops, tabling at local tribal events, and sharing our data and findings with the communities with whom we will engage.

***Research Question #5 (RQ5)*: How does governance—and associated institutions, values, and knowledge—shape past, current, and future transformational capacities, and how do those capacities affect the (in)equitable distribution of UEI and associated ES/EDS?** *Co-leads: Berbés, Cook, Iwaniec, Meerow, Vanos, York*

RQ5 Rationale: Decades of CAP research have shown the spatial inequalities in the distribution of and access to UEI and ES/EDS in the CAP region (e.g., Bolin et al. 2000, 2005; Harlan et al. 2006; Jenerette et al. 2016; Larson et al. 2019). Beyond the documentation of past and present inequities in air quality, heat mitigation, and other ES/EDS, this question explores the governance structures that underpin

UEI and associated ES/EDS across multiple scales. We define "governance" as the suite of formal and informal processes, including institutions, regulations, and norms, by which societies organize (Shrestha et al. 2012; Wutich et al. 2013; York et al. 2014; York et al. 2020). These are classic human→ environment feedbacks. Our approach will be to understand how governance structures influence UEI by paying particular attention to who is making decisions and the roles they play. We will expand our conceptualization of knowledge and values to align with cognitive and recognitional dimensions of environmental justice (Yazar et al. in press) that emphasize the uneven attention paid to non-Western perspectives of the landscape and role they play in achieving just outcomes (York et al. in press).

Prior CAP research has revealed entanglements among important influences on UEI management at scales of individual households (Kane et al. 2014; Kane and York 2017; Locke et al. 2020; Yazar et al. 2021), of neighborhoods and cities (York et al. 2014; York and Boone 2018), and of regions (York et al. 2020). PASS data have shown that income and homeownership were significant predictors of household implementation of UEI (Meerow et al. 2021). We will fill this gap by explicitly interrogating governance across spatial and temporal scales (*sensu* York et al. 2019, York et al. 2021) to reveal the underlying cultural and contextual circumstances that shape how people view, access, use, and collectively produce UEI. As well, multi-level, cross-scale governance research must explore different arrangements across policy domains and the impact of scale mismatches. As an example, air quality, water quality, and water quantity are governed by decades-old, formalized institutions in which actions are, in part, guided by federal legislation. But for other hazards, notably heat, there have been no formalized institutions or relevant federal legislation around which governance is structured (Keith et al. 2021). Instead, informal networks, ad hoc programs and policies, and individual actions are dominant. Likewise, land use policies that affect much of the UEI generated in urban systems are largely governed by city zoning ordinances or HOA rules. We will investigate the impact of this mosaic of governance arrangements to understand how social-ecological governance structures evolve over time and how to realize new futures through changing institutions that influence UEI.

More research is also needed on the temporal dimensions of cross-scale institutional dynamics that influence and are influenced by UEI in order to elucidate pathways to sustainable futures. Co-produced future scenarios demonstrate what more sustainable, resilient, and just UEI futures for the region might look like across multiple scales, and they will broadly sketch out pathways to achieving these futures (Iwaniec et al. 2020a). The burgeoning literature on sustainability transitions (Markard et al. 2012; Torrens et al., 2021) and transformations (Westley et al. 2011; Iwaniec et al. 2019; Scoones et al. 2020) provides a theoretical foundation for understanding how more equitable UEI scenarios can be achieved. These scenario visions combine past trends from long-term datasets with present-day aspirations to co-create a range of future scenarios that project future changes on land use and temperature (Iwaniec et al., 2020b) and water availability (Sampson et al., 2020) that can guide decision-making. For example, Bennett et al. (2016) argued that to achieve sustainability transformations it is important to identify promising initiatives ("seeds") that, if scaled up, could change social-ecological systems and improve the equitable distribution of UEI and ES provided.

RQ5 Approach: Our approach to answering RQ5 will leverage both existing and ongoing long-term data collection and relatively new CAP projects and data resources, augmented by new analyses of long-term archival records using qualitative coding and natural language processing and the initiation of several new case studies and pilot projects. The PASS will remain a primary resource for understanding household-scale and neighborhood-scale relationships between governance and UEI, along with data on socio-economics, perceived ES/EDS, local social capital and norms, and HOAs or other neighborhood organizations. Complementing prior work, our efforts in CAP V will more deeply probe temporal trends at the household and neighborhood scales, leveraging the repeated cross-sectional and longitudinal nature of the data. We will conduct semi-structured interviews with a subsample of PASS respondents to deepen our understanding of how perceptions and management approaches toward the urban landscape are shaped by different knowledge bases, power dynamics, and entitlements. These interviews will also afford us the opportunity to understand cross-scalar governance relationships relevant to UEI, from the perspective of individual residents and households.

At the scale of municipal and regional actors, we will deploy multiple strategies used in ES governance analysis (Sattler et al. 2018). Shifting away from dominant scientific strategies that view governance systems as "outsiders," we will explicitly co-produce action-oriented research with neighborhood to regional actors and entities both inside and outside extant governance structures to understand the co-evolution of governance and UEI. Using a multi-method approach, we will seek to understand who has been invited to the table (procedural justice), and what policies and programs are being developed to address inequity. Additionally, we must better understand power and empowerment within governance arenas. To advance this research, we will use key informant interviews, social network analysis, and surveys conducted with local government officials and related stakeholders to understand and measure the evolving nature of governance networks, and their justice and power dimensions, for UEI related to urban heat, air quality, land use, and water quantity and quality.

We have long documented relationships among LULCC, water governance, and urban climate (especially heat; Larson et al. 2013; White et al. 2015), but governance emerged as a focal domain during CAP IV (*sensu* Hondula et al. 2019; Keith et al. 2021). We will expand this work in CAP V to also consider air and water quality governance, which will closely link our governance research to long-term CAP datasets on air and water quality. Methods from relevant water supply studies will be adapted to other environmental factors and to reflect the varying levels of maturity of existing governance networks. We will build on existing social network analyses of climate resilience governance related to drought, heat, and flooding that were conducted as part of the UREx SRN project. We will complement the social network and PASS data with studies analyzing policy and planning documents from the CAP region across sectors and scales. Here we will leverage existing datasets of qualitatively coded governance documents (Iwaniec et al. 2020b; Kim et al. 2021; Hoover et al. 2021) and apply natural language processing methods to trace the historical evolution of the framing of UEI and relevant urban environmental factors and relevant actors and mechanisms that influence UEI. This will provide foundational data and understanding of the governance structures and knowledge systems coming to bear on the vulnerabilities and resilience of the region.

In CAP V we will connect our scenarios and futures work with insights from our long-standing engagement with ongoing, innovative local initiatives that aim to address both grand challenges and disparities across the region (Text Box 20). For example, we will use our existing scenarios to develop a greenhouse gas strategies decision support tool and use it to synthesize a multi-scale net-zero carbon scenario to support just and sustainable climate planning. We will also analyze the strengths and weaknesses of different governance structures represented by these diverse local initiatives to identify procedural pathways and governance changes needed to achieve sustainable scenarios. As part of this work, we will assess adaptive and transformative capacities, such as anticipatory capacities, foresight knowledge, knowledge co-production, and new collaborative networks that we expect are essential to implementing solutions and sustainability transitions toward more equitable UEI (Fig. 3.13). We will compare these empirical insights with existing literature on the factors leading to social-ecological system change (*sensu* Raudsepp-Hearne et al. 2020) to advance emerging theories of sustainability transitions and transformations.

Finally, we will continue the tradition of our researchers being dynamic and active participants in social-ecological governance networks. This allows us to directly observe important processes and networks that can authenticate our research

TB 20: Scenarios and futures

In CAP IV we studied the future of the CAP study area by co-producing multiple, alternative scenarios at regional and neighborhood scales with governance policymakers and community members from South Phoenix (Iwaniec et al. 2020a,b; Sampson et al. 2020). We used these multi-scale scenarios to explore alternative future actions, policies, and strategies—with different forms of UEI, built infrastructure, and governance—to improve urban sustainability and resilience (Fig. 3.13). These participatory scenarios were evaluated by participants using modeling and assessment outputs that addressed a range of future changes. This CAP research has been leading the way for futures research conducted in other cities (Berbéz-Blásquez et al. 2021; Cook et al. 2021; Iwaniec et al. 2021a,b).

findings and create a more direct conduit for achieving broader impacts. For example, in October 2021 the City of Phoenix inaugurated its new Office of Heat Response and Mitigation (Keith et al. 2021). This new department is being led by longtime CAP researcher David Hondula, who is a member of the CAP V Leadership Team. We will conduct case studies of community initiatives in which CAP is engaged (e.g., Edison Eastlake, Paideia Academies, Tempe Cool Kids project, Academia del Pueblo) that aim to achieve a more equitable distribution and use of UEI. We will hold workshops as part of the annual CAP All Scientists Meetings where key stakeholders involved in these initiatives are invited to co-produce common lessons based on their experiences and co-learn with each other.

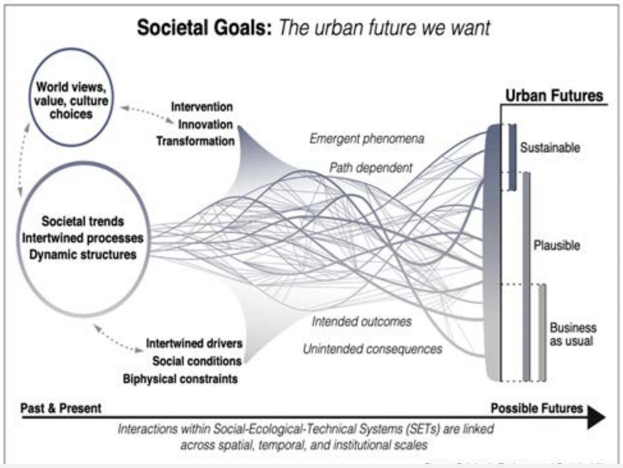

Figure 3.13: Conceptualization of the inter-linkages between factors and dynamic processes shaping urban futures (modified from McPherson et al. 2016). Visions are represented as societal goals influenced by multi-scalar governance (i.e., worldviews, values, culture, and choices) and ecological systems, and they play an important role in intervention, innovation, and transformation that can lead to alternative and more desirable urban futures.

D. <u>Related Research Projects and Activities</u>: Since its inception in 1997, more than $125 million in grants have leveraged CAP and its research platform. During CAP IV alone leveraged funding totaled nearly $75 million. In this section we briefly summarize these related and leveraged projects and note how they were or are connected to our core research activities. Three large grants make up more than half of the CAP IV leveraging: Two SRN projects and a new STC project. The Urban Resilience to Extreme Events (UREx) SRN ($12 million, based at ASU) is led by CAP researchers Redman, Grimm, and Chester and includes many CAP scientists. A signature UREx effort co-produced scenarios and futures across a hemispheric network of nine cities, including our CAP IV futures-directed work. The Urban Water Innovation Network (UWIN) SRN ($12 million, based at CSU) includes several CAP scientists whose research and expertise are focused on the nexus of urban heat and urban water. And in late 2021, a STC focused on phosphorus sustainability, which leveraged CAP, was funded ($25 million, based at NCSU). We will be revisiting our urban phosphorus budget (Metson et al. 2010) in collaboration with this STC.

Many of the other grants that have leveraged CAP IV can be bundled into those that have involved CAP in growing research networks, those that have expanded the interdisciplinary reach of CAP research, and those that explicitly support junior CAP scientists. Grants led by CAP ethnohydrologist Amber Wutich include an international network of cities where research is focused on water insecurity (GCR, $3.5 million) and building communities of practice around household water insecurity (HWISE, $500K), as well as a project focused on agricultural water use (USDA, $5 million). CAP is now part of an international network of researchers and cities studying nature-based solutions to urban sustainability challenges (AccelNet NATURA, $2 million, co-led by CAP scientists Cook and Grimm) and Phoenix continues to be one of six cities that are part of the 10-year urban homogenization project (Macrosystems Biology; $4.2 million). Several leveraged grants are allowing CAP researchers to expand our social-ecological research to include technological aspects of city infrastructure, following the SETS framework (e.g., McPhearson et al. 2016). Finally, new CAREER grants will support two of CAP's junior scientists (Ariane Middel and Jenni Vanos) in their urban microclimate, heat, and air quality research.

We share a long history of collaboration and collegiality with our companion urban LTER program in Baltimore (BES). Recent cross-site activities have included a comparison of results from the PASS with the Baltimore Phone Survey. We related long-term change in these social data to patterns of LULCC and socioeconomics from both cities. Many of the core activities of BES are still active, and we will continue these productive cross-site research efforts. We welcome the new MSP urban site to this mini-network of urban LTER programs and we are currently formalizing plans for cross-site investigations with them. Finally, we exchange researchers with BES and MSP at each program's annual meetings.

IV. Broader Impacts

Because we have infused an ecology *for* and *with* cities transdisciplinary approach into much of our work, as encouraged by the 2018 NSF ACERE convergence report, the lines between intellectual merit and broader impacts are somewhat blurred in our research. Despite the bold-faced header above, much of our research itself has broader impacts, on science and on our communities and cities. Three of our long-term datasets and experiments, and most of our research questions, involve explicit partnerships with practitioners and communities. Specifically, our RQ5 activities will constitute both research and broader impacts. After recognizing that Section III is rich in broader impacts, we describe our more traditional broader impacts below:

A. Justice, Equity, Diversity, and Inclusion (JEDI): We promote and implement JEDI principles and practices throughout the CAP endeavor to support a broader agenda focused on a more equitable and just future in the CAP community and across the CAP region. Our JEDI philosophy is guided by a JEDI Action Plan, which is available on the Internal Resources section of our website homepage. Our JEDI principles include: a) creating equitable space for CAP community members of diverse and intersectional identities to thrive by being elevated, not assimilated (*sensu* Halsey et al. 2020; Schell et al. 2020a); b) foster development of a culturally competent CAP community; and c) establishing accountability measures and actionable steps to ensure steady progress towards a more equitable, diverse, and inclusive research community. In addition to the focus on justice that we have purposefully integrated throughout our proposed CAP V research, the CAP JEDI Committee continues to lead broader impact JEDI initiatives. The JEDI Committee represents the variety of intersectional identities found in the CAP community; this group is critical to enhancing and sustaining diversity within the CAP endeavor.

In CAP V, the JEDI Committee will continue to actively foster and support diversity and historically marginalized groups in the CAP community. The JEDI Committee has initiated an annual community climate survey to evaluate and improve the CAP community working environment. Based on the most recent February 2022 survey (50 respondents), the CAP community currently includes 29% who identify as Black, Asian, Hispanic/Latinx, or Indigenous, 30% who identify as LGBTQ+, and 63% are women; many of these members are in leadership roles. Moreover, beginning with our strong recruiting efforts in CAP IV and throughout CAP V, we will continue to recruit and support additional students, staff, and academics from diverse backgrounds to promote just futures and to build diverse leadership. The CAP Executive Committee is implementing anti-racist policies and initiatives in CAP research, programming, and hiring following recommendations from our JEDI Committee. The committee has updated our Field Safety Guidelines to explicitly highlight reporting mechanisms and safety measures and to include guidance on challenges around personal identity (these guidelines are also available through our Internal Resources link). More details of our JEDI-focused initiatives are in the Project Management Plan.

B. Education and Outreach Activities (K-12 Schoolyard Program and Community Engagement): Ecology Explorers, our K-12 Schoolyard program, connects teachers and students with CAP scientists through schoolyard friendly urban ecology protocols and learning modules. We host summer professional development workshops and programs to share our research with teachers and help implement these programs throughout the school year. These activities focus strongly on data literacy, formal and informal education, civic engagement, and alignment of content with state educational standards. This approach is the most cost-effective way to share our research and to impact classrooms (Bestelmeyer et al. 2015). Our Ed & Outreach Manager works closely with the Arizona Department of Education, the Arizona Association of Environmental Education, and the Arizona Science Teacher Association. We incorporate CAP research on ES and UEI into lessons and curriculum modules. Notably, these ideas link well with the Next Generation Science Standards and the New Arizona Science Standards. Additionally, we work with

CAP researchers to develop "citizen science" protocols and to create teaching materials that use CAP data in "Data Nuggets" lessons (Bestelmeyer et al. 2015).

To create community-led opportunities, we will strengthen our partnerships with organizations and community entities in South Phoenix. In addition to our close collaborations with the Roosevelt School District, we are active in on-the-ground community activities with diverse organizations such as CHISPA AZ, Project Roots, the Orchard Community Learning Center, The Sagrado, and the Tiger Mountain Foundation.

C. Education and Outreach Activities (Municipal and NGO Partnerships): We continue to work with city governments and regional organizations to co-produce urban ecological knowledge that informs decision-making. We have a long-standing collaboration with the Central Arizona Conservation Alliance (CAZCA), administered by our long-time community partner, the Desert Botanical Garden (DBG). The CAZCA is a partnership among public, nonprofit, and academic entities (e.g., City of Phoenix Parks and Recreation, The Nature Conservancy, Audubon Arizona, and Maricopa County Parks and Recreation). We also have strong partnerships with The Nature Conservancy and McDowell Sonoran Conservancy (MSC) Field Institute (see below). We reach our 26 area municipalities through the ASU-based Sustainable Cities Network, and we have long-term relationships with many decision-makers and planners through our scenarios and futures work. Our Tres Rios constructed treatment wetland work is in collaboration with the City of Phoenix Water Services Department. Finally, we collaborate on various projects with the City of Phoenix, the City of Tempe, and the Maricopa County Flood Control District.

D. Education and Outreach Activities (Citizen Science Programs): Citizen Science, or Community Science as we prefer to call it, is a form of participatory action research. In CAP V we will continue our most active project with the MSC Field Institute, where community scientists collect data that are used to manage Scottsdale's McDowell Sonoran Mountain Preserve. The CAP staff entomologist identifies these samples for them. The DBG trains citizen botanists to document plant diversity in regional parks, and these volunteer botanists often participate in our DesFert sampling. The MSC Field Institute has been working with CAP and our CAZCA partners to develop citizen-science trainings/workshops for other regional parks. In CAP V we will use community-collected data (e.g., iNaturalist) to assess where human-wildlife interactions occur throughout the CAP study area. Combining landscape-level data with records of wildlife encounters will provide insight into where people find satisfying opportunities to interact with nature.

E. Education and Outreach Activities (REU and Other Student Support Programs): We will continue our successful REU Program in CAP V with stipend and research support for 3 - 4 students per summer. Beginning in Summer 2017, we merged our REU program with the UREx SRN REU program and with REU students supported by other NSF grants to CAP scientists, creating a summer cohort of up to a dozen undergraduate researchers. Programming includes a workshop every two weeks where the students learn about topics such as research ethics, the academic profession, and the publication process. We take advantage of the ESA SEEDS SPUR Program as a minority recruitment vehicle as we endeavor to provide REU support to as many underrepresented students as possible.

The CAP Student Group is active. They organize our annual CAP Welcome every fall semester and coordinate our monthly CAP seminar series. During 2021 these seminars featured the newest members of the CAP community. In CAP V we will continue to support graduate research experiences and education in various ways. We will continue our successful Grad Grants program, which will provide support to CAP graduate students every year (with a $50,000 annual budget). As part of this program, we follow the NSF panel review model where previous Grad Grant awardees are asked to be panelists. CAP also provides travel funds to students to present their research at conferences and our students benefit from the use of CAP research infrastructure, including vehicles, lab analysis, technical support, and publication costs.

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Note: All in-text citations shown in blue are publications that acknowledge CAP support

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