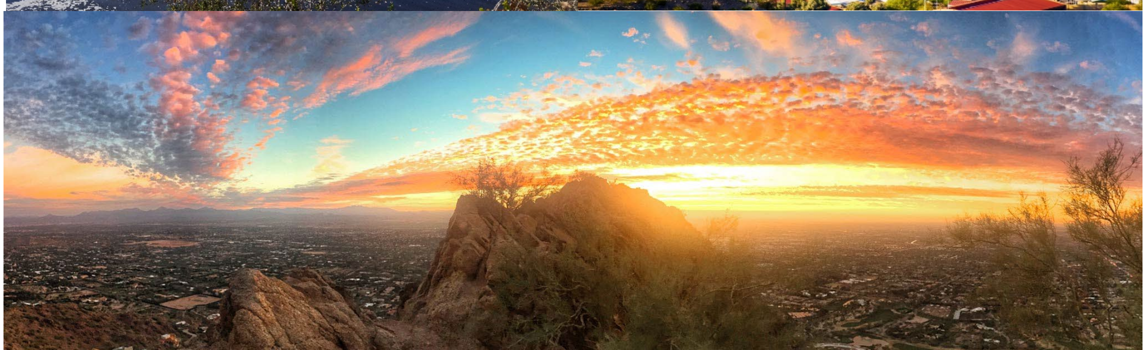
CAP LTER 2020 Progress Report

NSF Site Review: October 21 – 23, 2020
CAP IV: December 2016 - Present






Contents

1. INTRODUCTION

1.1. Overview of Report Organization and Structure

In this report we cover activities by the CAP LTER Program (hereafter CAP) during our fourth round of funding (CAP IV), from December 2016 through the present. We have organized the report to follow the NSF guidelines and begin with a brief history and overview of CAP, followed by our central conceptual framework, guiding concepts and how we are organized. We wrap up this introductory section with a discussion of our Diversity, Equity, and Inclusion Social Contract and related activities. Section 2 will detail our site-based research, followed by a summary of our network-level and cross-site activities in Section 3. Our information management efforts will be detailed in Section 4, and Section 5 will cover our education and outreach activities. We conclude the report with information on site/program management (Section 6). Throughout the report, we only cite references that have been published since 2017, for the sake of brevity, but a bibliography of all of CAP's publications may be found here.

1.2. A Brief History of CAP

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. 1.1) since 1997. Research in CAP I (1997–2004) and CAP II (2004–2010) addressed the question: ***How does the pattern of development of the city alter ecological conditions of the city and its surrounding environment, and how do ecological consequences of these developments feed back to the social system to generate future changes?***

From CAP I and II, we learned that land-use legacies have strong effects and that other social variables help explain ecological patterns (e.g., the “luxury effect,” whereby biodiversity is higher in wealthier neighborhoods). Our regional-scale research showed a high degree of heterogeneity in atmospheric deposition, soil nutrients, the nitrogen budget, exposure to toxic hazards, and landscape pattern. We also conducted historic analyses of land use/land cover change (LULCC) and of development and impact of the urban heat island (UHI) effect.

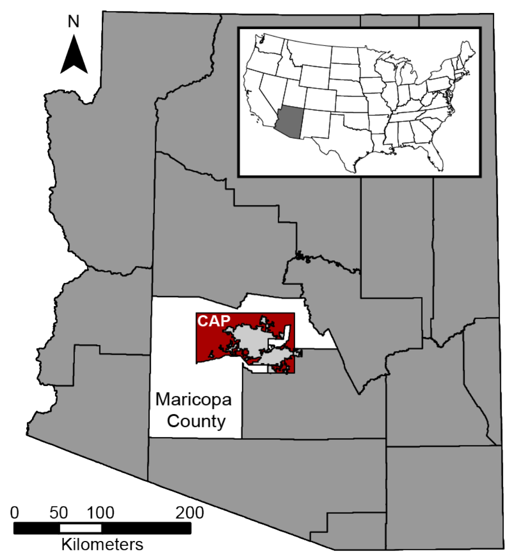


Figure 1.1: The 6400 km^2 CAP IV study area in central Arizona (red) that includes the Phoenix Metro Area (light gray within the red). Dark lines are county boundaries.

In CAP III (2010–2016), we addressed feedbacks between social and ecological systems more explicitly, as mediated through ecosystem services (hereafter ES, defined as the benefits that people derive from ecosystems). We investigated human behavior and outcomes in addition to ecological change, asking: ***How do the services provided by evolving urban ecosystems affect human outcomes and behavior, and how does human action (response) alter patterns of ecosystem structure and function and, ultimately, urban sustainability, in a dynamic environment?***

CAP research has always adopted a long-term perspective to understand how urbanization (e.g., changes in population, demographics, land, and infrastructure) interacts with external forces (e.g., global climate change, economic change, human movements) to determine urban social-ecological system structure and function. The central conceptual frameworks of CAP III and CAP IV (Fig. 1.2) have human/social elements as both drivers and responders (Grimm et al. 2017). Key elements include: 1) how ecological structure and function interact; 2) how the delivery of ES or disservices condition human outcomes; and 3) how human outcomes, in turn, affect human decisions and behavior that influence ecosystem structure and function. Internal presses and pulses that we study include: LULCC (e.g., housing development); UHI; storms and urban flooding; atmospheric deposition of nutrients; water, air, and soil pollution; and a key addition to the CAP IV framework—the design and management of Urban Ecological Infrastructure (UEI; Section 1.5). External presses and pulses include climate change and variability (e.g., drought, warming), human migration (interstate and international), and economic disruptions (e.g., the Great Recession). We remain committed to studying urban ecosystems using an ecology *in*, *of*, and *for* cities framework. A fundamental goal 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.

1.3. Introducing CAP IV

Understanding urban ecosystems has motivated CAP since 1997 and continues to inspire CAP IV. As we continue our urban social-ecological investigations, the central question that guides CAP IV research is:

How do the ecosystem services (ES) provided by urban ecological infrastructure (UEI) affect human outcomes and behavior, and how do human actions affect patterns of urban ecosystem structure and function and, ultimately, urban sustainability and resilience?

This question articulates the interconnectedness of human motivations and behaviors with urban ecosystem structure and function. Human actions transform the urban ecosystem but the connections are not unidirectional. People respond to ES as they perceive and experience them and, as such, people are integrated within the system—a central tenet of social-ecological theory. This interconnectedness makes sense given that *Homo sapiens* is the dominant species—the ecosystem engineer—of urban ecosystems. Thus, social-ecological research is a unique and hybrid endeavor; neither pure social science nor pure ecology.

A new focus for CAP IV is on UEI as a bridge between the biophysical and human/social components of the system (Section 1.5). Our **overarching goal** is to foster interdisciplinary social-ecological urban research aimed at understanding these complex systems using a holistic, ecology *of* cities perspective, while contributing to an ecology *for* cities to enhance urban sustainability through transdisciplinary partnerships with city practitioners. We are meeting this goal in **four ways**. We: 1) use our long-term observations and datasets to articulate 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; and 4) 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.

1.4. The CAP IV Central Conceptual Framework

The CAP IV conceptual framework (Fig. 1.2; Childers et al. 2019) defines the urban ecosystem as including both the biophysical and the social-cultural-economic realms as well as presses and pulses that originate within the ecosystem (the largest gray box in Fig. 1.2). The biophysical and human/social templates are joined with a porous, "zipper-like" boundary; these templates are separate only because of disciplinary constraints and different questions asked in these two realms. Myriad human behaviors and decisions lead to a host of outcomes that, in turn, affect future decisions and behaviors (A in Fig. 1.2). The functional and structural components of the biophysical template link to human outcomes through the purveyance of ES and their benefits (B and C in Fig. 1.2). UEI is an extension of biophysical structure and it bridges the porous boundary between the biophysical and human templates. UEI affects human outcomes through function (e.g., transpirational cooling by trees in a park; D and B in Fig. 1.2), but some UEI benefits are strictly structural (e.g. shade provided by park trees; E in Fig. 1.2). Human decisions affect the rules (i.e., institutions) that, in turn, influence the design and management of UEI (F in Fig. 1.2), and the various functions of UEI affect outcomes by providing a wide range of ES to city dwellers. These ES directly affect human outcomes (C and E in Fig. 1.2). The double-headed arrows that connect the two templates with internal presses and pulses demonstrate that these environmental and human-sourced disturbances operate in both directions (G in Fig. 1.2). For example, the biophysical template produces floods—a pulse perturbation—while the human template produces land cover change, which is a press perturbation. In some cases, presses and pulses act in concert; regardless, they affect both templates irrespective of their source. External presses and pulses influence the urban ecosystem (H in Fig. 1.2), while cities also have influence beyond their boundaries (I in Fig. 1.2). Our long-term datasets, research questions, models, and programmatic structure map to this central conceptual framework; it is the glue that binds CAP IV together. Finally, we recognize that urban ecosystems are temporally dynamic (the third dimension of time in Figure 1.2). A long-term approach is necessary to study and understand these dynamics.

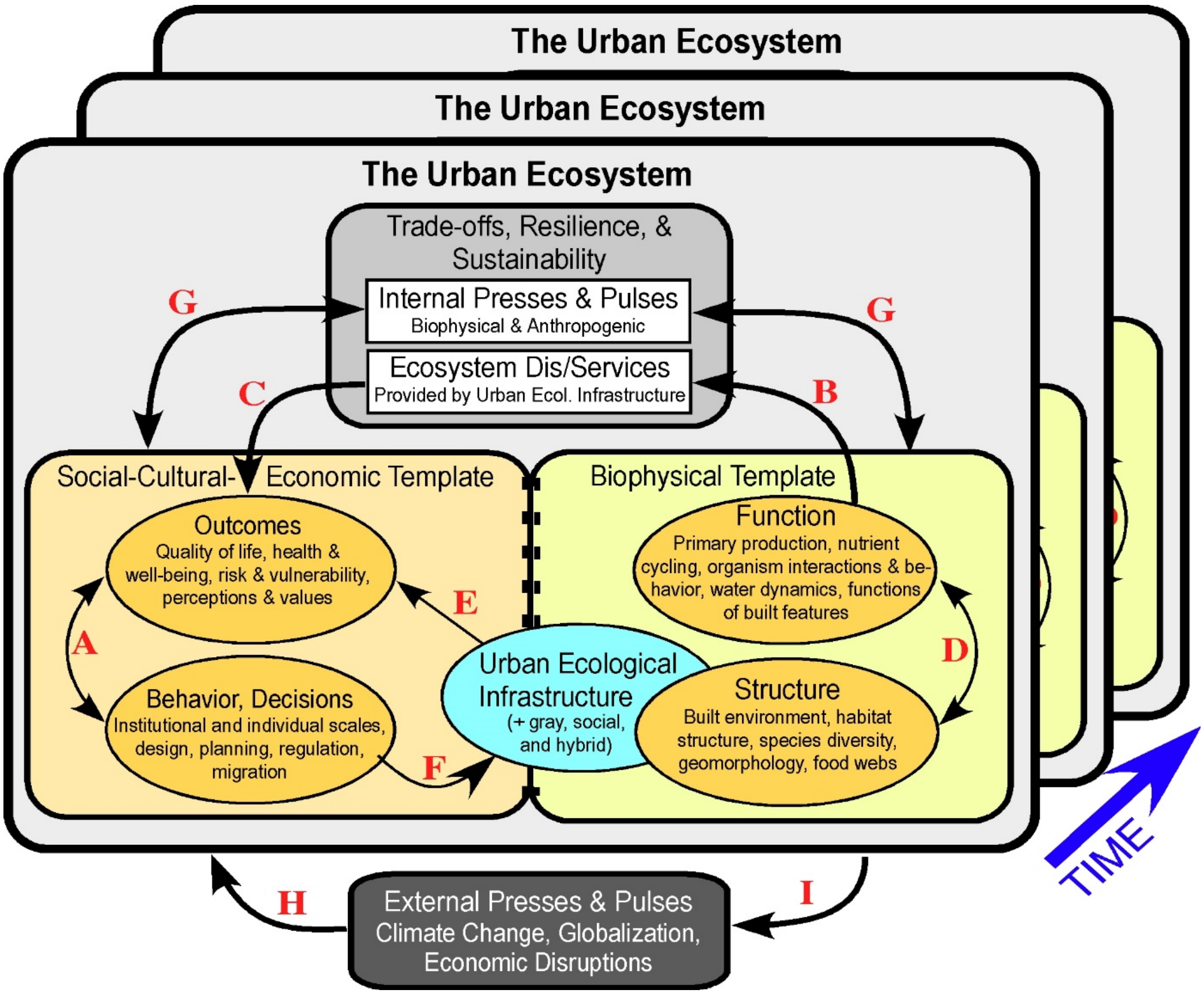


Figure 1.2: CAP IV central conceptual framework. See text for details and descriptions of the red letters.

1.5. The Concept of Urban Ecological Infrastructure (UEI)

Cities are designed and built human habitats, and urban infrastructure is the result. Infrastructure is typically defined as the physical components of interrelated systems that provide commodities and services essential to enable, sustain, or enhance societal living conditions. We define UEI as all infrastructure in a city that supports ecological structure and function, and by extension, provides ecosystem services to urban residents (Childers et al. 2019). UEI is a broad, all-encompassing concept for "nature in cities". This idea includes commonly recognized forms of infrastructure, such as parks, residential yards, community gardens, lakes and rivers, and street trees. But UEI also includes less recognized forms, such as vacant lots, agricultural fields, canals, and stormwater retention basins. Childers et al. (2019) categorized UEI into terrestrial, aquatic, and wetland ecosystem types because each type supports unique ecological structures and functions and thus provides different ecosystem services. Other terms used in the urban literature to identify "nature in cities" include Urban Green Space (UGS) and Green Infrastructure (GI). These terms and concepts tend to de-emphasize non-terrestrial features, whereas our definition explicitly includes aquatic and wetland features found in cities. With a growing interest in designing more livable cities, it is important to think beyond how “green” or vegetated a city is to consider the diversity of UEI and their characteristics in cities. Notably, our definition is distinct from the enviro-political definition of GI that includes, for example, solar panels and recycling programs (Childers et al. 2019).

1.6. How CAP is Organized

The CAP study area includes 6400 km^2 of rapidly urbanizing Central Arizona—effectively the entire Phoenix metro area, surrounding agricultural lands, and desert (Fig. 1.1). The region is home to more than 4.5 million residents, and this population grows substantially every winter during “snowbird season.” The CAP study area includes 26 independent urban municipalities as well as agricultural areas and undeveloped Sonoran Desert. The CAP IV enterprise is comprised of four components: 1) long-term datasets and experiments; 2) seven LTER Core Areas; 3) education, outreach, and citizen-science initiatives; and 4) the co-production of knowledge to enhance urban sustainability. Supporting these foundational components are eight Interdisciplinary Research Teams (IRTs; legend to the right). Two IRTs are process-based (Climate & Heat; Water & Fluxes), three are thematic (Adapting to City Life; Governance & Institutions; Urban Design), two are location-specific (Residential Landscapes & Neighborhoods; Parks & Rivers), and one is broadly synthetic (Scenarios & Futures). All eight are highly interdisciplinary, interconnected, and depend upon our long-term foundational datasets, resources, and activities. Everyone participating in CAP is a member of at least one IRT.

1.7. The CAP Diversity, Equity, and Inclusion (DEI) Social Contract

We are at a notable turning point in in the recent history of our country when the need for serious social introspection has finally been raised to the forefront of public discourse. It is time for transformative thinking and approaches to deal with our society's deeply embedded issues of racial inequities and injustices, and white privilege. This is a challenge that must be met by our nation as a whole, but also at a more local level. We have been very proactive in rising to this challenge at CAP. We have long had a Diversity and Inclusion Plan, but in the last few months we have recognized that we must go much further than this. This summer we formalized a CAP Diversity, Equity, and Inclusion (DEI) Committee, which is being co-chaired by Elizabeth Cook (co-lead of the Scenarios and Futures IRT) and Quincy Stewart (senior technician). They have produced a framework for filling out this committee and for guiding its work, which we include below, and their framework has been approved by the CAP Executive Committee. The first task of this new DEI Committee will be to embolden our Diversity and Inclusion Plan into a robust DEI Social Contract.

CAP LTER Diversity, Equity, and Inclusion (DEI) Committee Framework: As an urban social-ecological research program, CAP studies the places where people live, work, and play. This situation presents us with exciting opportunities, but also with unique responsibilities. To meet these opportunities in responsible ways, we have recently initiated a Diversity, Equity, and Inclusion (DEI) Committee. As noted in the CAP Diversity and Inclusion Statement (published in 2018), the overarching CAP diversity goal is to maintain an environment that is open to and supportive of all, where individual differences are understood, valued, and integral to our collective empowerment as a scientific and academic community. The CAP DEI Committee will be critical to enhancing and sustaining diversity within the CAP endeavor. We recognize that diversity includes, but is not limited to, race, nationality, ethnicity, gender, age, sexual orientation, gender identification, language, religion, disability or health status, socio-economic status, veteran status, and geographic origin.

The DEI Committee is guided by an initial set of responsibilities and goals. The goals and initiatives of the committee, as currently stated, have evolved from ongoing discussions with current CAP community members, the CAP Executive Committee, and the LTER Network Diversity Committee. Our DEI Committee's preliminary goals are to lead initiatives to: a) Actively foster and support diversity within the CAP community and STEM more broadly; b) Enhance representation and support underrepresented minorities in STEM career advancement through CAP initiatives; c) Proactively review anti-racist policies and initiatives related to CAP research, programming, and hiring practices; and d) Build awareness in the CAP community about the multiple facets of diversity encountered in the Greater Phoenix region every day.

In order to actively work toward these goals, in Year 1 the CAP DEI Committee will: a) Review the existing DEI initiatives, resources, and community composition within CAP and ASU in order to establish collaborations at ASU and to serve as a baseline for CAP DEI initiatives; b) establish both short-term (1 year) and long-term (3+ year) timelines to meet the DEI Committee objectives; and c) Develop the existing CAP Diversity Statement (2018) into a broader and stronger CAP DEI Social Contract. The CAP Social Contract will include explicit short- and long-term action items, mechanisms, and timelines to ensure we actively work toward meeting our DEI goals. The DEI Social Contract will include a clear process for evaluation and assessment of success, and targets for success. These initiatives are the starting point for CAP's DEI work, and the goals and initiatives will continue to evolve and be refined. The DEI committee will establish an open engagement process with the larger CAP Community in order to ensure an inclusive planning and decision-making process. The committee will have regular interactions with the CAP Executive Committee and Director.

In collaboration with CAP Director and Executive Committee, the DEI Committee was initiated by Elizabeth Cook and Quincy Stewart, both of whom also represent CAP on the LTER Network Diversity Committee. We have established the following guidelines for the CAP DEI Committee structure (membership, term length, commitment, and appointments):

- The DEI committee will be comprised of six to seven members from within and outside the CAP community.
- The committee will reflect the diversity of the CAP community and beyond, including diversity in career stage, discipline, race/ethnicity, gender, and other individual and community characteristics.
- Members will include two ASU faculty members, one non-ASU faculty member, one CAP staff member, one CAP graduate student, and one or two non-CAP members (e.g., non-CAP academic or community members).
- DEI Committee term length will be two years. Terms may be renewable and three committee members will be appointed every year (i.e. half of the committee members will be on alternate term cycles to avoid full turnover at one time).
- The committee will meet monthly and members agree to actively participate in addressing the committee goals.

Additional appointments to the CAP DEI Committee will be made by the existing committee members. Approximately three months prior to the end of a term (end of August), the DEI committee will hold an open call for nominations or self-nominations to join the DEI committee. Nominees will be asked to submit a short statement (≈250 words) explaining why they would like to be involved and any experience or background in DEI initiatives. The existing DEI Committee will vote if there is more than one nominee for a position.

Committee participants:

1. **Quincy Stewart** (Arizona State University; CAP staff),
2. **Elizabeth Cook** (Barnard College; non-ASU-CAP senior personnel),
3. **Tara Nkrumah** (Arizona State University; Center for Gender Equity in Science and Technology, non-CAP member)
4. **Nancy Grimm** (Arizona State University; ASU-CAP faculty member)
5. TBD: 1 additional ASU-CAP faculty member
6. TBD: 1 CAP graduate student
7. TBD: 1 non-ASU member from the community at large (tentative position if identified)

1.8. Response to 2018 Program Officer Comments

After review of our 2016 renewal proposal, the NSF put CAP on probation. Our 2018 proposal was well received and reviewed favorably. The Program Officer comments, which summarize the reviews, panel discussion, and overall outcome of our review process, were positive and even complimentary. These comments did present a few weaknesses in our 2018 research plan, and we address those below:

1. *Although there was praise for the integration between social- and ecological concepts, there was concern amongst reviewers that the core ecological questions were not as well-integrated with each other.* We were optimistic that Figure 3.2 in our proposal (p. 13) would demonstrate the programmatic integration of our IRT research, the central concepts that guide our work, and how the eight research questions link all of these elements together. This progress report, and our site review presentations, will emphasize how much of our research is integrative and cross-IRT.
2. *There was some ambiguity in some of the core ecological questions that may reflect this lack of integration, which was a concern amongst the reviewers given the importance of advancing basic ecological knowledge as well as social-ecological.* As we planned our proposed CAP IV research, our list of research questions grew quite long; many questions were very specific and detailed. For the sake of both simplicity and space, we chose to bundle these many questions into eight broad research questions that were inclusive of these many creative ideas. As such, we can see how the research questions in our proposal might be interpreted as ambiguous, as the core ecological questions were embedded into necessarily broader questions. Throughout this progress report, we demonstrate how these overarching questions have been used to enhance our basic ecological understanding of the CAP ecosystem.
3. *Several reviewers pointed out weaknesses with Research Question 2 on animal adaptations. The main thrust of these comments was a lack of depth in the description of how adaptation and acclimation would be addressed, why long-term data are required to answer RQ2, and a lack of connection to a broader set of ideas from the literature on these concepts.* We understand the reviewer concerns, which hinge, we argue, on some inherent challenges of studying adaptation/acclimation in the LTER context. CAP scientists have been at the forefront of developing a mechanistic understanding of the ecological, physiological, and behavioral adaptations of organisms to city life. However, our long-term datasets mostly focus on the community or population level, whereas individual researchers often focus on individual organisms. Analyses across these levels of organization are needed to form a generalizable, mechanistic understanding of how animals respond to urbanization. Over the first few years of CAP IV, we have worked to better integrate the individual-/species-level behavioral, genetic, and physiological studies with the population- and community-level studies that employ the long-term faunal datasets. We have refined our approach to the central question for the Adapting to City Life IRT, taking a trait-based approach to examining how organisms adapt and acclimate to urban stressors, disturbances, and resources. In addition, we held a workshop in January 2020 in

conjunction with our annual All Scientists Meeting, that brought together key personnel and outside experts on urban evolution and social change. A grant proposal and a manuscript from this event are in progress.

4. *Other issues of minor concern include 1) a lack of clarity on the definition of press and pulse disturbances and how they will interact with ecosystem processes and community structure; 2) the reliance on correlative approaches to answer most of the research questions; and 3) weaknesses in the development of ideas related to feedbacks and resilience which likely relate to an underdeveloped analytical framework for detecting factors contributing to them.* 1) This is a fair criticism. We address disturbance in many ways, and focus on a wide array of both press and pulse disturbances (*sensu* Table 3.2 in our proposal, p. 15). What we failed to do is to explicitly call out these phenomena as disturbances. Examples include extreme heat, various urban stressors that affect non-human organisms, human-wildlife conflict associated with closely sharing habitats, atmospheric deposition of human-derived pollutants, periodic floods, and persistent drought. 2) It is very difficult, if not impossible, to perform controlled ecosystem-scale experiments--for which many LTER sites are well known--when working in a human-dominated habitat where land ownership and management is varied and diverse. We do have a long-term desert fertilization experiment (DesFert, Section 2.5), and much of our organismal work on adaptation is experimentally driven. Our urban design research leans heavily on before-after-control-intervention (BACI) approaches to experimentally understand how implementing UEI-based designs change local environments for all organisms. But a long-term and persistent challenge we face, as do most urban ecologists, is that we have to rely on comparative approaches to study our ecosystem. 3) Also a fair criticism, and again largely because we were not explicit about where we are studying feedbacks related to resilience. In fact, we are studying these dynamics at a range of scales. For example, urban stressors affect the morphology, physiology, and health of urban birds which feeds back to reproductive success and population resilience. Inherent in all of the forms of UEI that we study is our desire to understand how using these "nature-based solutions" makes the city more resilient. And resilience and adaptation are a major focus of our scenarios and futures research, which seeks opportunities to make a future Phoenix more sustainable and resilient, to a variety of disturbances and challenges, than it is today.

2.A. CAP RESEARCH: LONG-TERM EXPERIMENTS AND DATASETS

2.1. Overview

The foundation for all CAP research remains our long-term observational datasets and experiments, many of which began with CAP I (Table 2.1; Fig. 2.1). The original intent 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 we have recently 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 eight IRTs and with our conceptual framework (Fig. 1.2). We are confident that these recent redesigns, which free up critical resources (technician time, driving time, supplies, sample analysis costs), enhance our ability to explore new research questions while taking full advantage of our long-term data to answer them. Where we have re-thought our long-term data collection, the re-designed sampling schemes now more closely articulate with our specific research questions *while maintaining the long-term integrity of our existing datasets*.

Arguably, the single most important metric of urbanization and evolving urban ecosystem structure is LULCC (Section 2.2) and its variation across our 6400 km^2 study area. Research documenting spatiotemporal heterogeneity arising from LULCC continues to produce long-term data in four broad categories (Section 2.3). The first of these is the Ecological Survey of Central Arizona (ESCA, formerly Survey 200), which generates core biophysical observations. In urban ecosystems, where humans are effectively the ecosystem engineers, we must also document spatiotemporal variability in social-ecological interactions. Since CAP's inception we have done so with the Phoenix Area Social Survey (PASS). We must also understand the spatiotemporal dynamics of the socio-economic and demographic underpinnings of those social characteristics that affect UEI. These long-term data, which are closely coupled with our LULCC and PASS data, provide the foundational spatial interconnections for our Economic and Census Data Analysis (Economics). Finally, we focus on long-term spatiotemporal variability in key non-human communities through our Faunal Sampling (Fauna).

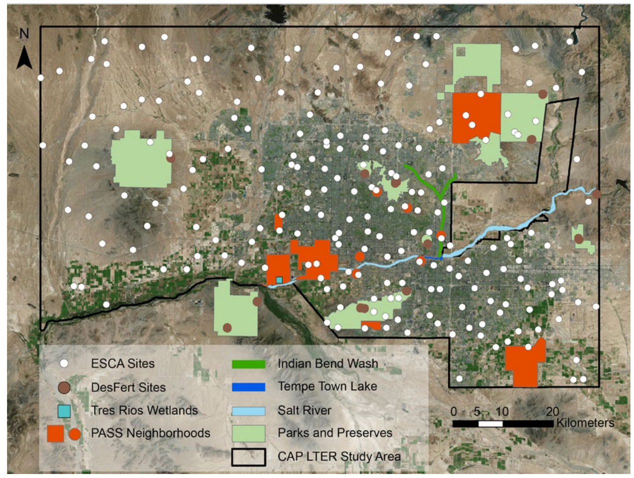


Figure 2.1: CAP study area (shown in red in Fig. 1.1) showing the specific locations of many long-term observational and experimental sites and where much of the CAP IV place-based research is taking place.

Table 2.1: Long-term datasets and experiments + abbreviations for each that are used throughout the report.

ABBR.	DATASET/EXPERIMENT
LULCC	Change in land use/land cover/land configuration
ESCA	Ecological Survey of Central Arizona
PASS	Phoenix Area Social Survey
Economics	Socio-economic demographics
Fauna	Faunal community surveys
Drinking Water Quality	Regional water quality surveys
Stormwater	Stormwater biogeochemistry & hydrology
TTL	Tempe Town Lake water quality
Tres Rios	Tres Rios constructed treatment wetlands
DesFert	Desert Fertilization experiment & urban-rural gradient

Water is critical to all cities, and to life itself. Water is particularly important in our desert city, and we use four long-term observational datasets to encompass water entering, water within, and water leaving CAP (Section 2.4). Most of the water entering the metro area is for direct human uses and it is transported via a highly-engineered water supply system. We have worked with water providers and regional cities since 1998 on issues affecting drinking water supplies, treatment, and distribution through our Regional Water Quality program (Drinking Water Quality). Water also enters the study area via precipitation, if infrequently (annual average ≈ 20cm). Management of urban stormwater, particularly when that management takes advantage of UEI, is an important aspect of our long-term water-based sampling. Thus, our long-term Stormwater Quality & Hydrology monitoring (Stormwater) is focused on urban watersheds with different types of infrastructure. For a desert city, Phoenix has a surprising amount of open water UEI—approximately 1000 artificial water bodies. Perhaps the most iconic of these is Tempe Town Lake (TTL), and since 2005 we have measured water quality in this lake. We also track water leaving our desert city. We know from our whole-ecosystem nutrient budgets that most water entering CAP leaves via evapotranspiration. One place surface water does leave, though, is from the largest wastewater treatment plant in Phoenix. However, before the effluent enters the Salt River it first passes through the Tres Rios constructed treatment wetland, where we have been conducting research since 2011 (Tres Rios). Finally, in an effort to understand how atmospheric enrichment from the city affects nearby native desert ecosystems, in 2006 we initiated a long-term desert fertilization experiment (DesFert; Section 2.5). The DesFert experimental design is also a CAP-wide urban-rural gradient based in protected areas, allowing for research beyond the fertilization experiment itself.

2.2. Change in Land Use/Land Cover/Land Configuration (LULCC)

We continue to document LULCC at spatial resolutions of 1m, 30m, and 250m. Some of these data are integrated with Maricopa County Cadastral data (land-use parcels) and ASTER land-surface temperature data. The following LULCC products are available through the CAP data portal: 1) 1m resolution land-cover classifications based on 2010 and 2015 NAIP (National Agricultural Imagery Program) data that employed an object-based imagery assessment method, coupled with cadastral data, to generate 12 land classes; 2) 30m resolution land-cover classification based on 2010 Landsat TM data that employed a similar approach to generate 21 land classes; 3) 30m resolution land-cover classifications for 1985, 1990, 1995, 2000, 2005, and 2010 based on Landsat ETM data that employed a systematic land classification consistent with the 2010 product but with 9 land-cover classes because of a lack of cadastral ancillary data for each year assessed; and 4) 250m resolution land-cover that informs complementary research at ASU and NCAR (National Center for Atmospheric Research) using WARF (Weather Research and Forecasting Model), which will project climate changes for the CAP area.

The fine-grain resolution (1m) LULCC data inform our 30m resolution time-series data. We have continued this work in CAP IV, including completion of the 2015 1m land-cover classification and the 2015 30m land-cover data. The 2020 land-cover data at both scales of resolution are to be developed next. In addition, we can hierarchically integrate our LULCC information such that the 1m land-cover classes may be aggregated to 30m and the 30m may be aggregated to 250m. Beyond these uses of land-cover data and mapping, the following products have been generated: 1) 1m resolution vegetation indices for 2005, 2010, 2015, and 2017; 2) 1m resolution “open” or “vacant” land cover for 2010 and 2015; 3) 1m suitability mapping of vacant parcels for urban gardens and greening (heat mitigation); and 4) 30m land surface temperature data for 1985, 1990, 1995, 2000, 2005, 2010, 2015. These data products are used to address a large number of CAP research questions, in addition to research directly tied to LULCC dynamics (e.g., Smith et al. 2017; Zhang et al. 2017; Stulmacher 2019; Stulmacher & Watkins 2019a,b; Zhang et al. 2019; Middel et al. 2020; Stuhlmacher et al. 2020; Smith et al. in review).

2.3. Spatiotemporal Heterogeneity

Long-term Ecological Survey of Central Arizona (ESCA): With ESCA, we are approaching 20 years of documenting environmental heterogeneity across the CAP region by revisiting ≈ 200 sampling sites every five years since 2000. These efforts have allowed us to quantify spatial variation in soil black carbon, soil microbial communities, biogeochemistry, and various flora and fauna. We have also developed innovative statistical approaches to assess biophysical and social controls on spatial patterns of biophysical variables. Time-series analysis of changes in soil biogeochemistry with changing land use is ongoing. After the 2021 ESCA sampling, we will more closely integrate ESCA with our other long-term sampling efforts and question-based research. We will redesign ESCA to enhance this research synchrony by redistributing a subset of the sites to align them with other long-term data collection efforts and with the place-based focal areas. This redesign will happen as part of our preparation for CAP V. We have already begun some of this transition moving to remote-sensing-only sampling for 12 sites to confirm no change in land use since 2015 (these sites are buildings or streets with no vegetation where sampling has not been possible). Thus, in our upcoming ESCA sampling, we will reduce to 185 sites, allowing us to streamline efforts and boost integration with other long-term projects, while maintaining the long-term integrity of the dataset. We are currently in preparations for the 2021 sampling in which both PASS and ESCA will be sampled in the same year.

Phoenix Area Social Survey (PASS): In 2006 and 2011, the PASS surveyed approximately 20 participants in 40 neighborhoods. In this configuration, PASS quantified the social and spatial heterogeneity of a host of variables, including heat stress and vulnerability, water-risk perceptions and consumption rates, and landscape preferences and practices (Larson et al. 2017). For the 2016–17 survey, we re-designed our sampling strategy to focus on fewer neighborhoods, but more residents per neighborhood— many of which are strategically located near distinct UEI features and other CAP IV research. This PASS targeted 12 neighborhoods (Fig. 2.1), nine of which carried over from the 2006 and 2011 design. We were able to sample 496 households, with neighborhood-level sample sizes of 22-60 respondents. This new design, which we will repeat in 2021, allows for multilevel modeling to test for neighborhood effects and enables more integrated social-ecological analysis of focal areas, including those that have long been CAP research sites (e.g., the Salt River, Tempe Town Lake, Indian Bend Wash, and urban mountain parks and preserves). PASS 2016-17 delved more deeply into our CAP IV research questions, and the survey questions focused explicitly on human-environment interactions including perceived ecosystem services and disservices (Larson et al. 2019); landscape preferences and practices (Wheeler et al. 2020); and attitudes toward bees and other wildlife (Larson et al. 2020). PASS research has also facilitated coupled analyses of social and ecological datasets, for example, linking resident attitudes and perceptions of birds to bird community composition. For the 2021 survey, we will maintain the 2017 approach and stress longitudinal analysis of 2021 responses relative to 2017, in addition to increasing the spatial environmental data linked to the survey data.

Long-term Socio-Economic Data: The interconnections between people and UEI are both heterogeneous and bidirectional. Unpacking these connections requires using consistent spatial scales for representing human behavior and tracking ES while measuring both over time. The US Decadal Census offers fundamental social science data, and we match the spatial dimension of these records to parcel level records of housing sales and to past Census and PASS data. Thus, we are able to track neighborhood-scale changes in economic and demographic variables, and in environmental attitudes. We have used these datasets to understand the impacts of changes in UEI and associated ES on household locational choices (Fishman and Smith 2017). Our ability to link housing-transaction records with indices of ES (from PASS and other data sources) allows us to better understand the spatiotemporal differences in these services (Klaiber et al. 2017). Maintaining these connections over time requires consistent participation of PASS survey respondents over time. As a part of PASS 2017 we used a field experiment to investigate how different types of incentives affected response rates (Smith et al. in prep.). We have also linked parcel-scale records for housing sales and residential UEI use to metered household water use in selected municipalities. Although these data are confidential and onerous to use, we will continue these efforts while exploring new strategies for aggregating protected datasets that will remove confidential information while maintaining the spatiotemporal variation that make our socioeconomic demographics data so valuable. In a new line of research, we investigated new indices to gauge when the size of a policy intervention requires consideration of the feedback and interactions between market responses and ES in the benefit cost measures used to assess those policies (Smith and Zhao 2020).

Long-Term Faunal Community Data: We have learned a great deal about the influence of human activities and behaviors on urban biodiversity and, in turn, how biodiversity links to human perceptions, values, and actions (Warren et al. 2019). We will continue to quantify species abundance/distribution for birds (Banville et al. 2017, Allen et al. 2019), ground-dwelling arthropods (Andrade et al. 2017), and riparian herpetofauna, but we recently redesigned our faunal community sampling to align more closely with the ESCA, PASS, and DesFert long-term datasets and to our question-driven research. Because we have re-designed PASS, in CAP IV we refocused our residential bird sampling on these 12 PASS neighborhoods, with increased sampling density to better characterize the bird community at the neighborhood level. We consolidated many of our desert bird sampling locations to the DesFert sites, to other desert parks/preserves where we are pursuing question-driven research, and to the Salt River (Andrade et al. 2018). These changes have enhanced synergies among our long-term data collection efforts and our question-driven research (e.g., Andrade et al. in review; Andrade et al. in revision; Brown et al. in revision).

2.4. Water Into, Within, and Out of the City

Water is critical to all cities, and it is particularly important in our desert city. We use four long-term observational datasets to encompass water entering the city for human use and via precipitation, water within the city, and water leaving the city.

Regional Drinking Water Quality: We have been working with regional water providers—the Salt River Project, the Central Arizona Project—and metropolitan Phoenix cities since 1998 on algae-related issues affecting drinking water supplies, treatment, and distribution. The six upstream reservoirs on the Salt and Verde Rivers, which provide the Phoenix Metro Area with half of its water supply, are sampled either monthly or quarterly, and key supply canals are also sampled monthly or twice a month. We analyze samples for organic carbon, total nitrogen, arsenic, conductance, and taste and odor compounds, and we continue to leverage these datasets with cooperation from local and federal agencies. These long-term water quality data have improved our understanding of taste and odor occurrence, control, and treatment, and of disinfection byproducts. For example, methyl-isoborneol 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). We have used these long-term data to document the impacts of severe weather events and the inability of quagga mussels to infest the Salt and Verde River watersheds. We developed and applied new analytical methods to: 1) understand the presence of organic vs inorganic phosphorous molecular weight species in river water and treated wastewaters and how to recover phosphorous for reuse (Venkatesan et al. 2018a; Li et al. 2019); 2) to characterize organic matter fractions from reservoirs and wastewater and to quantify the impacts of upstream wastewater discharges on downstream drinking water quality (Nguyen et al. 2018, Nguyen and Westerhoff 2019); 3) detect per- and poly-fluoroalkyl substances in groundwaters used for drinking water supplies and to evaluate engineering technologies to remove this emerging class or of trace level organic pollutants (Zeng et al. 2020); and 4) to examine how recreational uses of these water bodies influences the occurrence of engineered versus natural nanoparticles (Venkatesan et al. 2018b). The latter work with nanoparticles informed a multi-university collaborative *Science* publication on natural, incidental, and engineered nanoparticles in global ecosystems (Hochella et al. 2019). 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.

Stormwater Quality and Quantity: Watershed studies in our desert city capture the occasional flow events initiated by summer monsoon or winter frontal storms; no perennial streams exist in the metropolitan area. Our long-term stormwater quality and hydrology monitoring focuses on a large, urban watershed, Indian Bend Wash, which historically was drained by an ephemeral wash but now features a greenbelt park that uses UEI to manage for flooding. The 505 km^2 watershed encompasses a wide range of land cover types, including native Sonoran Desert, commercial and recreational land uses, but is predominantly residential. The lower 230 km^2 in central Scottsdale drains to the greenbelt park and Tempe Town Lake. We have instrumented this part of Indian Bend Wash with automated water samplers near the mouth and on two smaller but nested watersheds that differ in housing age and the type of stormwater UEI present. We sample chemical constituents of stormwater during all runoff-producing storms to identify: 1) the primary source of water and materials transported by stormwater, and 2) factors controlling these exports, such as antecedent weather, event precipitation, catchment characteristics, and human activity. To date we have sampled more than 90 events. Ongoing analyses of these data indicate that overall solute export is driven consistently by discharge, but export patterns (hysteresis, timing of delivery) within storms and across chemical species show complex patterns influenced by catchment land cover and storm features. We included our Indian Bend Wash data in an analysis comparing the flashiness of urban vs. desert streams and showed that aridland urban streams are less flashy than their desert counterparts (McPhillips et al. 2019).

Tempe Town Lake Water Quality: Since 2005, we have measured temperature, pH, conductivity, dissolved oxygen, dissolved organic carbon concentration and composition, and total nitrogen in Tempe Town Lake (TTL), which is located just north of downtown Tempe and ASU's Tempe campus. We regularly harvest relevant meteorological and hydrologic flow data for interpretation. Sampling frequency has varied somewhat: In 2005, we sampled daily; from 2006–2012 we sampled weekly-to-monthly and after monsoon storms; and since 2012 we have sampled twice-weekly and after most rain events (Fig. 2.2). Storm-event sampling allows us to evaluate the effects of extreme events on aquatic biogeochemistry. 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. We used ARIMA time-series modeling of our TTL data to show that high-resolution sampling is necessary to determine how exogenous versus endogenous drivers control biogeochemical processes. In 2018, we installed an *in situ* water quality datasonde that measures basic parameters (pH, temp, conductivity, O_2, chl *a* as well as fluorescent DOC) at 30-minute temporal resolution. We have been supplementing these sensor data with twice-weekly samples and are now developing calibrations that relate optical characteristics to bulk organic carbon concentrations. Our next steps are to assess rates of lake metabolism (NPP) and develop statistical models that may allow us to reduce the number of grab samples needed over time. While the pandemic has substantially disrupted our routine sampling since March, we expect to have our systems back up and running in Fall 2020. We also note that a recent train derailment, fire, and ensuing bridge collapse has caused significant disruption in

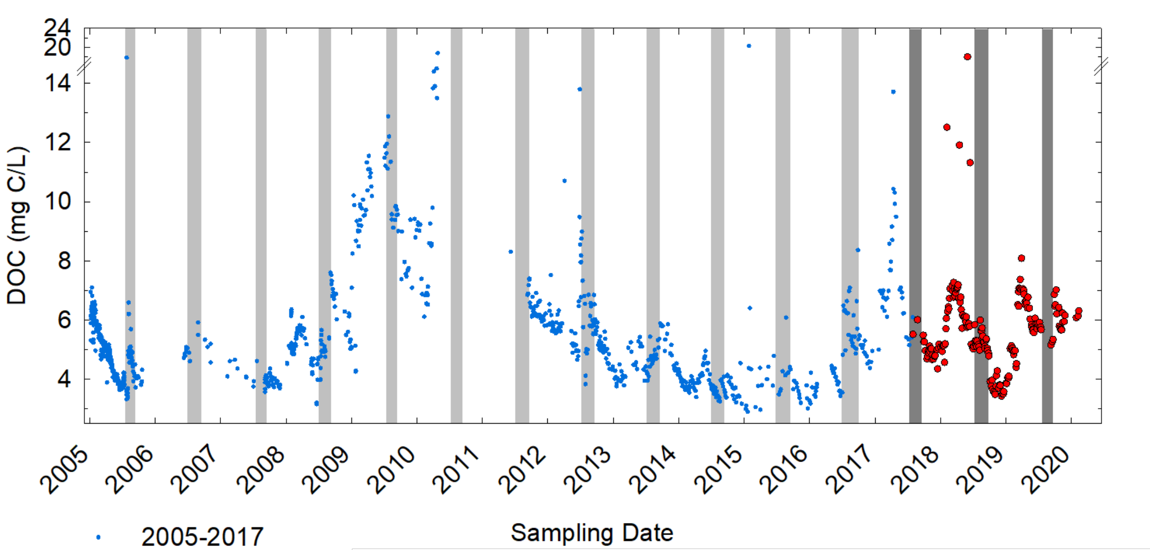


Figure 2.2. Timeseries data collected roughly twice a week for dissolved organic carbon (DOC) in TTL. Blue data are 2005 - 2017, red data are 2017 - present (CAP IV). The gray bars represent the monsoon seasons. The data reveal variability at sub-season The data reveal variability at sub-seasonal, seasonal, and interannual time scales. Occasional rain storms and flow events are often associated with high DOC concentrations due to terrestrial runoff or riverine sources (e.g., winter/spring of 2018).

our ability to restart our field sampling in addition to some likely contamination of the lake. We plan to assess both short- and long-term effects from this urban disaster on the TTL system.

Tres Rios Constructed Treatment Wetland: We have been conducting research, mostly with student volunteers, at the Tres Rios CTW since 2011 (Fig. 2.3). This 42 ha "working" wetland (21 ha of vegetated marsh, 21 ha of open water) was built to remove nutrients--in particular nitrogen--from effluent being discharged into the Salt River. In our regular bimonthly sampling we measure marsh plant productivity and nutrient uptake, whole-system and within-marsh water quality, and open water aquatic metabolism. We use these data to estimate whole-system nutrient and water budgets. Our budgets have shown near-complete uptake of nitrogen by the marsh (Treese et al. 2020; Childers in press), and we have demonstrated, for the first time, transpiration-driven plant-mediated control of surface water hydrology in this wetland (Bois et al. 2017). This phenomenon, which we call the Biological Tide, brings new water and nitrogen into the marsh, increasing nutrient uptake of the system (Treese et al. 2020; Childers in press). We have also measured greenhouse gas fluxes from this system and found that the water overlying the marsh was a source of CH_4 and N_2O while *Typha* sp. leaves were a source of CH_4 but a sink for N_2O (Ramos 2017). When we accounted for the large greenhouse gas potential of N_2O, we found that the entire Tres Rios constructed treatment wetland may be a sink for greenhouse gases. We hypothesize that a large manure composting facility adjacent to Tres Rios may be the source of this N_2O that the plants are sequestering (Childers in press). Finally, we continue to host research charrettes with the City of Phoenix Water Services Department to communicate our findings to their administrators, managers, and staff.

Figure 2.3: The Tres Rios CTW showing the 10 marsh transects (in white), those where water quality is also sampled (white numbers), and the inflow and outflow (blue arrows; Childers in review).

2.5. The DesFert Long-term Experiment

Since 2006, the DesFert experiment has simulated how atmospheric enrichment from the city affects nearby native desert ecosystems using a fully factorial nitrogen (N) and phosphorus (P) fertilization design. DesFert doubles as an urban-rural gradient experiment in which we have been exploring the impacts of the urban environment and nutrient enrichment on biotic and abiotic ecosystem properties in protected desert areas. Fortuitously, the experiment also crosses a precipitation gradient, with desert sites to the east of the city having nearly twice the mean precipitation of desert sites west of the city and within the urban area. In these plots we quantify plant community composition, primary production, soil biogeochemistry, and atmospheric deposition. Measurements of ambient N deposition from this project comprise the longest spatially and temporally explicit dataset of N deposition in drylands, from which we highlight the need for long-term, mixed methods to estimate atmospheric N enrichment in aridlands (Cook et al. 2018). In CAP IV we have continued our experimental fertilization at all 15 sites, but have down-scaled the regularity of sampling to a "tiered" approach in order to redirect critical resources elsewhere. The focus is now on continuing regular plant and soil measurements at nine sites, balanced across the urban and outlying regions. Recent results from this experimental framework demonstrate the importance of water (e.g., season and timing of precipitation) in driving atmospheric N enrichment (Cook et al. 2018). Both N fertilization and low precipitation decrease winter annual plant diversity, with lasting effects of low precipitation on subsequent years (Wheeler et al. in revision). Nitrogen fertilization not only affects living plant communities, but also speeds their subsequent decomposition and N-release dynamics. Photodegradation (UV radiation) also increases rates of litter decomposition and nutrient loss, except when fertilized by enriched urban litter (Ball et al. 2019). Notably, numerous graduate and undergraduate students benefit from these long-term study plots. For example, at two of the sites a University of New Mexico a graduate student has set up rainout shelter experiments as part of the global DroughtNet network, and several ongoing undergraduate research projects are investigating the interaction of long-term N fertilization with altered precipitation regimes to influence the activity and abundance of soil biota.

2.B CAP RESEARCH: IRT-SPECIFIC RESEARCH

2.6 Overview

Per Section 1.6, we organize CAP research around our eight Interdisciplinary Research Teams (IRTs). Each IRT has a broad research question that has been guiding that group's CAP IV research and their interactions with other IRT groups. In the sections that follow we overview the accomplishments by each IRT. We identify the long-term data that justify each question, the long-term data and models that we are using to answer each question, and how each question addresses the seven LTER core areas (Table 2.2). Under each IRT question, myriad hypotheses are being tested and detailed analyses involving long-term data are being conducted. However, we use research questions rather than hypotheses for consistency and to highlight relationships among the questions.

Table 2.2. Research Questions from the 2018 CAP IV proposal, lead IRT for each, and how each relates to the seven LTER Core Areas.

Research Question	Lead IRT	LTER Core Areas being addressed
RQ 1	Climate & Heat	Disturbance, LULCC, Social-ecological system dynamics
RQ 2	Adapting to City Life	Populations & communities, disturbance, LULCC, Social-ecological system dynamics
RQ 3	Residential Landscapes & Neighborhoods	Primary production, nutrient cycling, organic matter dynamics, disturbance, LULCC, Social-ecological system dynamics
RQ 4	Governance & Institutions	LULCC, Social-ecological system dynamics
RQ 5	Parks & Rivers	Primary production, populations & communities, nutrient cycling, organic matter dynamics, disturbance, LULCC, Social-ecological system dynamics
RQ 6	Water & Fluxes	Primary production, nutrient cycling, organic matter dynamics, disturbance, LULCC, Social-ecological system dynamics
RQ 7	Urban Design	LULCC, Social-ecological system dynamics
RQ 8	Scenarios & Futures	Primary production, nutrient cycling, organic matter dynamics, disturbance, LULCC, Social-ecological system dynamics

2.7. Adapting to City Life

The Adapting to City Life IRT continues to be focused on this research question: *In a rapidly changing urban ecosystem, how do non-human animals respond at individual, population, and community levels to stressors, disturbances, and resource availability, and how does the presence of these animals affect resident satisfaction with life and their neighborhoods, and their perceptions of risk?* Our general approach to addressing this question includes: 1) the use of consistent trait-based approaches using our long-term datasets; 2) analyses that span several levels of the ecological hierarchy, from organismal to population to community; 3) focusing on rich taxonomic variation; and 4) the application of several ideal ecological models, including those that focus on pest species and on common and conspicuous visitors to people's yards.

In our work with the Residential Landscapes and Neighborhoods and Parks and Rivers IRTs, we have found that bird communities in residential yards and riparian areas have been domesticating over time, shifting toward broadly distributed, human-associated species rather than those unique to the region (Banville et al. 2017, Warren et al. 2019). In yards, bird species from all guilds are decreasing in

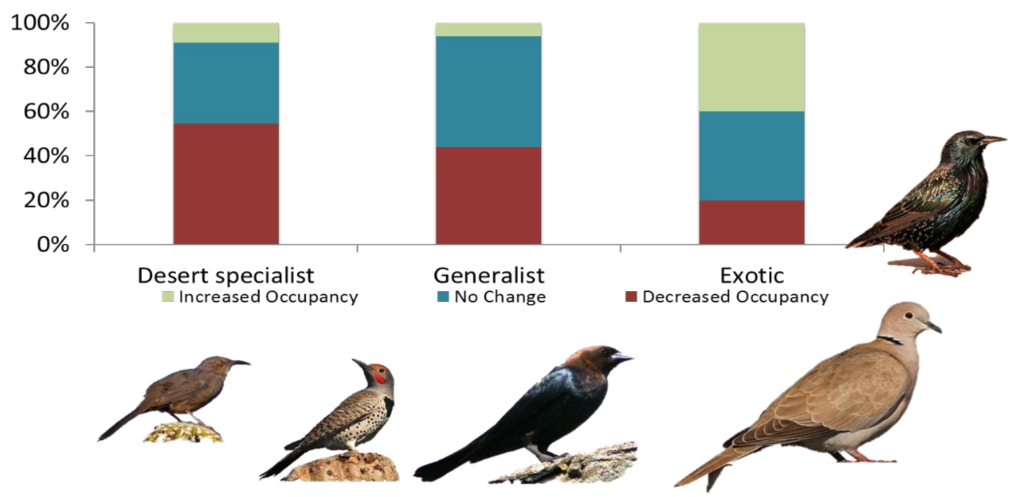
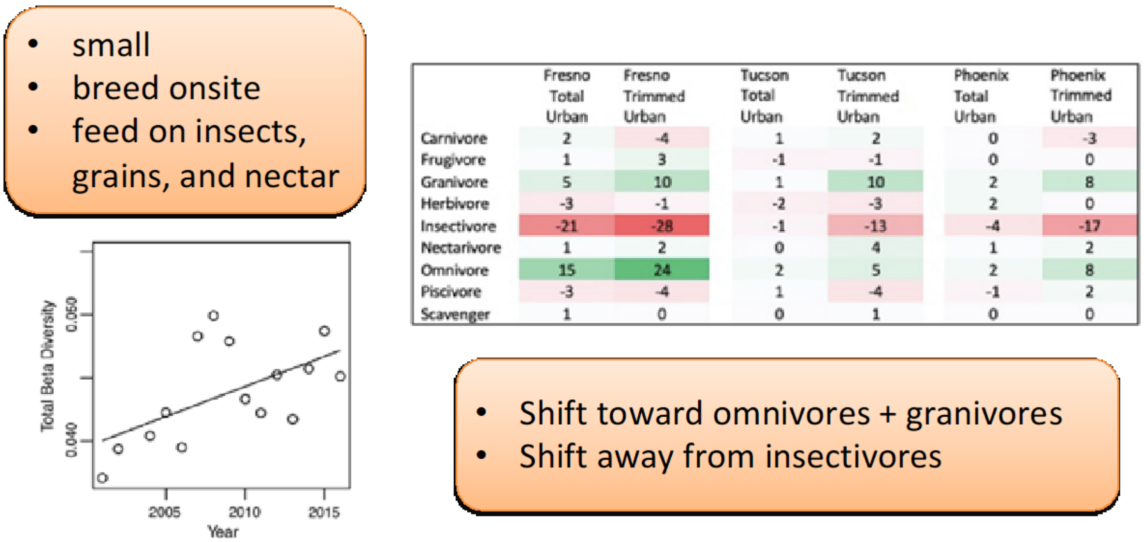


Figure 2.4. Birds in residential neighborhoods are domesticating with time at the same time occupancy has been decreasing (Warren et al. 2019).

occupancy (i.e. the number of sites at which the species is detected; Warren et al. 2019). This decrease in occupancy has been occurring in all categories of species (desert specialists, generalists, and exotics; Fig. 2.4). We have seen increases in only a small number of species, and the result is a domesticating bird community. Interestingly, we have also found that, in PASS neighborhoods, resident satisfaction with the wildlife in their yards continues to be higher in more speciose neighborhoods, even though bird species richness and satisfaction with the variety of birds in their neighborhoods have both declined over time (Warren et al. 2019; Section 2.8).



	Fresno Total Urban	Fresno Trimmed Urban	Tucson Total Urban	Tucson Trimmed Urban	Phoenix Total Urban	Phoenix Trimmed Urban
Carnivore	2	-4	1	2	0	-3
Frugivore	1	3	-1	-1	0	0
Granivore	5	10	1	10	2	8
Herbivore	-3	-1	-2	-3	2	0
Insectivore	-21	-28	-1	-13	-4	-17
Nectarivore	1	2	0	4	1	2
Omnivore	15	24	2	5	2	8
Piscivore	-3	-4	1	-4	-1	2
Scavenger	1	0	0	1	0	0

Figure 2.5. Bird community "winners" and "losers" in response to urban land use change. Right: Percent change in prevalence of each diet guild in spring urban species assemblages compared to spring regional species pool. Guilds that are over-represented in urban species assemblages are shaded in green, while guilds that are under-represented in urban species assemblages are shaded in red. Left: Beta diversity has been increasing over time (Allen et al. 2019; Hensley et al. 2019).

We have been using our long-term faunal community datasets to investigate "winners" and "losers" (i.e., species that are decreasing versus increasing in abundance) in response to land use change. We have found that species traits at least partially predict winners and losers (Allen et al. 2019; Hensley et al. 2019; Fig. 2.5). For example, across all land uses, bird communities have shifted toward small species, those that breed on site versus those that winter on site, and those that feed on insects, grains, and nectar (Allen et al. 2019). Furthermore, bird communities in urban habitats are shifting toward omnivores and granivores and away from insectivores. We have also found that bird traits--in particular being more colorful and unique to the surrounding ecoregion--predict how positively they are viewed by residents of PASS neighborhoods (Andrade et al. in revision; Fig. 2.6). Specifically, birds that are colorful and unique to the Sonoran Desert ecoregion are viewed more positively.

Figure 2.6. Birds that are more colorful and unique to the Sonoran Desert ecoregion are perceived more positively by residents. People perceived birds in the Distinctive and Hummingbird trait groups more positively, particularly in affluent neighborhoods close to natural preserves. (Andrade et al. in review).

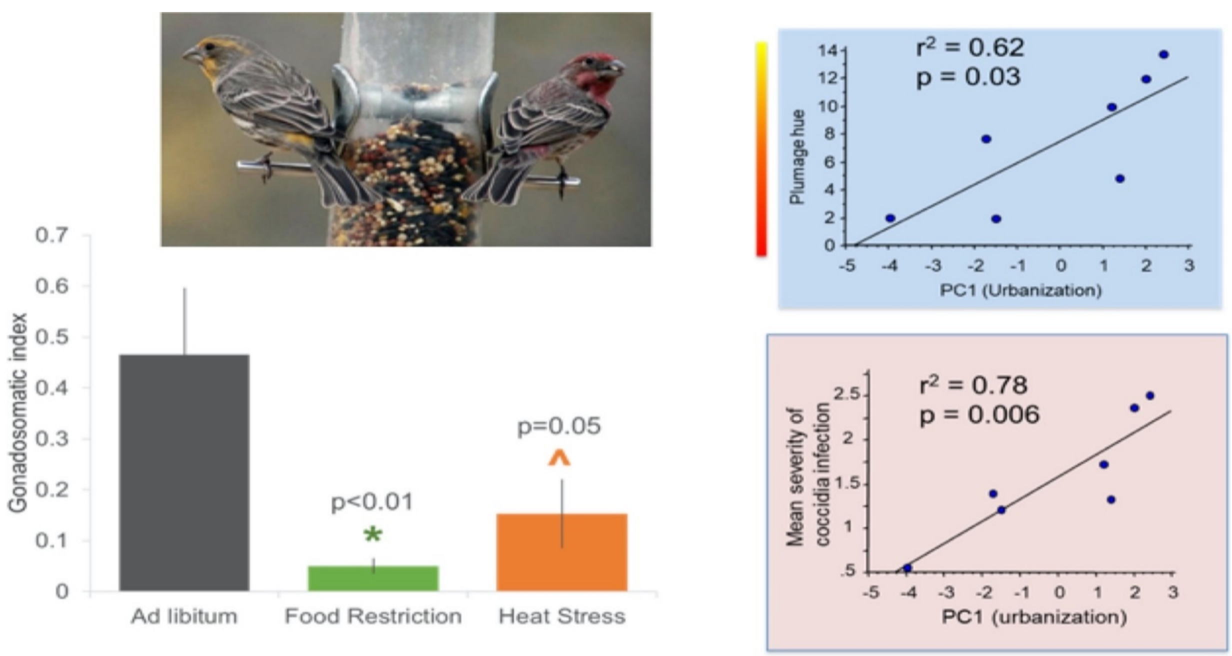


Figure 2.7. Urban heat, disease, and other urban stressors affect the physiology, behavior, and morphology of house finches. Left: Experimental exposure to stressors often experienced in urban environments influences gene expression in the gonads (reproductive organs) of House Finches. Right: Urban finches are less sexy and more sick, and mate preferences track the color/health gradient (Valle et al. 2019; Girardeau et al. 2018).

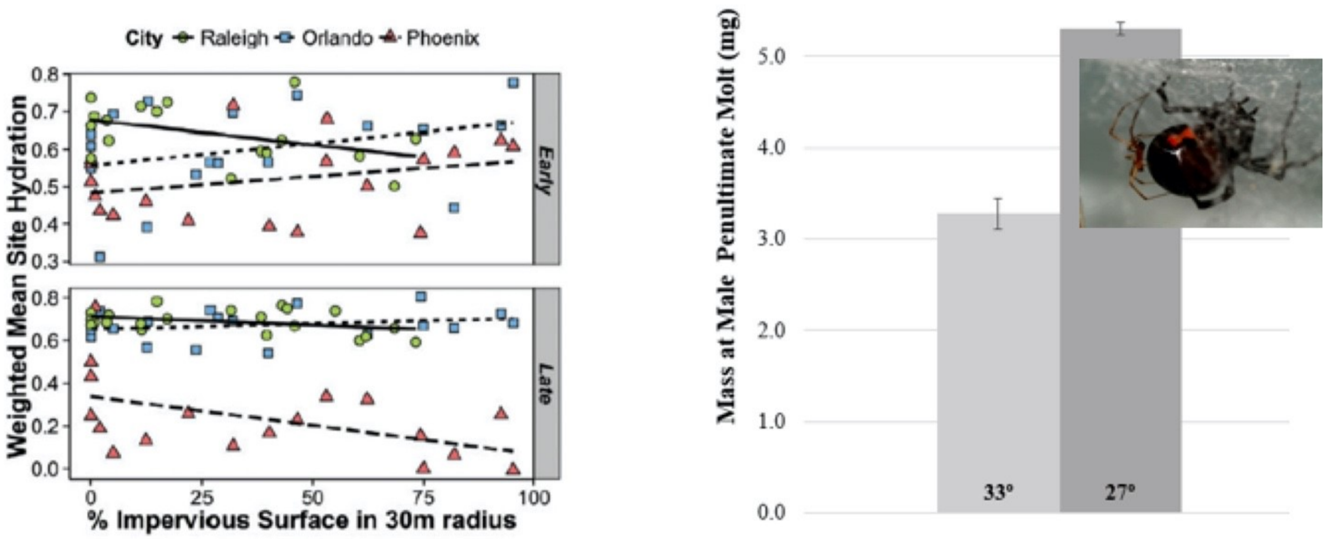


Figure 2.8. Left: Mean arthropod water content converges in Phoenix and Raleigh at high levels of impervious surface, early in the growing season, but diverges later in the season. Right: The effects of heat on cannibalism are different in desert vs. urban lineages of black widow spiders, suggesting the potential for genetic adaptation. (McCluney et al. 2017; Johnson et al. 2019).

We have also been working with members of the Climate and Heat IRT to investigate how urban heat affects non-human organisms. We have found that urban heat, disease, and other stresses associated with living in the city affect the physiology, behavior, and morphology of house finches, a colorful and common species in the CAP study area. Experimental exposure to stressors often experienced in urban environments influences gene expression in the gonads (reproductive organs) of house finches (Valle et al. 2019; Fig. 2.7). Urban finches are also less sexy and more likely to be sick, and their mate preferences track an urban-rural gradient in color and health (Girardeau et al. 2018; Fig. 2.7). We have also found that urban heat strongly impacts the physiological and behavioral traits of arthropods. Some of these effects are plastic while others may reflect genetic adaptation. In a cross-city comparison of arthropod physiology in Phoenix and Raleigh, we found that mean arthropod water content converges in these two cities at high levels of impervious surface and early in the growing season, but it diverges later in the season (McCluney et al. 2017; Fig. 2.8); this is an example of a plastic response. By contrast, the effects of heat on cannibalism by black widow spiders are different in desert versus urban lineages, which also suggests the potential for genetic adaptation (Johnson et al. 2019; Fig. 2.8).

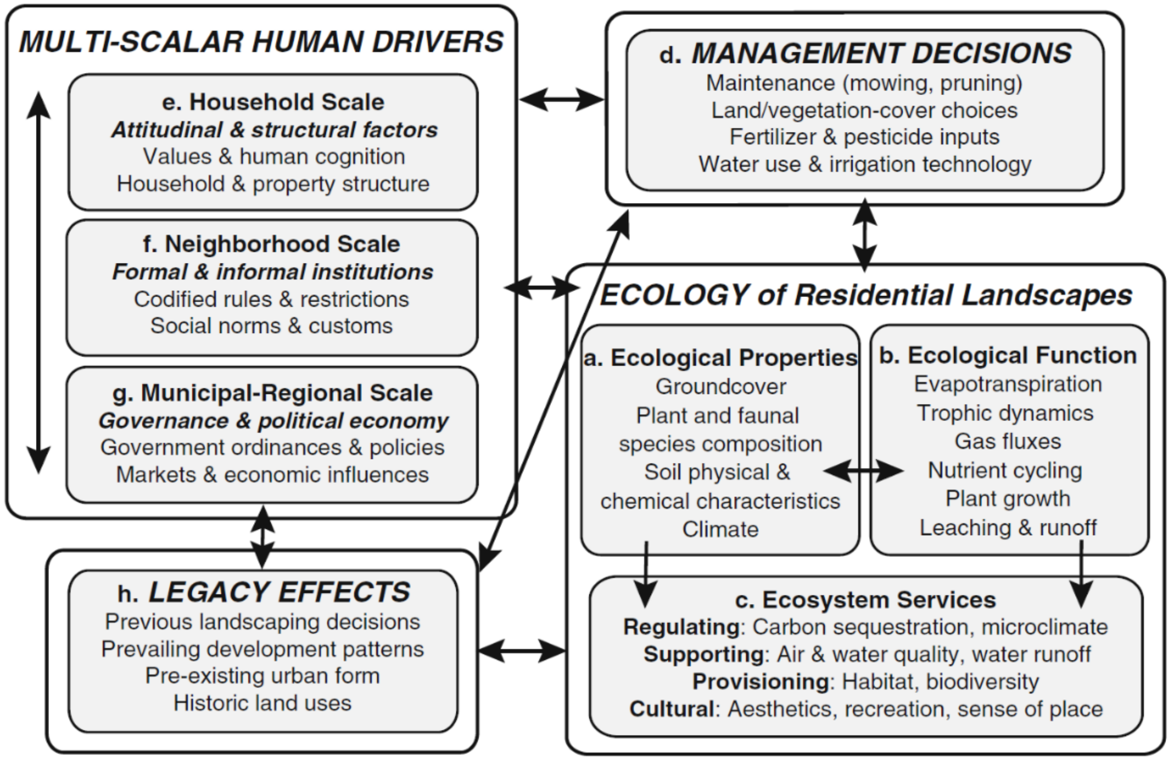


Figure 2.9. The conceptual framework guiding the research of this IRT.

2.8. Residential Landscapes and Neighborhoods

The overarching question guiding this IRT is: *How do the environmental and social settings of residential landscapes affect urban ecological infrastructure (UEI) services and disservices, environmental risks and perceptions, and management decisions and tradeoffs at various scales? Moreover, how do these factors vary in the long term across space?* (Fig. 2.9). To answer this question, we integrated data from the PASS and ESCA to understand household experiences with ecosystem services and disservices, attitudes toward wildlife, long-term trends of urban biodiversity, and relationships between management behaviors and biological outcomes region-wide. Through leveraged grants, our comparative research has spanned the continental scale. Our results highlight how to strengthen urban stewardship and connections between the regional environment and local communities.

Understanding perceived ecosystem services and disservices informs the social and ecological value of UEI. Larson et al. (2019) revealed overall positive views among residents, with variation in perceived beneficial or detrimental outcomes across a socio-economic gradient (Fig. 2.10). In collaboration with the Parks and Rivers IRT, Brown et al. (in revision) investigated resident perceptions of aesthetic and biological qualities in relation to diverse UEI (Fig. 2.11). While desert preserves and local parks with water are perceived most positively, vacant land, cropland, and segments of the Salt River are viewed negatively. Social factors (i.e., place identity, neighborhood cohesion, and income) most strongly influence perceived bio-cultural services and disservices.

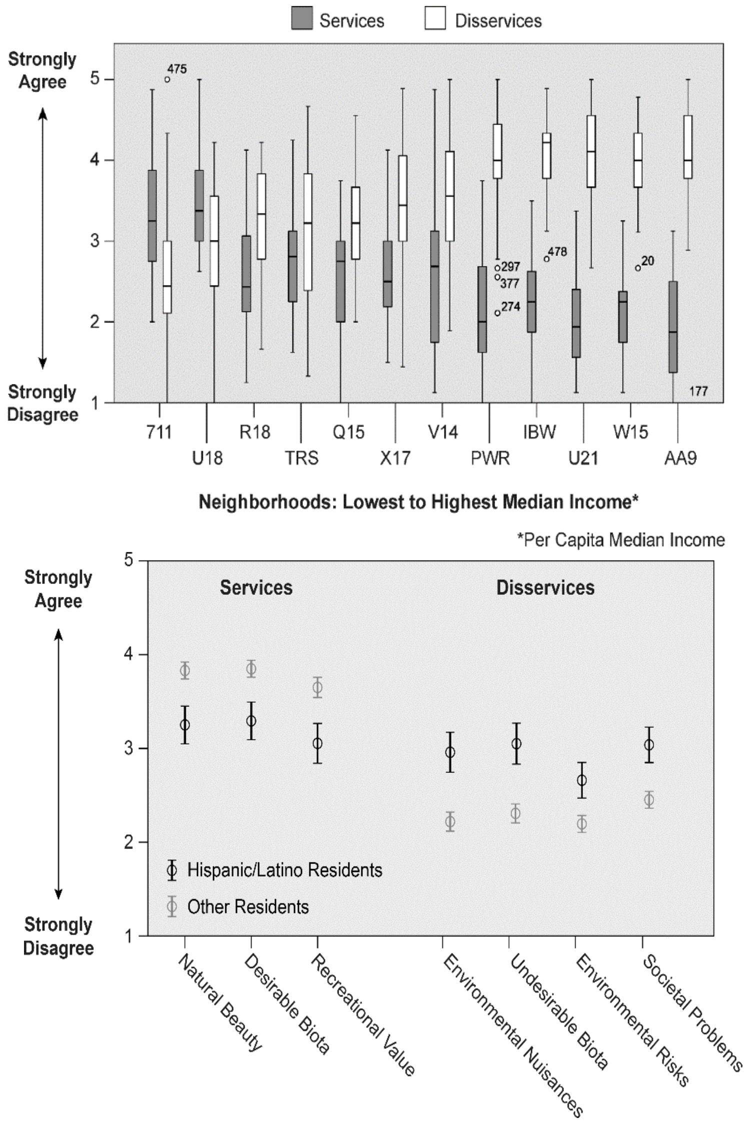


Figure 2.10. Resident perceptions of ecosystem services and disservices provided by their local, neighborhood landscapes. Top: Overall perceptions by socio-economic gradient across neighborhoods; bottom: Perceptions of distinctive services and disservices by Latinx residents compared to others (from Larson et al. 2019).

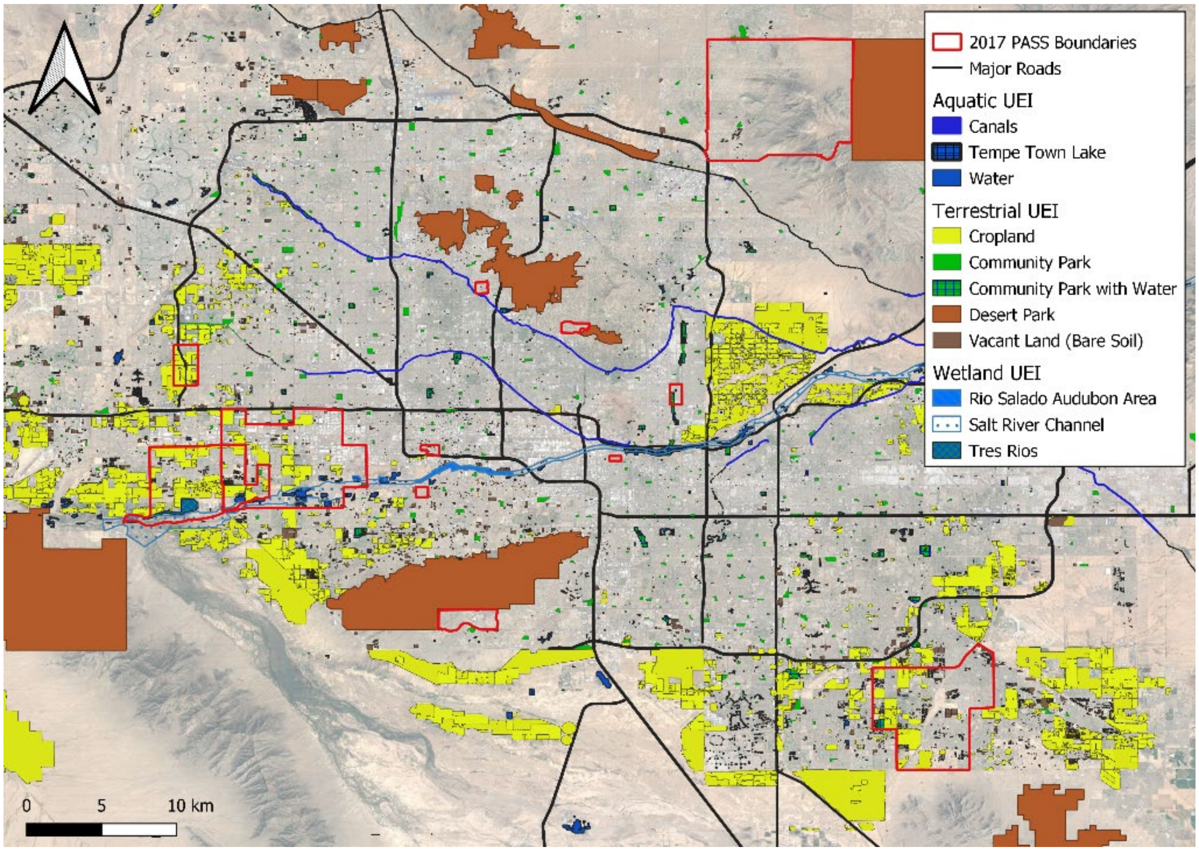


Figure 2.11. Diverse UEI in metropolitan Phoenix, Arizona (from Brown et al. in revision).

Spatially analyzing environmental risks and perceptions of UEI and wildlife builds knowledge about their distribution and outcomes. Andrade et al. (2019), in their work with the Parks and Rivers IRT, found that attitudes toward the desert spatially cluster; positive views are strong in high-income areas near desert parks, and negative views cluster in lower-income areas with grassy landscaping (Fig. 2.12). Latinx residents also had relatively negative desert attitudes and coincided with environmental hazards such as extreme heat. Larson et al. (2020) found mostly neutral attitudes toward bees, while most Phoenicians do not believe bees are problematic locally (Fig. 2.13). People living closer to desert parks like bees more than others, as do people with strong ecological worldviews and those who own pets. In these latter analyses, we worked closely with the Climate and Heat and Parks and Rivers IRTs, respectively. Examining land management decisions advances insights for conservation actions and outcomes. Larson et al. (2020) found that planting desert vegetation was positively associated with positive views of bees, whereas negative views of bees were linked to pesticide use. Meanwhile, Wheeler et al. (2020) revealed that many Phoenicians (54% of PASS respondents) do not have their ideal yards and, although yards have become increasing xeric over time, many individuals (46%) still want more mesic, turf lawns (Fig. 2.14). While values and lifestyles drive what people want, parcel attributes and the legacy of previous decisions structures actual yard types (Larson et al. 2017).

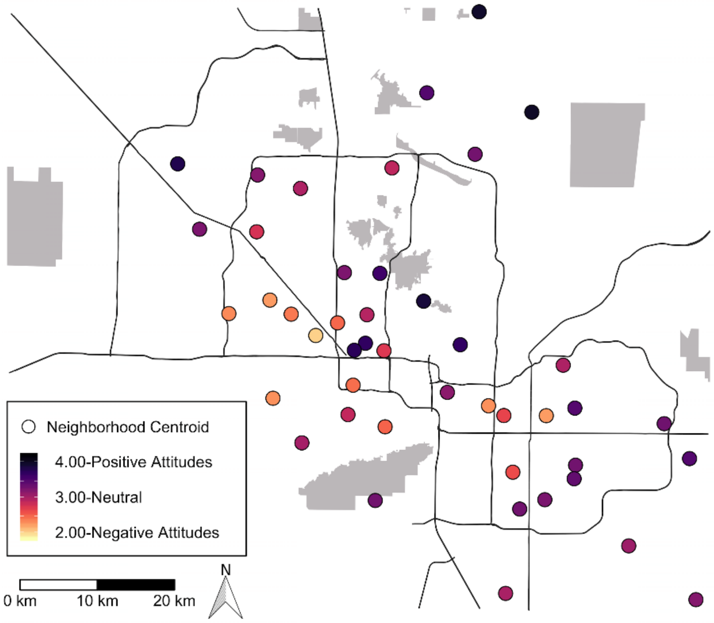


Figure 2.12. Attitudes towards the desert by PASS neighborhood, using 2011 data (Andrade et al. in 2019).

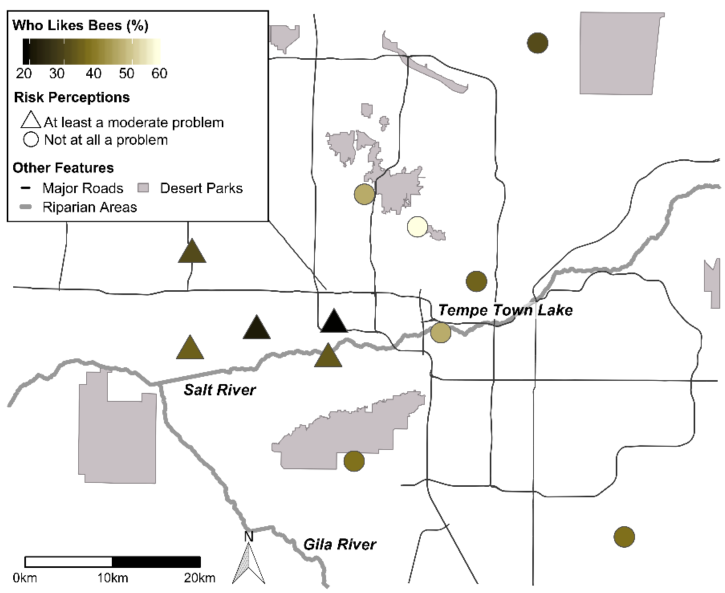


Figure 2.13. Attitudes towards and perceptions of bees by PASS neighborhood, using 2017 data (Larson et al. in 2020).

Analyzing social-ecological dynamics longitudinally reveals distinct trends over time and space. In our work with the Adapting to City Life IRT, we used our long-term observations of bird communities to document significant declines in desert species richness and occupancy (Warren et al. 2019). Patterns remained consistent with time--neighborhoods with higher native plant abundances and household incomes and neighborhoods that were closer to desert patches supported more desert birds. While satisfaction with neighborhood bird diversity remained high in neighborhoods that had more desert birds, satisfaction declined slightly over time as overall bird diversity declined from 10 to 7 species (Fig. 2.15).

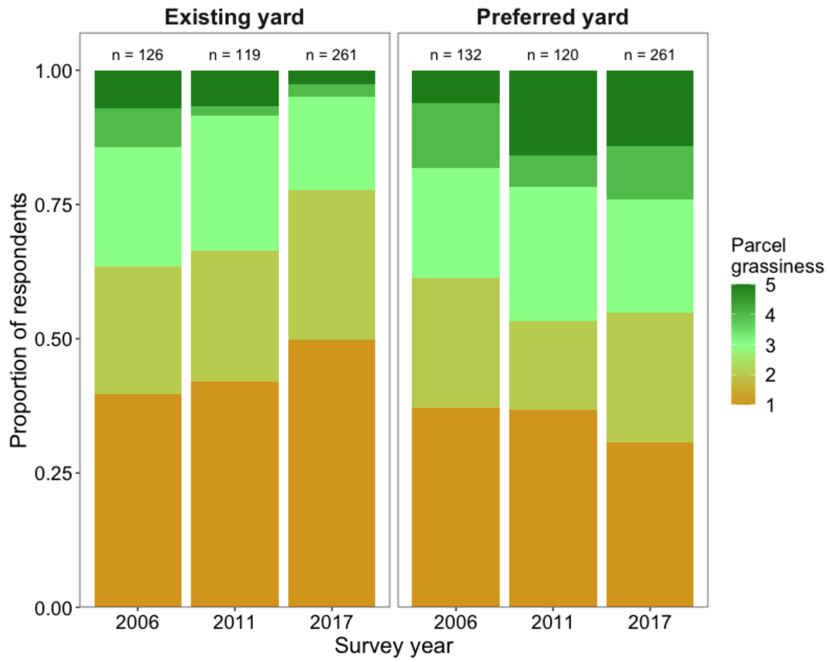


Figure 2.14. Mismatch between existing and preferred yards (Wheeler et al. 2020 and unpublished PASS data).

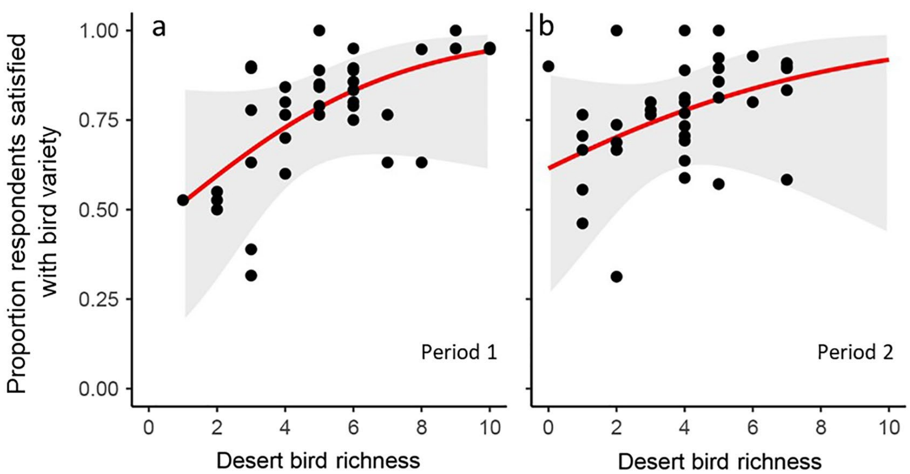


Figure 2.15. Resident satisfaction with bird diversity in their neighborhoods relative to actual bird species richness in 2011 and 2017 (Warren et al. 2019).

2.9. Climate and Heat

As of Labor Day, Phoenix had recorded 54 days where the high temperature was ≥ 110° F (43.3°C). The previous record for this, set in 2011, was 33 days, and that record included all 12 months of the year. Central Arizona is a very hot place, and it is rapidly getting hotter. The overarching question guiding efforts of the Climate & Heat IRT is "*How do evolving configurations of urban ecological infrastructure influence social-ecologically relevant climatic variables, at what scales are (dis)services realized, and how are these (dis)services impacted by presses and pulses?*" Since 2016, we have engaged in field campaigns (Colter et al. 2019) and modeling efforts (Aragon et al. 2019) oriented around this central research question and complemented those activities with analysis of social survey data (Andrade et al. 2019) and involvement with community organizations and other stakeholders (Guardaro et al. 2020). Many of our activities are closely coupled with the Urban Design IRT, although we have additional linkages with Adapting to City Life and Governance and Institutions.

Figure 2.16. Peter Crank and Yuliya Dzyuban installing a rooftop weather station in Edison-Eastlake

The Edison-Eastlake neighborhood near downtown Phoenix, which is a low-income and predominantly minority community, has emerged as a focal point for our Climate & Heat research and broader impacts, in coordination with the Urban Design IRT. In Edison-Eastlake, we deployed meteorological instrumentation for long-term, continuous monitoring at seven locations (including two with live internet feeds; Fig. 2.16), and we are conducting annual high-resolution microclimate assessments with a mobile biometeorological platform (MaRTy; Figs. 2.17). We are using simulation modeling to understand the potential microclimate effects of a large-scale redevelopment project, funded by a U.S.H.U.D grant to the City of Phoenix that is planned for the neighborhood in the coming years. Our meteorological measurements, transects, and the longer-term CAP archive of LULCC and land surface temperature data will ultimately enable us to measure the realized impacts of this large-scale change to the urban landscape with respect to ecologically and socially relevant climatic variables and to validate and improve state-of-the-art microclimate models. In a validation study conducted outside of the Edison-Eastlake neighborhood, CAP-supported graduate student Peter Crank identified serious limitations in a commonly-deployed microclimate model with large errors under extreme heat conditions and for complex urban topography (Crank et al. 2020). In 2018, we engaged more than 30 residents of Edison-Eastlake in a novel community "HeatWalk" that created opportunities for the public to participate in microclimate assessment and express their perspectives on urban climate and design through walking interviews (Fig. 2.18). We plan to repeat this exercise once the neighborhood redesign is complete to measure perceived impacts of the changes.

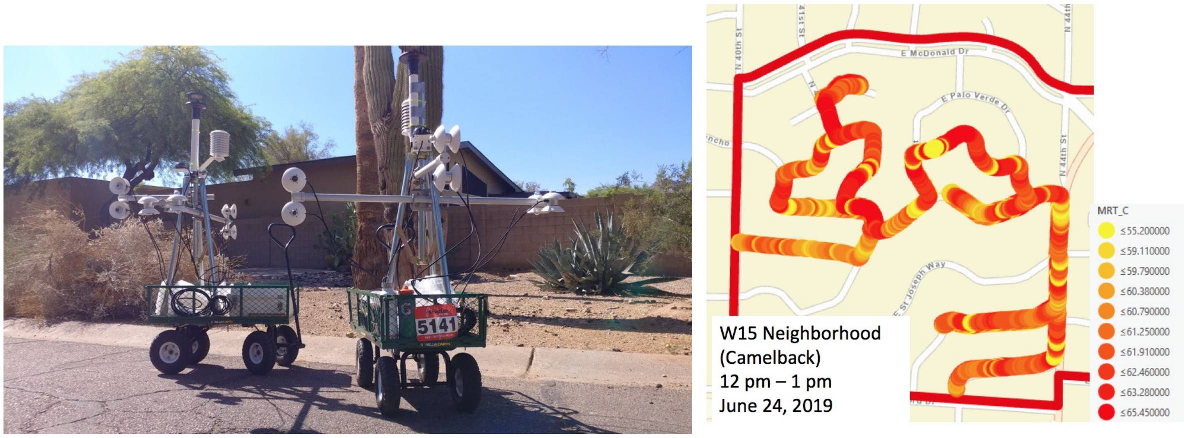


Figure 2.17. Left: MaRTy visits a PASS neighborhood. Right: Mean radiant temperature (MRT) measurements captured with MaRTy in a PASS neighborhood, fall 2019.

Figure 2.18. HeatWalk participants engaged in a walking interview

Other examples of Climate & Heat IRT efforts over the past year include:

- A quantitative analysis of satellite and LiDAR-derived land use and land cover data sets to assess regional tree coverage at fine spatial scales and measure progress toward municipal greening goals (e.g., target = 25% in City of Phoenix; sample neighborhood has 12% canopy coverage in residential areas but only 8% in commercial).
- Microclimate modeling studies to understand the relative efficacy of different tree planting arrangements on parcel-scale cooling and shading (Zhao et al. 2018). We found that an equal-interval tree planting arrangement led to the largest benefits with respect to microclimate conditions and human thermal comfort compared to clustered and dispersed arrangements.
- Development of a consistent and publicly-accessible archive of satellite-derived land surface temperature and greenness indices (multiple data sets are available through the CAP data portal; Stulmacher and Watkins 2019a,b).
- A meta-analysis of regional social survey data (including PASS) related to climate, heat, health, and ecosystem services, leading to a scientific publication (Fig. 2.19; Wright et al. in prep.).

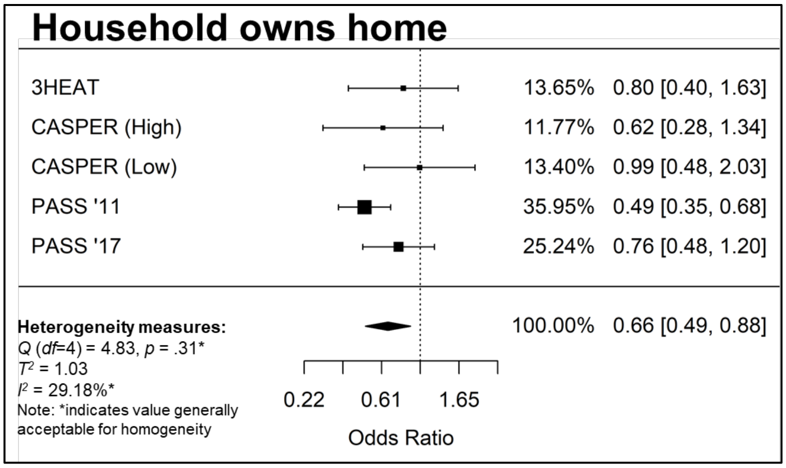


Figure 2.19. Sample meta-analysis result – home ownership is a statistically significant PROTECTIVE factor against heat illness when pooling results from five separate heat surveys conducted in the region (including PASS twice).

- An assessment of resident satisfaction with the urban forest and associations with biophysical and social parameters, using PASS data, leading to a scientific publication (Andrade et al. in review).
- We have deployed 15 microclimate and air quality monitors at two local schools to enrich K-12 education and measure impacts of redesign and redevelopment projects; our 2020 - 21 RET instructors are working with us on this project (Section 5.3; Fig. 2.20).

Figure 2.20. Microclimate and air quality sensors installed at Paideia Academies

- We have installed a web-connected weather station at a new "Carbon Sink and Learning Forest" on ASU's West Campus to understand long-term changes in local climate conditions associated with large-scale tree plantings and growth. Researchers from the Water and Fluxes IRT will be tracking carbon fluxes and storage, and we have integrated this information into ASU coursework related to carbon storage (Fig. 2.21).

- We are measuring near-surface (~0.01m height) microclimate conditions in desert parks and preserves to support investigation of the impacts of urban heat on small mammal biomass and well-being, in coordination with the Adapting to City Life and Parks and Rivers IRTs.
- Analysis of administrative health records to understand linkages between year-to-year weather variability and heat-related mortality outcomes. Our attribution study indicated that the large increase in heat-related deaths in the Phoenix area in 2016 was unlikely to have been driven by changes in the weather, and instead appears to have been driven by changes in social systems that support human health (Putnam et al. 2018).
- Enhancement of statistical models that relate urban form to spatial variability in satellite-derived land surface temperature using Google Street View imagery (Zhang et al. 2019). Geographically weighted regression models that incorporated Google Street view imagery explained approximately 80% of the regional variance in land surface temperature.

2.10. Parks and Rivers

Our Parks and Rivers IRT is focused on the Salt River, the desert parks and preserves, and [to a lesser extent] the urban parks found in the CAP study area. This IRT continues to pursue this research question*: What ecosystem services are provided by the ecological properties, processes, and land-cover mosaics in protected areas and open spaces (e.g. Salt River, urban and near-urban mountain parks), how does this UEI respond to presses, pulses, and management practices, and how do humans respond to these services with respect to their perceptions and uses of these areas?* Our location-based research employs the long-term data collected in desert parks and open spaces and along the Salt River, as well as PASS data. We survey various faunal communities using bird point counts, ground-dwelling arthropod collections, game/trail cameras, and herpetofauna visual encounter surveys. We collaborate with several other CAP research efforts and we have integrated our data, analyses, and findings with work by the Residential Landscapes and Neighborhoods, Climate and Heat, and Water and Fluxes IRTs.

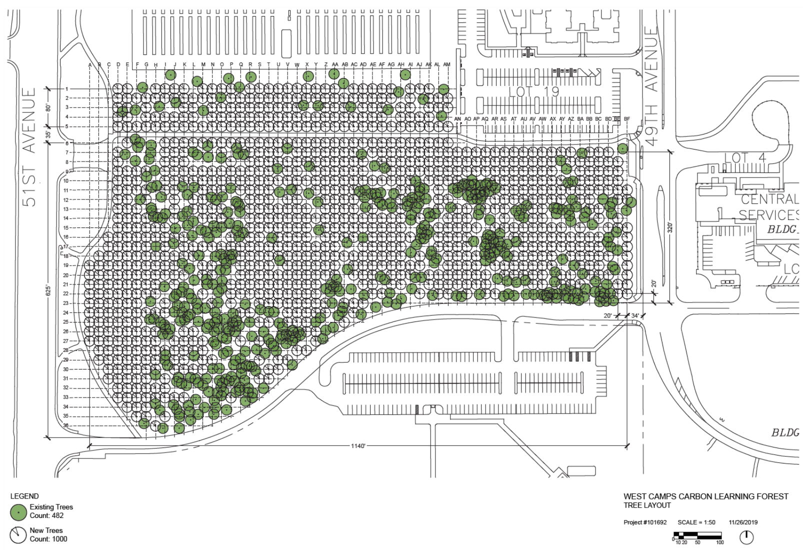


Figure 2.21. Tree planting plans for the West Campus Carbon Learning Forest

Our work on urban wildlife includes a number of both charismatic and not-so-charismatic taxa. We have deployed 50 wildlife cameras across the CAP study area in a range of different urban, peri-urban, and rural habitats. In early fall, we will be relocating many of these cameras to focus on wildlife use of the Salt River corridor, from upstream in the Tonto National Forest through the urban core to downstream areas that are more agricultural and desert. We have also deployed bat monitors and conducted night surveys of scorpion activity in desert parks and open spaces across an urban gradient. Some wildlife species were more likely to occur in wildlands, whereas others exploited highly urbanized landscapes. We are using these findings to predict areas of conservation value and to identify places where human-wildlife conflict is at the highest risk. We have found that some highly venomous species (e.g., bark scorpion) occur across the entire urban-rural gradient while others (e.g., the giant desert hairy scorpion and the stripe-tailed scorpion) are more prevalent in wildland and suburban habitats. Coyote (*Canis latrans*) are adaptable carnivores; however, in Phoenix, we have found that coyote occupancy was highest in areas with the lowest degrees of urbanization and the lowest human densities (Fig. 2.22). Small mammal communities in both desert parks and preserves and in urban parks are diverse and have high abundances. However, we found that urban parks were dominated by pocket mice and deer mice, compared to a greater diversity of pocket mice, woodrats, kangaroo rats, and grasshopper mice in the larger desert parks and preserves. This is likely a reflection of the greater diversity of habitat types in the larger parks (Alvarez Guevara and Ball 2018).

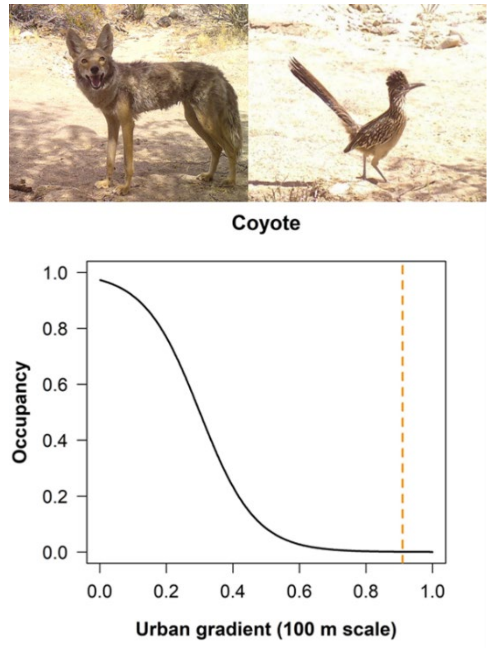


Figure 2.22. Coyote occupancy decreased with increasing urbanization, based on wildlife camera data.

In our collaborations with researchers in the Parks and Rivers and Residential Landscapes and Neighborhoods IRTs we have found that species with aquatic habitat requirements are declining while species closely associated with agricultural land uses are increasing. This is interesting because we have seen a steady decline in agricultural lands over the last 2+ decades with suburbanization. Specifically, bird communities from urban riparian areas have experienced a 26% decline in abundance over the past 16 years (Allen et al. 2019; Fig. 2.23). Many groups of bird species have declined in abundance and these declines go beyond desert specialists and include generalist and common species such as house finches and house sparrows (Banville et al. 2017; Warren et al. 2019). Along the Salt River and other riparian areas, bird diversity is driven by the degree of urbanization and the amount of perennial water. We have found lower bird diversity where levels of urbanization are high and the riverbed is dry, and greater diversity at intermediate levels of urbanization but where river reaches are wet (Banville et al. 2017; Andrade et al. 2018; Fig. 2.23). Finally, we used an 11-year dataset to find that aphids are able to take advantage of favorable environmental conditions (i.e., warm and moist) in Phoenix because they are tolerant of a range of urbanization levels (Andrade et al. 2017). Agricultural and mesic habitats were able to support twice the abundance of aphids compared with drier land cover types (Andrade et al. 2017).

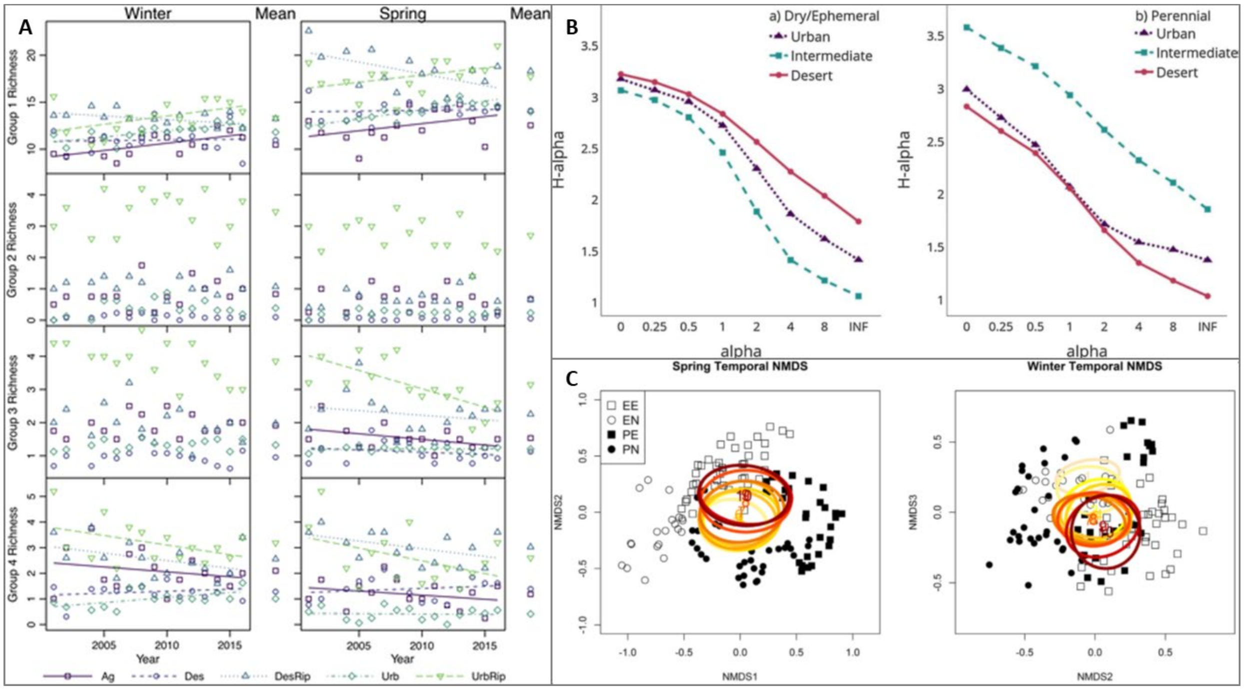


Figure 2.23. Three studies on bird communities from the Salt River and surrounding urban landscapes. (A) Groups of species based on body size (big vs small) and migration status (breeder vs non-breeder). Species tied to water and riparian areas have decline over time (Allen et al. 2019). (B) Along the Salt River, dry reaches have high bird diversity in non-urban desert and wet reaches have high diversity at intermediate levels of urbanization (Andrade et al. 2018). (C) Riparian bird community composition is moving toward species found in dry sites (EE, EN) (Banville et al. 2017).

We have been working closely with the PASS data and with our social science colleagues to explore what controls people's attitudes about the desert and about desert animals. These collaborations have demonstrated that people who live nearer to desert parks and preserves have more positive views about bees (i.e., they more strongly like bees) than those who live closer to urban centers (Larson et al. 2020). This result has implications for the urban bee community because if residents near urban parks use more native vegetation in their yards they can help to conserve bees, but this may be more difficult to achieve if these same people have negative perceptions about bees (Larson et al. 2020). We found a similar response for general attitudes toward the desert—people who live closer to open space have more positive attitudes of the desert (Andrade et al. 2019, Fig. 2.24). These neighborhoods are also more affluent than the lower income PASS neighborhoods that are located closer to urban centers.

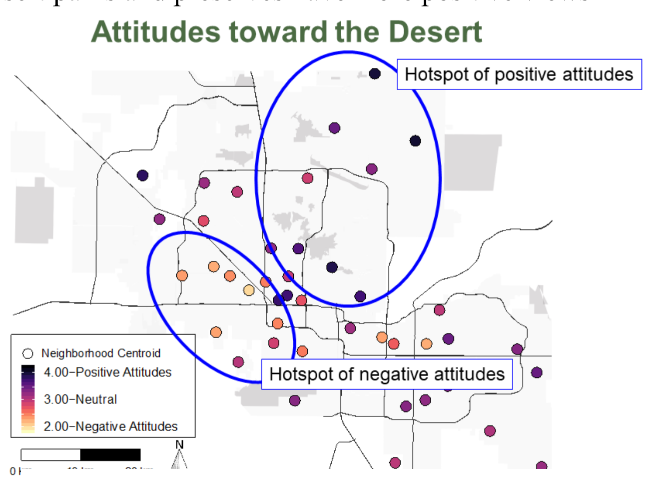


Figure 2.24. Attitudes towards the desert

Partnering with a local company, Rattlesnake Solutions, we are pursuing new research evaluating the social-ecological predictors of commercial services that people use to have venomous snakes (rattlesnakes) removed from their yards. Rattlesnakes are removed more often from properties that are in close proximity to desert parks and preserves. Interestingly, people also pay for services to remove harmless, non-venomous snakes and from 2018-2019 more than 2,000 snakes--22 different species--were removed from people's yards (Bateman et al., in prep). More snakes, both venomous and non-venomous, are removed from high income and high education neighborhoods and from areas with new home construction. Non-venomous snakes were removed more frequently from neighborhoods that have over 50% of residents identifying as Latinx. We also analyzed 2017 PASS data to explore whether residents felt that snakes were a problem. With this survey, we identified one neighborhood where residents strongly agreed that snakes were a problem and this neighborhood also had the most snakes removed.

One of our teams, led by Dr. Meg du Bray (former ASU grad student, now a tenure-track assistant professor), has been working to put the Salt River into a cross-cultural context to better understand local valuations of the ecosystem services it provides. Across four cities in three continents, we found that residents recognize the ecosystem services provided by their urban rivers. The findings highlight the local importance of priceless, inalienable values perceived to be conferred by these rivers, challenging conventional categorizations that restrict such values to cultural services (du Bray et al. 2019; Table 2.3). This work was conducted in the context of broader research that integrates findings about water scarcity from CAP into cross-cultural contexts and comparisons (Wutich 2020, Wutich et al. 2020a, Wutich et al. 2020b, Wutich et al. 2020c, Wutich et al. 2020d, Gartin et al. 2020, Stotts et al. 2019, Rice et al. 2019). This research also connects to the Residential Landscapes and Neighborhoods IRT through our focus on understanding public perceptions and valuation of ecosystem services in relation to varied environmental features (Larson et al. 2019; Brown et al., in revision).

Table 2.3: Population and demographics data and river features from a cross-cultural and international comparison of four cities on three continents (du Bray et al. 2019).

	City Population	City Demographics	Sample Demographics	River Features
Thames River, London, England	6.7 million	79.8% white/European; 10.3% Asian; 8.1% black	74% white/European; 12% Asian; 7.6% black	Longest river in UK; tidal; used for sports; minimal transportation; widely used for river walk recreation; swimming discouraged
Brisbane River, Brisbane, Australia	2.4 million	79.2% white/European; 14.6% Asian; 2.4% Aboriginal/Torres Straits peoples	70% white/European; 8.3% African; 5% Asian	Long, tidal regional river; used as key component of within-city transport; major issues with flooding; some private boat use; sometimes safe for swimming in some locations
Salt River, Phoenix, AZ, United States	1.3 million	69.5% white; 40.8% Hispanic/Latino; 2.2% Native American	57.4% white; 14.8% Hispanic/Latino; 11.5% Asian; 8% Native American	A tributary of the Gila River; bed mostly dry due to upriver damming; minimal use within the city outside of a single reservoir allowing boating with an attached park; swimming prohibited
Waikato River, Hamilton, New Zealand	165,500	69.5% Pakeha/European; 21.3% Maori (indigenous); 13.8% Asian; 5.1% Pacific peoples	70.3% Pakeha/European; 14.9% Maori (indigenous); 2.7% Asian	Longest river in New Zealand; strong spiritual connection to Maori, especially Tainui tribe; used for recreation (shooting, boating, cruises); generally safe for swimming

2.11. Water and Fluxes

The Water and Fluxes IRT is one of the largest and most comprehensive research groups in CAP. Our researchers and students investigate the movements of a variety of materials via the flows of air and water through the urban landscape. We continue to focus on this research question: *How does the design and landscape configuration of UEI interact with presses and pulses to influence urban* *hydrobiogeochemical patterns and processes over space and time, and how do people respond to these changes?* To address this, we have continued our long-term watershed and airshed approaches to study the movement of water and materials into, within, and out of the city. We have continued collection and analysis of long-term hydrological and biogeochemical data associated with terrestrial UEI using our stormwater, and DesFert datasets, aquatic UEI using our Drinking Water Quality and Tempe Town Lake datasets, and wetland UEI using our Tres Rios and accidental wetland datasets. Below we summarize key findings from these efforts.

We continue to use the experimental treatments and measurements of our DesFert experiment to evaluate the impacts of atmospheric deposition of nitrogen and phosphorus on this terrestrial UEI. In our 2018 proposal we documented plans to downscale some activities at six of the original 15 DesFert sites, all of which are located in desert parks and preserves. We have completed this streamlining of effort and remain confident that we are continuing to maintain the long-term integrity of this important experimental dataset. We have also added rainout shelters to two DesFert sites, in collaboration with colleagues at the SEV LTER, and CAP is now a member of the global DroughtNet network as a result. See Section 2.5 for updates, recent results of our long-term analyses of these data, and CAP IV citations.

We are now in our second decade of collecting long-term hydrological and biogeochemical data from Tempe Town Lake (TTL; aquatic UEI), which is a large human-made lake in the center of Tempe. Our twice-weekly measurements include water temperature, pH, conductivity, and samples for dissolved organic carbon and carbon characterization. We have been evaluating interannual patterns in TTL water chemistry using an ARIMA model. These data, in concert with publicly available meteorological data and river flow data, are used to assess long-term patterns in lake chemistry and the effects of climate variability (monsoon storms, winter storms, and dust storms or Haboobs). These analyses help us assess the impacts of atmospheric deposition, alongside the DesFert experiment. Disturbance of the TTL system often takes the form of flood and drought. The lake occasionally experiences significant anthropogenic impacts, most notably in Summer 2020 a train derailment and subsequent fire on the bridge crossing the lake caused significant debris input as well as a cyclohexane spill of as yet indeterminate scale. We have been experiencing long-term drought and the 2020 monsoon season is among the driest and hottest on record.

In late 2017 we installed a datasonde and began *in situ* measurements of oxygen concentration and other key parameters in TTL (Fig. 2.25). Using these data, we have begun to implement a Lake Metabolizer model to continuously model gross primary productivity, ecosystem respiration, and other ecosystem metabolic processes in the lake. The Lake Metabolizer model calculates net ecosystem production from diurnal changes in dissolved oxygen. We are coupling these estimates of primary production with measurements of organic carbon degradation and carbon composition to assess organic matter production, loss, and accumulation. We expect that, given the abundance of sunlight and high year-round temperatures, TTL and other blue UEI ecosystems in the city are typically autotrophic, but that disturbances (e.g., floods, dust storms) will result in transient shifts to heterotrophy. See Section 2.4 for updates, including recent results of our long-term analyses of these data.

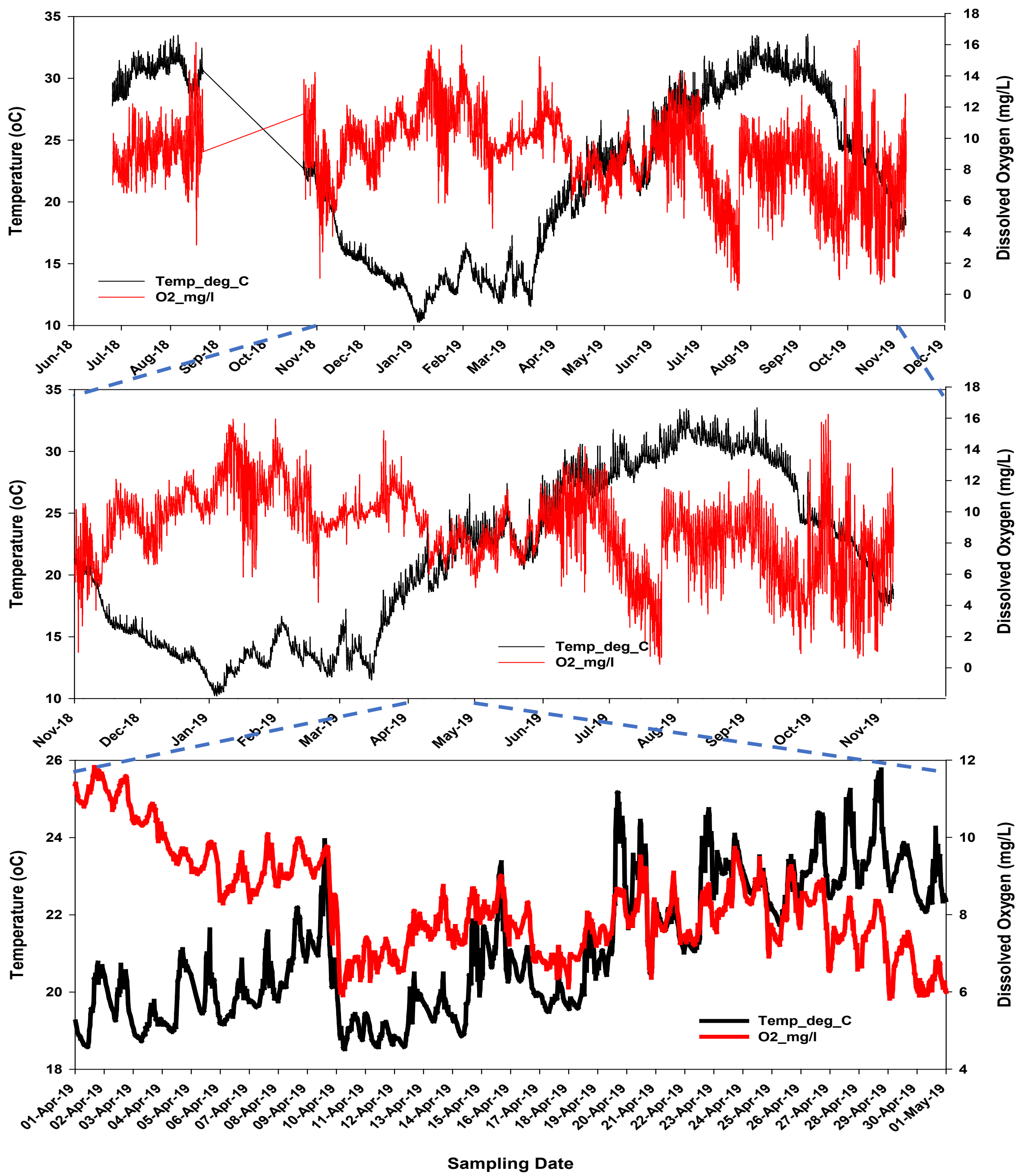


Figure 2.25. Temperature (black) and dissolved oxygen (red) data from the in situ datasonde in TTO (30-minute intervals). Upper panel: The full dataset from June 2018 to Dec 2019. There is excellent agreement between our discrete sampling and the *in situ* datasonde. Middle panel: One year of data (Nov 2018 - Nov 2019) that demonstrates the strong seasonal pattern apparent in the long-term data. Bottom panel: one month (April 2019) showing the strong diurnal pattern in temperature and oxygen; these data are being used to model lake metabolism.

Table 2.4: Enhanced N removal due to the Biological Tide (% improvement) for each dissolved inorganic nitrogen species at the whole system and marsh subsystem scales, where the Growing Season = March - September (Childers in press; Treese et al. 2020).

Analyte	**Season**	**Whole-System N Removal Enhancement** *42 ha* [%]	**Marsh N Removal Enhancement** *21 ha* [%]
NO_2^-	Year-round	35.7	96.3
	Growing Season	18.3	126
NO_3^-	Year-round	9.54	145
	Growing Season	12.1	184
NH_4^+	Year-round	2.04	110
	Growing Season	2.37	133

Our collection of long-term hydrological and biogeochemical data from wetland UEI continues at the Tres Rios Constructed Treatment Wetland (CTW), where since July 2011 we have been tracking water as it leaves the city. We sample bi-monthly for herbaceous biomass and productivity, water quality, transpiration rates, and aquatic metabolism. We also quantify belowground biomass, plant tissue nutrient content, and soil nutrients annually, and measured greenhouse gas fluxes from 2012 - 2014. Our peak summer biomass values are among the highest reported in the literature, and high rates of transpiration are associated with this biomass. Using our whole-system water budgets and tracer studies we have documented a slow movement of surface water into the marsh from adjacent open water areas that is driven by transpirational losses; we call this the "Biological Tide" (Bois et al. 2017). Using nitrogen (N) budgets for the whole system and the vegetated marsh, we showed that roughly 50% of the annual N uptake by the vegetated marsh is driven by new water entering via this biological tide (Table 2.4; Treese et al. 2020). Our aquatic metabolism sampling suggests that the N uptake associated with the autotrophic water column was roughly 27% of the average annual N uptake by the vegetated marsh (Evans 2020). The marsh is a source of CH_4 and N_2O across the air-water interface and the plants are a net source of CH_4 but a net sink for N_2O (Table 2.5; Ramos 2017). Our combined flux estimates suggest that the Tres Rios marshes are actually a net sink for greenhouse gas equivalents because of this plant-mediated net uptake of N_2O (Childers in review). Finally, over the years our Tres Rios CTW project has provided a platform for dozens of students and young people to experience ecological research, both in the field and in the lab. See Section 2.4 for updates, including recent results of our long-term analyses of these data.

Table 2.5: Average (±SD) of greenhouse gas fluxes from the Tres Rios marshes (Childers in press; Ramos 2017).

Season	CH_4 flux Air-water interface (mg m^{-2} h^{-1})	CH_4 flux *Typha* spp. leaves (mg $kgdw^{-1}$ h^{-1})	N_2O flux Air-water interface (µg m^{-2} h^{-1})	N_2O flux *Typha* spp. leaves (mg $kgdw^{-1}$ h^{-1})
Spring	1.95 ± 0.5	No data	165.0 ± 15	No data
Summer	3.36 ± 0.6	59.1 ± 110.2	225.0 ± 20	-2.4 ± 8.4
Fall	2.32 ± 0.6	79.7 ± 195.1	200.0 ± 20	-13.7 ± 30.9
Winter	1.29 ± 0.4	-0.5 ± 4.9	190.0 ± 20	-0.3 ± 0.5

Our ecohydrologic sampling of stormwater dynamics is focused on two spatial scales. At the large scale we have continued to quantify stormwater dynamics in greater Scottsdale, with a focus on the Indian Bend Wash (IBW). Because IBW is the lowest elevation in Scottsdale, it effectively drains most of the city. It is a large urban park that is a much-enjoyed amenity but that is sacrificial during rare large rain events as it fills with stormwater. As such, IBW is an excellent example of large-scale UEI. See Section 2.4 for updates, including recent results of our long-term analyses of these data.

We are also tracking stormwater dynamics at the local scale. In August 2017, ASU completed renovation of Orange Mall on its Tempe Campus. This renovation included the addition of several bioretention basins (i.e., bioswales), planted with native species, to manage stormwater on site. We have been monitoring several ecohydrologic processes in these bioswales in partnership with the ASU Office of the University Architect. This partnership has two primary goals: 1) Increasing our knowledge about how UEI may be applied to best manage stormwater at local or site-specific scales; and 2) Providing data that the university needs to apply for SITES certification (Sanchez 2019). Since 2018 we have been collecting data on water quality and quantity, transpiration rates, local microclimate, and soil moisture. We collect water samples using five ISCO 6712 automated pump samplers located throughout Orange Mall. Effluent discharge volumes are determined with ONSET HOBO U20L water level probes and V-notched weirs. We quantify transpiration rates with a LICOR LI-6400 handheld infrared gas analyzer and we measure soil moisture using probes located in the bioswales. Rainfall data are collected by a nearby Maricopa County Flood Control District Rain Gauge and an EarthNetworks meteorological station located on the ASU Tempe Campus. In August 2018 we began collecting these data from all rain events that generated sufficient volumes of runoff to engage the bioswales. Since then, there have been nine such storm events: September 2018, October 2018 (two events), January 2019, November 2019 (two events), February 2020, and March 2020 (two events). We have also been collaborating with UREx SRN colleagues from Hermosillo Mexico to document the accumulation of metals in the bioswale soils.

Our Water and Fluxes IRT scientists routinely apply what we are learning about biogeochemical and hydrologic processes in the city. We work with municipal managers and decision-makers to help inform better decisions about how UEI is managed and designed. These transdisciplinary collaborations include partnerships with the Scottsdale and Maricopa County flood control offices (IBW), the City of Tempe (TTL), the City of Phoenix Water Services Department (Tres Rios), and ASU (Orange Mall). Members of this IRT have also initiated annual "data roundups", which are informal mini-retreats where CAP scientists meet to discuss and collaboratively analyze our long-term data. Our first data roundup was a very positive experience for the participants. In future roundups we plan to include tutorials and training on codes and software that are being used by CAP scientists, which a targeted emphasis on our student and postdoctoral researchers.

2.12. Governance and Institutions

Our Governance and Institutions IRT group continues to investigate the question: *How do long-term socioeconomic and institutional dynamics affect and control Urban Ecological Infrastructure and associated ecosystem services, and do infrastructure failures and/or concerns for services induce societal actions regarding infrastructure and its governance?* Institutional temporality, including differences in policymaker time horizons, periodicity of policy choices, path dependence, and reproduction of systems through time, are critical areas of inquiry for us (York et al. in review). For example, we have found that temporal trends, such as changes in the economy, interact with policymaking and individual choices relative to farmland development (Kane and York 2017) and political-economic influences on water use and conservation (Hester and Larson 2016; Hirt et al. 2017).

Vulnerable communities are often further exposed to risks through inaction, or perversely through institutional change (York and Boone 2018; Hoover et al. in prep a). Individuals in these communities may have different beliefs, values, and knowledges that are not included in decision-making processes (Hoover et al. in prep b). As a whole, institutional dynamics may reproduce inequities and tensions in policymaking (York et al. 2020) and resilience of socio-technical-systems is contingent on the temporal scale in question (Gim et al. 2019). We have found that differences in policymaker time horizons may exacerbate problems with the collective action and coordination that are needed to solve problems, including challenges with water provisioning and infrastructure development (York et al. 2019), while lags and path dependencies may induce decisions such as farmland conversion (Kane and York 2017). That said, shadow networks (Wutich et al. 2020) and the salience of looming Colorado River water shortages have led to successful negotiations of Arizona's Drought Contingency Plan (Sullivan et al. 2019). But long-running divisions, such as tensions between settler agricultural interests and Indigenous communities, were exposed during the state and regional conversations about water use and the larger socio-hydrological system in Central Arizona (York et al. 2020). Likewise, green infrastructure planning processes interact with, mitigate, or exacerbate existing injustices, but we have found that more equitable decision-making and centering, and prioritizing environmental justice communities and residents, may reduce injustice (Hoover et al. b). Diverse knowledge systems, especially through coproduction with communities, may improve resilience and reduce chances of failure (Feagan et al. 2019; Rosenszweig et al. 2019; Wyborn et al. 2019).

We continue to evaluate the relationships between infrastructure provisioning and individual or community beliefs and actions--a critical scientific frontier. We know that UEI provides ecosystem services, such as cooling during the extended warm months in Phoenix. In our work with the Climate and Heat and Residential Neighborhoods and Landscapes IRTs, Yazar et al. (in review) found that personal exposure to heat-related illnesses resulted in stronger beliefs in climate change and global warming. Science communication and better understanding of the environment is often seen as a pathway to improve support for pro-environmental government or voluntary action, but Locke et al. (2020) found mixed results in Phoenix and Baltimore. Clearly, simply educating the public is not a panacea. We have also found that socio-demographics are also important factors in residents' support for policies, such as those aimed at reducing sprawl (York et al. 2017). Social concerns about failures in the purveyance of ecosystem services are contributing to rethinking infrastructure and the ways in which potential designs of future energy systems could intersect with and help shape diverse possible future urban socio-ecological systems (Eschrich and Miller 2019; Eschrich and Miller in prep.). We have also found that new narratives are emerging around adaptation for more sustainable Central Arizona agricultural production (Eakin et al. 2016). Public attitudes and beliefs about the need for transformational change may enable or constrain transitions to UEI use. White et al. (2019) found that environmental value orientation and perceived personal responsibility predict perceived need for transitions, and these two variables, along with socio-economic resources and trust in government, predict support for specific transformational changes in water infrastructure and associated services.

As might be expected, members of our Governance and Institutions IRT are actively involved with community engagement. For example, IRT co-lead Dave White was recently appointed by City of Phoenix Mayor Gallego to be Chair of the Phoenix Water/Wastewater Advisory Committee. White and Amber Wutich (co-lead of the Parks and Rivers IRT) worked with City of Phoenix to develop its "Water Equity Initiative" and presented it to the Citizen's Water Rates Advisory Committee on June 23, 2020. The initiative has since been approved by City Council and the Mayor's Office.

2.13. Scenarios and Futures

Our Scenarios and Futures IRT continues to explore and produce scenarios of sustainable and resilient futures for the Phoenix Metro Area. In these futures, we examine tradeoffs and uncertainty to guide local and regional decision-making. The question focusing our research is: *What are the ecosystem services, trade-offs, and uncertainties among co-developed, long-term future scenarios of resilience and sustainability at scales ranging from neighborhood to metropolitan area across the Phoenix region?* In this work, we follow the conceptual approach shown in Fig. 2.26. Since 2017, our synthetic work on scenarios and futures has shifted focus from the regional scale to the village scale. Notably, Villages are subunits delineated by the City of Phoenix that encompass several contiguous neighborhoods with similar character. We first describe the findings from the regional scenarios, then ongoing analysis of the village scenarios, and then comparisons of the two scales.

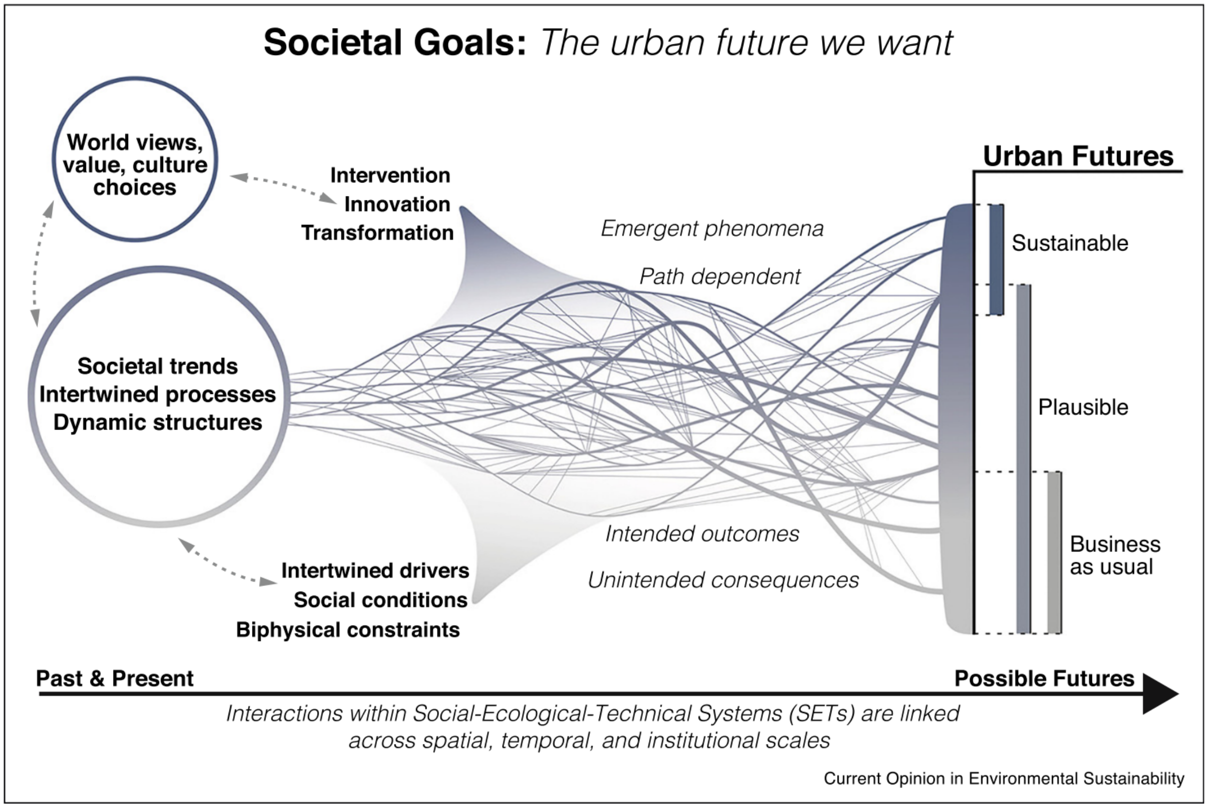


Figure 2.26: Conceptualization of the inter-linkages between factors and dynamic processes shaping urban futures. Visions are represented as societal goals influenced by worldviews, value systems, culture and choices, and play an important role in intervention, innovations, and transformation that can lead to alternative and more desirable urban futures.

Between 2015 and 2017 we hosted a series of six participatory workshops with CAP scientists and local practitioners. In these, we co-produced six regional scenarios that explore alternative sustainable futures for 2060 (Cook et al. in press; Iwaniec et al. in press a; Iwaniec et al. 2020a; Iwaniec et al. 2020b; Iwaniec et al. in press b; Iwaniec et al. in press c; also see this video). To examine the implications of alternative policy decisions, the scenarios we have developed compare differences in future land use and land cover (Figure 2.27), water supply and demand (Sampson et al. 2020), and regional and micro-temperature maps (Figure 2.28). We have also developed actor-narrated animations to help visualize potential responses to extreme heat, flooding, and drought in the Phoenix Metro Area (Fig. 2.29). This kind of output draws on the participatory work done in the scenario workshops, but brings the narratives to life for more visual learners.

Figure 2.27: Future land-use, land-cover outcomes of each scenario. Design vignettes were developed from the scenarios at specific locations (red squares; Iwaniec et al 2020a).

The model results have allowed us to quantify tradeoffs between different strategies or even large-scale goals. For example, contrasting the overarching goal of water conservation and water banking against future drought (True Cost of Water scenario) with a more balanced goal of resilience to heat, flood and drought (Emerald City scenario) showed that the balanced approach leads to greater abundance of UEI and lower temperature and cooler microclimates than the drought-focused goal (Fig. 2.28; Iwaniec et al. 2020a). However, much less water is saved to stave off future scarcity in the Emerald City scenario than the True Coast of Water scenario (Sampson et al. 2020). We also explored the extent to which the different regional scenarios—three of them 'adaptive' (in response to a climate-related threat) and three of them 'transformative' (introducing a normative element of what *should be*)—scored with respect to imaginaries for resilient (adapted to flood, drought, and heat) and transformative futures (EcoCity, Smart City, EquityCity). The transformative scenarios scored higher for transformative visions and as well for adaptive visions relative to the adaptive scenarios (Iwaniec et al. 2020a).

We also produced a 'strategic' scenario in which we explored the future of the region if the existing adaptations and policies—contained in policy plans—were to become actualized, thus exploring integration across different municipalities (Iwaniec et al. 2020b; Kim et al., in press).

Starting in 2018, we added a focus on the village scale to explore the implications and heterogeneity of scenario visions (regional scale vs. village scale). The scenario workshop in South Mountain Village, done in conjunction with the UREx SRN, examined alternatives for local adaptation to heat and flood, as well as positive community visions of equity, gentrification, and transportation. The resulting scenario data are currently being analyzed, but initial perusal indicates a much greater focus on goals and strategies to ensure equity and justice, which is perhaps unsurprising given the history of disenfranchisement experienced by this part of Phoenix. We also found that the Mountain to River scenario, with its focus on the unique geography and hence sense-of-place of South Mountain Village between the South Mountain Park and Salt River, had a strong focus on nature-based strategies (i.e., UEI).

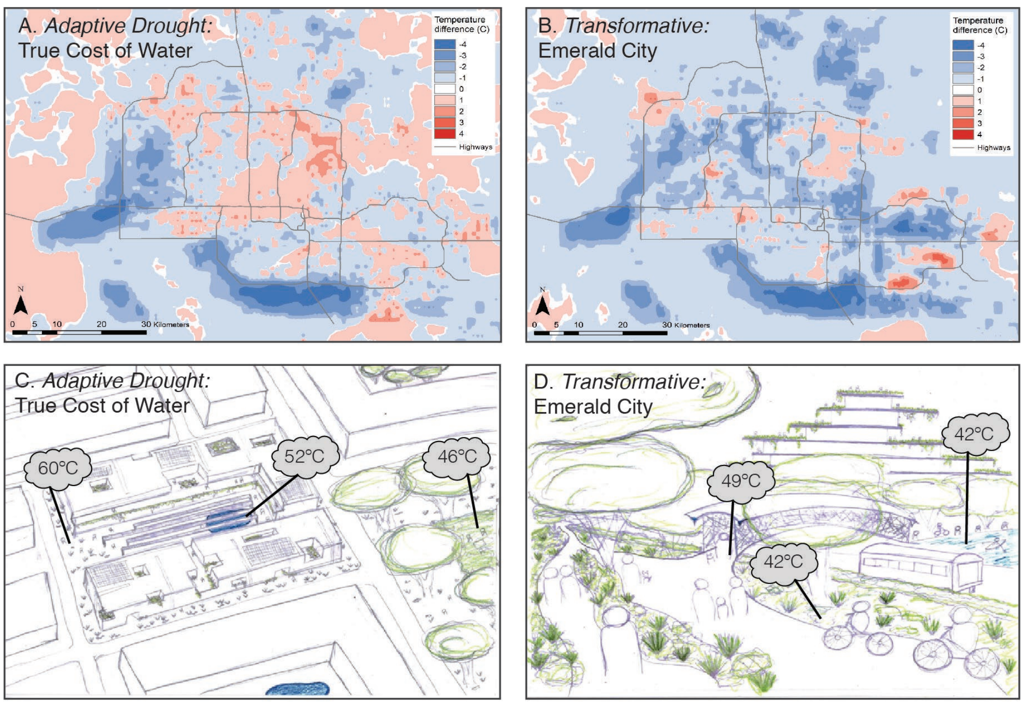


Figure 2.28: Regional heat at 5 AM for Adaptive Drought: True Cost of Water (A) and Transformative: Emerald City (B) relative to strategic Scenario from regional WRF model. Microscale thermal comfort for True Cost of Water (C) and Emerald City (D) scenarios. Microclimate temperature represents thermal comfort for specific locations in the region. In the workshop setting, microclimate was used to explore the implications of heat strategies (Iwaniec et al 2020a).

By exploring two different geographical scales, the co-developed scenarios offer us a unique opportunity to identify conflicts and synergies between resident conceptions of ecosystem services and governance. Preliminary results suggest that participants at the village scale were most concerned with political participation and amplifying their voices in decision making, while participants at the regional scale were most concerned with building UEI and associated ecosystem services (Berbés et al. in press; Berbés et al. in prep.). We are assessing these differences with a resilience, equity, and sustainability qualitative assessment (RESQ) being developed by Berbés et al. (in prep; see results for the village scale in Figure 2.30).

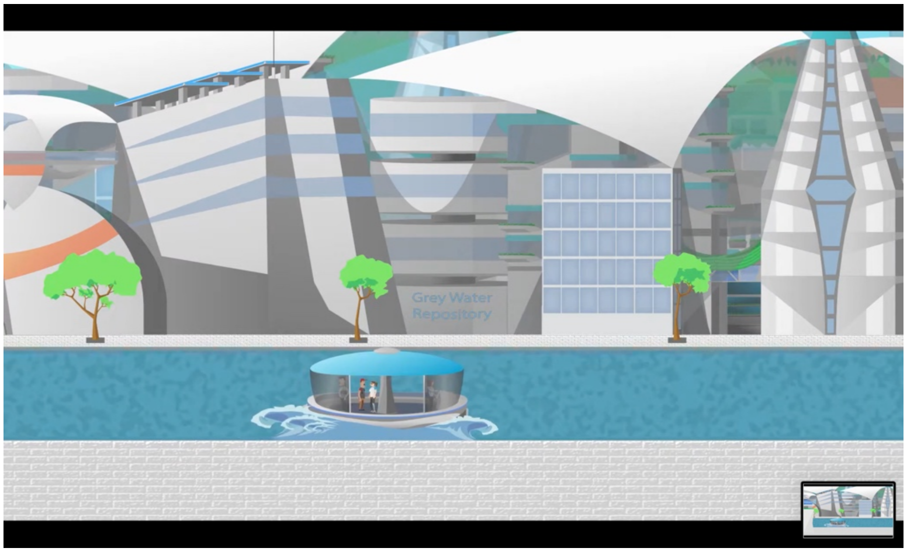


Figure 2.29: Animated videos, such as this one describing how metro Phoenix has worked to adapt to extreme heat in 2060, explore tradeoffs among regional responses to heat, flooding, and drought. See [web site](#) for narrative videos of adaptive scenarios.

In addition to the close relationships that we have developed with city officials and NGOs through our scenarios work, as a result of moving to the village scale we have been able to expand our outreach to the community. First, in a three-year collaboration with the Design IRT, Marta Berbés (co-lead of the Scenarios and Futures IRT) and Paul Coseo (co-lead of the Urban Design IRT) have been co-teaching a capstone studio class for Landscape Design students. The course uses the CAP sustainable future scenarios as an entry point to develop solutions for South Mountain Village. Students have designed UEI for flood control, heat mitigation, and to address social equity (Fig. 2.31). In an effort to

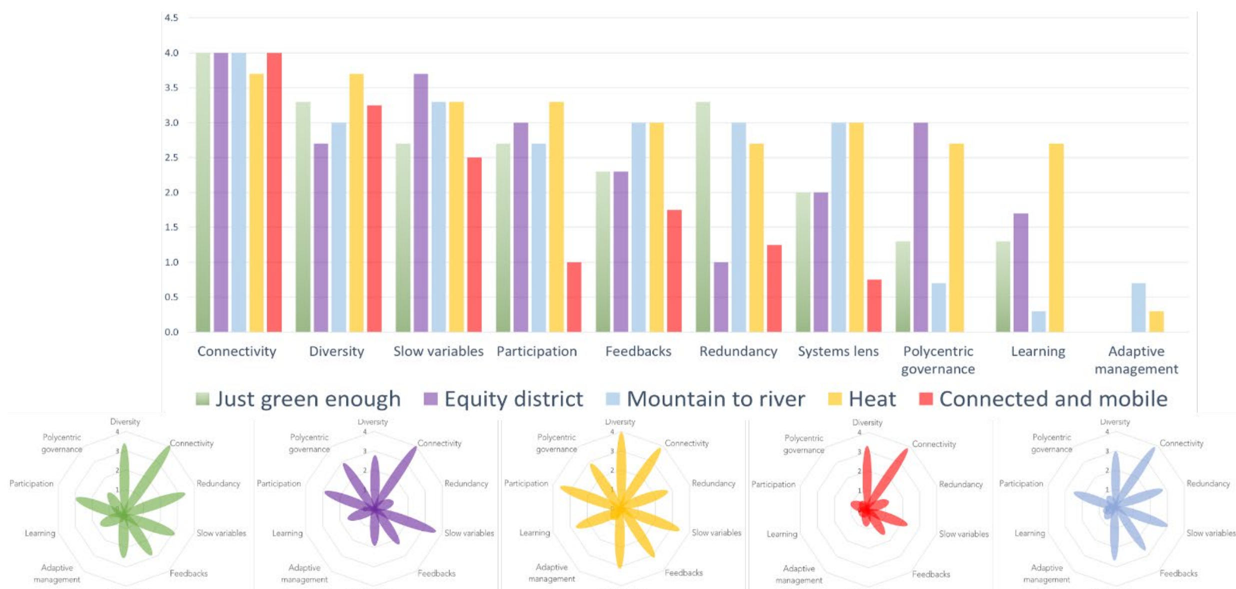


Figure 2.30: RESQ results for South Mountain Village scenarios, by resilience criteria (based on Biggs et al. 2012) and for each scenario (flower diagrams).

engage the community meaningfully, the results from the studio were presented, discussed, and prioritized by community members in a workshop using Q-sort methodology in May 2019 (see this presentation). Second, Berbés recently began working with Dr. Jenni Vanos and our two new RET instructors to install air-quality sensors (leveraged funding from Global Sport Institute Seed Grant Program, $14,500) to understand reasons for high rates of asthma that occur in children in South Mountain Village. These high rates are a major concern for this Latinx community. Finally, Berbés has initiated the Blackwards Project, which co-develops positive futures reflecting the aspirations of the Black communities of South Mountain Village by collecting oral histories from African Americans living in South Phoenix.

Looking ahead, the Scenarios & Futures IRT is now investigating ecosystem services across scales and visions. One of the first steps in this process is engaging with the City of Phoenix in a multi-year process to develop a climate action plan that builds upon emissions-mitigation strategies co-developed in the CAP Regional and South Mountain Village participatory scenario workshops. We are also a key partner in a recently funded NSF GCR: The SETS Convergence project. This project is exploring how urban SETS dynamics can be guided along more resilient, equitable, and sustainable trajectories in Phoenix, San Juan, Atlanta, and New York. We have also developed cross-city collaborations and comparisons of future urban visions as part of the recently submitted BES LTER proposal, and we optimistically look forward to starting this cross-site work with our newly funded BES colleagues in the near future.

Figure 2.31: A sampling of some of the designs for resilient strategies developed by students in the studio class, derived from scenarios developed in the South Mountain Village workshop. Below, photo of the final presentations

2.14. Urban Design

Our Urban Design IRT continues an action-research agenda focused on the question: "*How does governance and institutions support the design of sustainable and resilient urban ecological infrastructure?"* One of our central goals is to take existing and new CAP research and integrate both the research products and researchers themselves into urban ecological design processes using designed experiments (Coseo and Childers 2017; Coseo 2018; Hondula et al.,2019). We have established, maintained, and expanded several key partnerships that are central to this work. Cross-IRT teams have worked to co-design projects with partners, contributing to project implementation and monitoring ecosystem services pre- and post-construction. In doing so, we are refining our thoughts on urban ecological design principles for urban sustainability and resilience in hot arid regions and beyond (Coseo 2019a; Coseo 2019b; Hamstead et al. 2020).

Our designed experiment partnerships are in a variety of stages (i.e. design, implementation, and monitoring) and we have produced presentations, articles, and dissertation outputs with: 1) the City of Phoenix Housing Department on revitalization of Edison Eastlake using community-driven urban ecological infrastructure to cool the neighborhood (Crank et al. 2020; Dzyuban et al. 2020a; Dzyuban et al. 2020b; Guardaro et al. 2018; Guardaro and Messerschmidt, 2019; Guardaro et al. 2020a; Guardaro et al. 2020b; TNC 2019); 2) the Paideia School in South Phoenix on re-naturing their campus (Trakas et al. 2020); 3) the URExSRN via their on Climate Change Urban Resilience Scenarios in South Phoenix (Section 2.13; Berbés-Blázquez et al. 2019); 4) the Flood Control District of Maricopa County (FCDMC) on their low impact development (LID) Durango Campus retrofit (Cheng et al. 2019; Cheng et al. 2020); 5) ASU's Sustainable Campus projects including the Orange Mall bioretention basins (Sanchez 2019); 6) the Phoenix Zoo parking lot redesign to include urban ecological design features; 7) the City of Tempe climate action planning for resilience to extreme heat (Coseo et al. 2018; Coseo et al. 2020; Hamstead et al. 2018; Hamstead et al. 2020; Middel and Krayenhoff 2019; Schneider et al. 2019a; Schneider et al. 2019b); and 8) the Rio Reimagined initiative to revitalize the Salt River as a civic urban ecological park for Central Arizona (Coseo 2019b). At least two dissertations were products of the Edison Eastlake designed experiment with forthcoming articles from Dzyuban (2019) and Guardaro (2019) and Crank (forthcoming 2020).

The designed experiments are in early stages and our research has not yet generated publishable results, but some initial conference findings are helping build action-research projects and relationships with partners within our Valley UEI networks. A good example of this progress is the water harvesting UEI designed experiment basins that we installed at FCDMC in September 2018 (Fig. 2.32). The three different basin designs had three replicates (i.e. nine total) planted with the same pattern of four native Sonoran plant species (Fig. 2.33). The basins were artificially flooded multiple times (i.e., simulating monsoon storms) in Summer 2019 to test differences in water infiltration rates, soil moisture and temperature dynamics, energy balance between the basin and the lower atmosphere, and plant performance. Early results presented at the 2020 CAP ASM showed that the FCDMC standard rock mulch basins with native soils drained the slowest, but the plants in those performed better than those in the engineered biodetention basins that drained faster (Cheng et al. 2020). More analysis is forthcoming, but we hypothesize that the higher percentages of sand and organic matter did not match the ecological needs of the native plant species (Fig. 2.33). These UEI pilots are helping us build capacity for an expansion of UEI at the future LID FCDMC Durango Campus, with broader impacts for other UEI partners through networks such as Sustainable Cities Network.

An educational accomplishment that we are proud of is our development of a CAP-engaged landscape architecture studio model (Coseo et al. 2019; McPhillips et al. 2019) in which we integrate undergraduate and graduate students with CAP researchers and research products (Iwaniec et al. 2020a; Iwaniec et al. 2020b) to produce cross-IRT synthetic design products. These include the South Mountain Community Scenarios and the Paideia School Campus re-naturing. These studios have brought our IRT together with the work of the Scenarios and Futures and Climate and Heat IRTs to run these landscape architecture studio courses in fall 2017, 2018, and 2019. Products from these four studios contributed to community workshops and a final report for community partners (Berbés-Blázquez et al. 2019; Trakas et al. 2020). Students from the CAP studios went on to contribute to The Nature Conservancy's Heat Action Planning Guide for Neighborhoods of Greater Phoenix (TNC 2019), which includes the Edison Eastlake design experiment project. We are continuing this model in Fall 2020, working with the City of Tempe on its climate action planning and with the Landscape Architecture Foundation's Green New Deal Superstudio to reimagine Tempe's UEI.

Figure 2.32: Water harvesting UEI designed experiment basins were installed with the help of over 30 volunteers made up of CAP researchers, students, Watershed Management Group members, and other helpers at FCDMC (September 15, 2018).

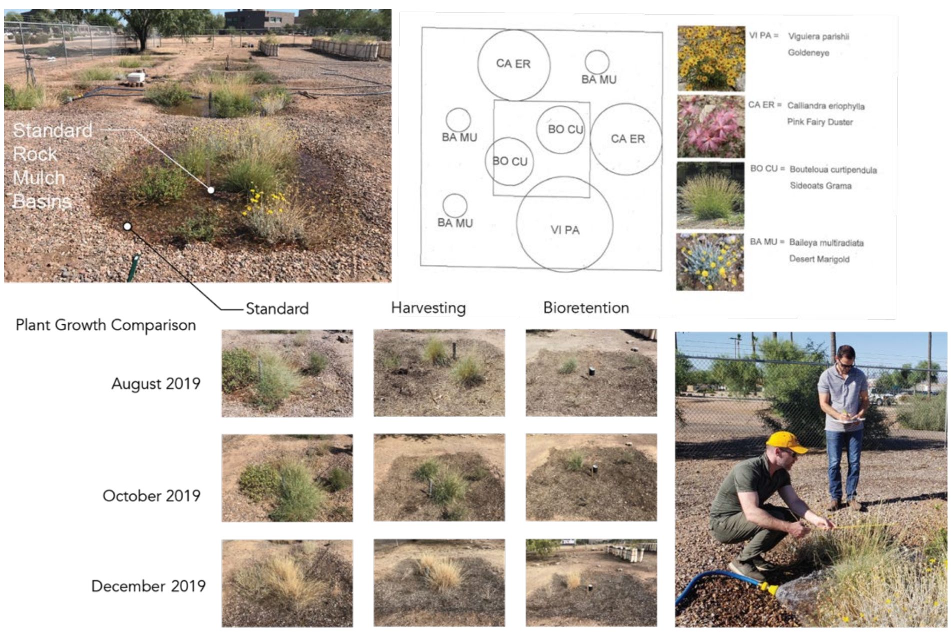


Figure 2.33: Three UEI basin designs were tested to help FCDMC better understand the ecological performance of each basins. The FCDMC wanted to prototype different approaches before larger scale interventions planned in 2021 as part of their LID Durango Campus redesign. Early indications show that although the bioretention basins drained the fastest and may meet stormwater infiltration goals, that design may drain too quickly to support optimal plant growth and thus not provide other ecological services and benefits that the standard basin provides (Cheng et al. 2020).

3. NETWORK PARTICIPATION AND CROSS-SITE RESEARCH

3.1. Network Governance

Members of the CAP community have always been committed to participation in Network governance, and we remain so. Lead PI and Director Childers is currently serving on the Executive Board, in the first year of a three year rotation. Co-PI Grimm is a new co-chair of the U.S. ILTER Committee, Leadership Team member Iwaniec is Vice Chair, and Executive Committee member Ball is serving on the committee. Leadership Team member Cook and CAP technician Quincy Stewart are serving on the Network DEI Committee. And Information Manager Earl is serving on the Network IM Executive Committee.

3.2. Collaborations with the BES LTER

We share a long history of collaboration and collegiality with our companion urban LTER program in Baltimore (BES). Much of this work has been organic and informal, though, and during CAP IV we have been strengthening and formalizing this valuable connection. Our researchers continue to publish together and get proposals funded together. Examples of the latter include cross-site research in Baltimore and Phoenix as part of the urban homogenization Macrosystems grants (PI: P. Groffman) and the UREx SRN (PI: C. Redman). Other examples of BES-CAP connections include: 1) the addition of future scenarios research at BES, in collaboration with our Scenarios & Futures IR; 2) our Urban Design IRT working closely with BES colleagues who have expertise with the ecology-design nexus; and 3) CAP PI York working with BES scientists Dexter Locke and Morgan Grove on a comparison of the results of the PASS with the Baltimore Phone Survey, with special emphasis on cultural ecosystem services. We are relating long-term change in these social data to patterns of land-cover change using high-resolution (0.8m) LULCC data and socio-economic data from both cities.

Prior to the termination of BES, we were beginning new comparative work: 1) examining how legacies of segregation and environmental injustices have created long-term social-ecological traps; 2) comparing how governance has changed over time, particularly relative to urban sustainability and resilience; and 3) investigating the social-ecological neglect and opportunity of vacant lots. In hopes that BES will soon be refunded, we have merely put these plans on the back burner. We send a CAP scientist and a student or postdoc to the BES Annual Meetings, and we host a BES student and scientist at our annual All Scientist Meetings. Each year, our Executive Committee works with the BES Project Management Committee to choose a cross-site research theme and we use that theme to decide which "ambassadors" to send to each other's meetings to initiate new cross-site comparative research projects, synthetic analyses, and publications.

3.3. Collaborations with other Urban Research Teams and other LTER Programs

CAP has always had a close and collaborative relationship with the ASU-based Decision Center for a Desert City (DCDC)—a NSF-funded Decision Making Under Uncertainty center that is now in its third round of funding. Three members of the CAP IV Leadership Team are on the DCDC Executive Committee, and cross-program integration and synthesis continues to grow. Several CAP scientists are part of an "urban homogenization" Macrosystems project (Lead PI: P. Groffman) supporting urban systems research at CAP and BES, as well as at the FCE, PIE, and CDR LTER sites. Our new focus on residential UEI and our Residential Landscapes & Neighborhoods IRT are both products of this collaborative effort. A second Macrosystems project, StreamPULSE (Lead PI: E. Bernhardt), is developing an open-source data and modeling platform on stream metabolism. It involves the LUQ and NTL LTER sites. Our Water & Fluxes IRT is involved in this research, acquiring data to model urban canal and lake metabolism. Several urban systems research networks have leveraged CAP, including the UREx SRN (Lead PI: C. Redman). The UREx SRN includes nine cities, two of which are LTER sites. It is based at ASU, and supports extensive urban climatic extremes research. A number of CAP scientists and students participate in UREx and much of their Phoenix-based research is being done at CAP field sites. CAP researchers are also involved with the Urban Water Innovation Network SRN (Lead PI: M. Arabi), a SEES Hazards grant (Lead PI: B. Stone), the Infrastructure Management for Extreme Events Program (Lead PI: M. Chester), and a GCR project focused on social-ecological-technological systems for urban resilience (PI: M. Chester)—all are NSF-funded. In collaboration with the SEV and JRN LTER sites, CAP is now part of the global DroughtNet network. Numerous CAP scientists have participated in cross-site synthesis projects funded by the LNO and directly by the NSF. Finally, examples of CAP scientists and students co-authoring publications with colleagues from other LTER programs or urban systems groups are too extensive to list individually.

3.4. Other Collaborations Relevant to CAP

The recently funded NATURA network of networks (PI: N. Grimm) is a global connection for researchers interested in urban resilience and the use of UEI to solve urban problems. CAP and BES are among many cities and research networks represented in NATURA. CAP is now a member of the Urban Wildlife Information Network, a NSF-funded RCN, through the work of J. Lewis (co-lead of the Parks and Rivers IRT). CAP scientist R. Aggarwhal participates in a Future Earth Flagship activity focused on urbanization, security of food-energy-water nexus, and extreme hazard risks. In addition, we continue to collaborate with a 6-year NSF-USDA program focused on Earth System Models (Physics-Based Predictive Modeling for Integrated Agricultural and Urban Applications) in which CAP-based LULCC 1 m and 30 m data were applied in various configurations for climate modeling projections by ASU and UCAR. These models include future precipitation projections for Central Arizona that we are incorporating into various activities of CAP, most notably the synthetic modeling work being done by the Scenarios and Futures IRT.

4. INFORMATION MANAGEMENT

4.1. Overview

Information Management (IM) is an integral component of CAP with the overarching goals of: 1) supporting data collection; 2) archiving well-structured and well-documented research data in a long-term data repository for the benefit of the scientific community, decision makers, and public; 3) enabling and promoting dataset discovery and access; and 4) providing leadership and education on sound information management. We maintain high standards for data archival and documentation to ensure the quality of the scientific data and metadata produced. The Information Manager works with CAP scientists, students, and staff in a variety of capacities to address data management throughout the knowledge-generating enterprise from research design to data publication. CAP is an active contributor to LTER Network IM, and we adhere to all NSF and LTER Network data policies.

Information Management and Structure: Our Information Manager, Dr. Stevan Earl, leverages a diverse suite of technologies and resources to meet CAP and NSF IM requirements (Fig. 4.1). He works closely with ASU Knowledge Enterprise, which provides web-, application-, and database-services hosted on virtual Linux servers in the Amazon Web Services (AWS) ecosystem. These resources host the CAP website, other web resources (e.g., personnel and citation databases, CAP's equipment reservation system, web-based data-entry applications), and centralized databases (MySQL, PostgreSQL) with appropriate access control, security, and recovery. ASU maintains an institutional agreement with Dropbox, which provides CAP with unlimited data and document storage, and we use Dropbox for document storage and as a collaboration tool. All networked systems and web applications are password protected, and ASU performs regular security sweeps to identify vulnerabilities or suspect behavior. We also use organizational GitHub and GitLab accounts to house project code, informatics documentation, and, increasingly, project documentation.

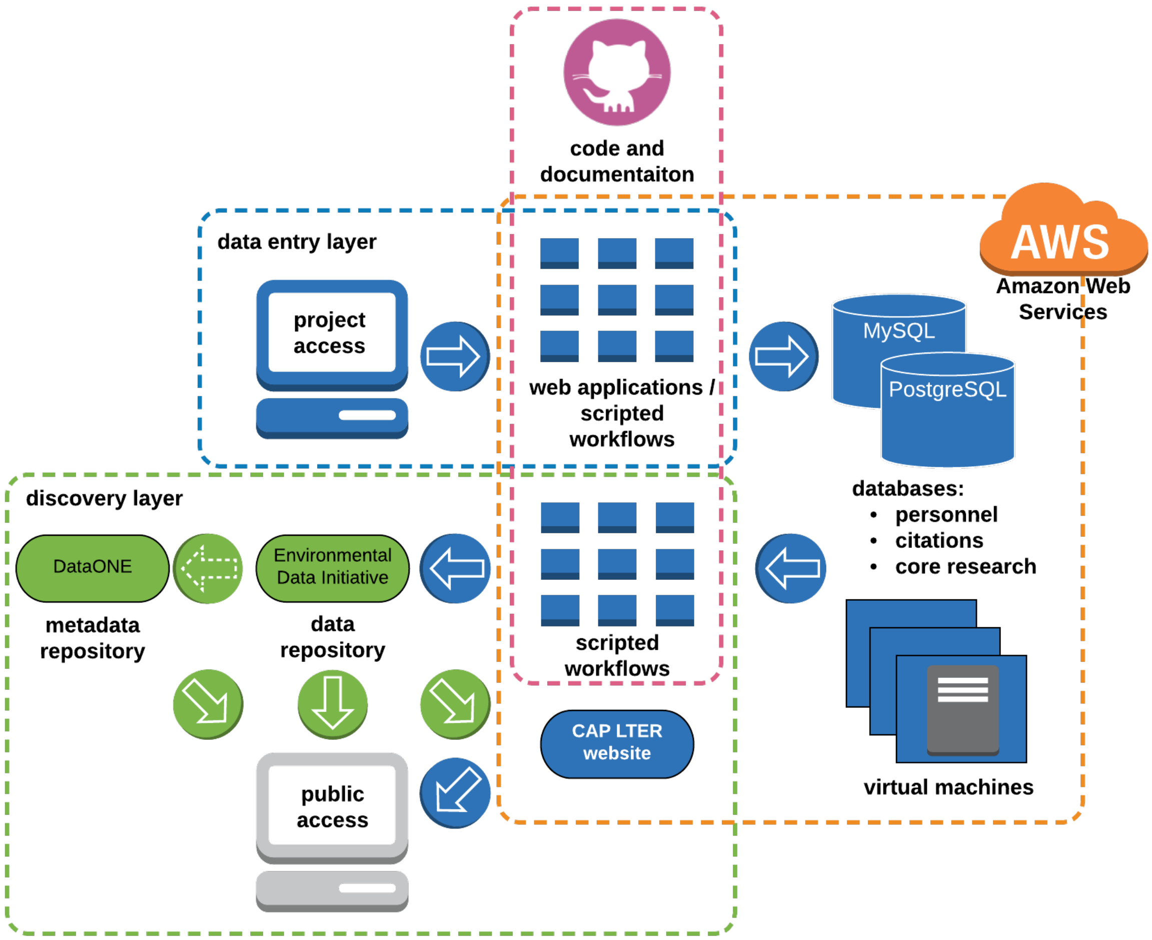


Figure 4.1. CAP LTER Information Management infrastructure and workflow.

Data Collection and Assurance: We employ a combination of tools and workflows to facilitate data collection, processing, transfer, and storage of data generated by our long-term observational and experimental (core) projects. Most field data are collected with pre-formatted field sheets or tablets. Data collected with tablets are uploaded to CAP databases with scripted (R) workflows. Observational data (e.g., bird surveys) recorded on field datasheets are double-entered into the CAP databases via web-based data entry applications developed with Ruby-on-Rails or Shiny. These tools are tuned to optimize workflow efficiency and quality control at the time of entry. Data generated from our analytical laboratory (Goldwater Environmental Lab) undergo rigorous quality control at the time of analysis. These data, along with data from sensor platforms (e.g., eddy flux towers, micrometeorological stations) are uploaded to databases using web entry tools (Shiny) or processed with scripted (R) workflows for efficient transfer of data to CAP databases while applying additional quality control measures. Many analytical workflows employ barcodes on samples, which greatly increases processing efficiency and minimizes data recording and transfer errors. All source materials (e.g., scanned field data sheets, sensor downloads) are archived in Dropbox for redundancy. All scripted tools and workflows are documented in GitHub or GitLab.

For novel datasets, investigators submit data and metadata with forms that are available on the CAP website along with submission instructions. The Information Manager works with data providers to address data and metadata issues to produce high quality, well-documented datasets with the goal of maximizing the potential reuse of the data. All datasets are processed with scripted workflows to ensure complete traceability of data processing. In addition to the published dataset, all materials contributed as part of the data submission, processing scripts, and documentation are archived in Dropbox.

Data Description: Metadata, stored as XML files, are encoded in the newest version (2.2.0) of the Ecological Metadata Language (EML) schema. Dataset EML metadata are generated using a suite of publicly-accessible R packages (capeml, capemlGIS). We use an additional R package (gioseml) to pull investigator details from ASU's Global Institute of Sustainability and Innovation (GIOSI) database. The integrity of CAP metadata is maintained through careful review and evaluation using the quality-control checks within the Provenance Aware Synthesis Tracking Architecture (PASTA+) system that ingests data into the Environmental Data Initiative (EDI) data repository. To maximize discoverability and interoperability with other ecological data, dataset keywords are mapped as closely as possible to the LTER Controlled Vocabulary, and measurement units are aligned with the LTER Unit Dictionary or otherwise detailed according to LTER Best Practices. Our Information Manager works with a wide array of data types (e.g., tabular, spatial, imagery), and these data types are often commingled in dataset packages. This approach aids ease-of-use by eliminating the need for data users to download multiple datasets to obtain, for example, both tabular and spatial components of a project.

4.2. Availability of Data, Metadata, and Other Relevant Digital Products

We are committed to maximizing the availability of CAP research products, and we adhere to the LTER Network Data Access Policy. Per the policy, most data are publicly available (Tier I). Only copyright-protected, third party data, and human subject data that cannot be anonymized are not public (Tier II). Tier II data may be available by request at the discretion of the data provider.

By default, CAP datasets are published in the EDI data repository, and are discoverable and accessible through several resources. The primary access point for CAP data is the data catalog on the data portal of our website. The catalog is populated from CAP datasets in EDI through a deployment of the PASTA+ architecture along with Apache Tomcat on an AWS server that retrieves CAP datasets from the EDI repository and makes them available through the catalog interface on our data portal. CAP data are available through a similar data catalog on the GIOSI website that features CAP data and non-CAP GIOSI data published in EDI. As CAP datasets are published in the EDI data repository, they are discoverable and accessible through the EDI Data Portal, and through DataONE by extension of EDI's participation as a member node.

4.3. Timeliness of Incorporating Relevant Data into the CAP Database

Updates to CAP's long-term (core) data are released at approximately annual intervals. Per the LTER Network Data Access Policy, investigators providing data from individual research projects (e.g., student research) are expected and encouraged to submit their data within two years of project completion, or sooner if in conjunction with publication of an associated journal article(s).

4.4. Other Accomplishments in the Last 4 Years

- We now have a unified data publishing and discovery system with EDI as the primary repository for all CAP data. A CAP data catalog that is populated by data in EDI is a relatively new implementation, replacing a previous version of the CAP data catalog that drew from a local index of datasets and custom styling of XML metadata files for display. This new innovation has numerous advantages, including: 1) mirroring the rich search and display features of the EDI Data Portal; 2) ensuring that CAP datasets published in EDI are the authoritative versions; and 3) greatly streamlining data management by eliminating a redundant system.
- To foster data literacy and promote sound data management skills, the current (Earl) and a former (Phil Tarrant) CAP Information Managers launched a semester-long course on research data

management methods that they offer through ASU's School of Sustainability. It has been taught every spring semester since 2016 and the course is well subscribed.

- We have developed tablet-based field data collection tools for a subset of long-term (core) monitoring programs, which greatly improves speed and efficiency of information transfer from the field sampling to CAP databases.
- We developed a suite of R packages (capeml, capemlGIS, gioseml) to enable a completely scripted approach to EML generation.
- We have consolidated CAP IM workflows and documentation in cloud-based version control systems (GitHub, GitLab).
- We created and are using a Slack team to improve project communication.
- Our Information Manager strives continually to improve data and metadata quality, and a notable advancement in this regard is a strong emphasis on including the ORCiD identifiers of data contributors.
- At the repeated urging of our IM, CAP scientists and students have dramatically increased their use of data citations, using dataset DOI numbers, in their publications. This visibility substantially increases ready access to CAP data and to our data resources.

4.5. Network Contributions

Our IM team is committed to making a strong contribution to informatics within the LTER Network and the ecological sciences generally. Our Information Manager participates in all network IM meetings and activities, serves as co-chair of the LTER Information Management Executive Committee (IM Exec), contributes to community-wide efforts (e.g., Dr. Earl is a contributing author of Ecological Metadata Language version 2.2.0), participates in and presents at numerous scientific conferences, and contributes to scientific- and informatics-focused publications. In addition, he is the embedded data manager for an LTER Network synthesis working group addressing soil organic matter dynamics, and is contributing to numerous products directly and indirectly related to that research effort.

5. EDUCATION, OUTREACH, AND TRAINING

5.1 Schoolyard LTER

Since 1997 Ecology Explorers has been our signature K-12 Schoolyard program. Ecology Explorers connects teachers and students with CAP scientists through schoolyard-friendly urban ecology protocols and learning modules. We host summer professional-development programs to share our research with teachers and help implement these programs throughout the school year. This teacher-focused approach is the most cost-effective way to share our research and to impact classrooms. Our summer teacher workshops trained 43, 24, 31, and 21 teachers from a variety of school districts in 2017, 2018, 2019, and 2020, respectively. Our Ecology Explorers program also hosted 39, 31, and 17 outreach events from 2017 – 2019, and these activities directly impacted the quality of STEM education for 1664, 2198, and 950 students, respectively.

We also share urban ecological knowledge directly with students through classroom visits and "out-of-school" programs. We incorporate CAP IV research on ES and UEI into lessons and curriculum modules. Notably, these ideas link well with the Next Generation Science Standards and 21st Century Skills. Additionally, we work with CAP researchers and students to develop "citizen science" protocols and to create teaching materials that use CAP data in "Data Nuggets" lessons (Section 5.4). Through Ecology Explorers, undergraduate students work directly with low-income and minority students in classrooms and in out-of-school settings. These students present active learning lessons around themes such as the urban heat island, urban biodiversity, and residential UEI. We include our scientists and graduate students in the summer teacher workshops, classroom visits, and family-oriented events. We highlight CAP research in the "Meet the Scientist" section of our Ecology Explorers website and through an Urban Ecology course taught in the Teacher's College Professional Learning Library.

5.2 REU Program

We have continued our successful REU Program in CAP IV by providing stipend and research support for 3 - 4 students per summer plus travel and subsistence support for out-of-town participants. Beginning in Summer 2017, we merged our REU program with the UREx SRN REU program, creating a summer cohort of nearly a dozen undergraduate researchers each year. This collaboration ended in Summer 2020, as the UREx grant is now winding down. We take advantage of the ESA's SPUR Fellowship Program as a minority recruitment vehicle as we endeavor to provide REU support to as many underrepresented students as possible. The ESA SPUR Program opens our diversity recruiting to economically-challenged students, in addition to more traditional types of underrepresentation; since 2017, we have placed four such students (three female and one male) with CAP researchers in our Summer REU Programs.

5.3 RET Program

In 2019 CAP received supplemental NSF support for a summer RET program, and based on the success of that we received additional support in 2020 for a larger "RET on steroids" program that will continue through Summer 2021. In both cases we were able to support research experiences for two K-12 teachers, with both cohorts from Roosevelt School District, which serves a lower income, predominantly Hispanic population (97% of the students are minority). Notably, Roosevelt School District includes one of our PASS neighborhoods (U18), where 93% of residents are Mexican/Latino, where the median annual household income is less than $37,000 and where fewer than 4% of residents hold a bachelor's degree or above (Larson et al. 2017). The district is also part of the City's South Mountain Village, which is 63% Hispanic and 15% Black. Our four RET educators represent each of these demographic groups.

The 2019 RET educators were paired with scientists and students from our Adapting to City Life IRT. Their collaborative summer research projects involved research on how birds adapt to the challenges of urban life (e.g. various stressors) or take advantage of resource subsidies that close habitation with humans may provide (e.g. bird feeders, water baths). Our new RET educators began their collaborative research with scientists from our Climate and Heat IRT, where they are focusing on extreme heat in school playgrounds, how the microclimate of playgrounds affects the health and wellbeing of children, and how UEI may be used to mitigate playground climate extremes while solving other health-related schoolyard challenges. These collaborations will continue through the 2020 – 21 academic year and into Summer 2021.

5.4 Graduate Students and Postdocs

The CAP Student Group is active and well organized, and they are a valuable and valued part of the CAP Community. The group has two co-leaders (currently Jeffrey Haight and Marina Lauck) who coordinate activities and encourage participation by primarily our graduate students, but also by our undergraduates. The Student Group currently includes approximately 60 graduate students from four academic units across ASU and from two different institutions beyond ASU. This group includes approximately 30 women and 5-10 students from under-represented groups.

We support CAP graduate research experiences and education in various ways. We are continuing our successful Grad Grants program, which provides up to $4000 each to nearly a dozen CAP graduate students every year (up to $6000 for collaborative research). As part of this program, we review student research proposals in a format similar to the NSF panel model, where panelists are previous Grad Grant awardees. In addition to Grad Grant support, CAP provides travel funds for students to present their research at conferences. Our students also benefit from CAP's research infrastructure, including vehicles, lab analysis, technical support, and publication costs. Also, we recently re-allocated funds to cover graduate RA support for a student to work with Amy Frazer and Billie Turner on our LULCC tasks. This student replaces a technician who was previously doing this work. Finally, all nine of the academic units at ASU that house CAP scientists have agreed to support graduate students (e.g., summer stipends) to conduct their urban research.

We are currently supporting two postdoctoral fellows: Dr. Jeff Brown and Dr. David Proffitt. Jeff started his second year with CAP in July, and he is working with a diverse group of mentors and researchers from three CAP IRTs: Residential Landscapes and Neighborhoods, Adapting to City Life, and Parks and Rivers. In his time with CAP, Jeff has been very productive: He has published two papers, has one in revision, two in review, and one in preparation. David began working with our Scenarios and Futures IRT group in June, and he is already embedded in a number of exciting research activities with this productive group.

5.5 Partnerships with Community Partners and Others

We continue to work with regional organizations to co-produce urban ecological knowledge that informs local and regional decision-making. 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 & Futures IRT. Our LULCC team works with researchers at ASU's Decision Center for a Desert City and Maricopa County water managers to track changes in residential turf landscaping. Our Tres Rios constructed treatment wetland work is in collaboration with the City of Phoenix Water Services Department. We have strong partnerships with the McDowell Sonoran Conservancy Field Institute and the Central Arizona Conservation Alliance. CAZCA, which is administered by our long-time community partner, the Desert Botanical Garden, is a partnership among public, nonprofit, and academic entities including the City of Phoenix Parks and Recreation, The Nature Conservancy, Audubon Arizona, and Maricopa County Parks and Recreation.

Ecology Explorers partners with schools and school districts in low-income, minority communities and with Homeward Bound to provide STEM programming at its residential community serving homeless families and those at risk of homelessness. CAP also supports myriad community programs with a large number of local and regional organizations, including Phoenix College, South Phoenix STEM Learning Ecosystem, the Environmental Literacy collaborative, the STEM Collaborative, the University of Arizona Agricultural Extension Agency, Arizona Power Service, Salt River Project, Tonto Creek Camp, Arizona Project WET, Desert Foothills Land Trust, and the Arizona Gem and Mineral Museum. Our previous E&O Coordinator, Lisa Herrmann, had strong working relationships with the Arizona Science Education Leadership Association, the Arizona Science Teachers Association, the American Association for Employment in Education, and the North American Association for Environmental Education.

CAP also participates in several citizen science projects across metro Phoenix. Our most active project is with the McDowell Sonoran Conservancy Field Institute (MSCFI). In this project, citizen scientists collect data that are used to manage Scottsdale's McDowell Sonoran Mountain Preserve. The Institute manages eight arthropod pitfall trapping transects and the CAP Entomological Research Specialist sorts and identifies these samples and provide the data back to the Institute and to the citizen scientists. The Desert Botanical Garden has trained citizen botanists to document plant diversity in regional parks, and in the past these volunteer botanists have helped with our DesFert sampling. The MSCFI is also interested in working with CAP and our CAZCA partners to develop citizen-science trainings/workshops for other regional parks. Finally, our Climate & Heat IRT researchers routinely collect personal temperature data from urban dwellers using "i-buttons." We recently expanded this i-button work to schools that use our Ecology Explorers urban heat island education module.

6. SITE MANAGEMENT

6.1. Program Management Plan and Leadership Structure

The main measure of success of an LTER program is the quality and quantity of its scientific products. Strong leadership and solid program management ensure relevance, integration, integrity, efficiency, and accountability—all of which are critical to scientific and research excellence. Our Program Management Plan: 1) facilitates CAP research and enables our scientists, students, and partners to realize their best research and educational outcomes; 2) enables and speeds the dissemination of knowledge, data, and products across all appropriate media; 3) guides junior faculty in both leadership and research roles; 4) nurtures students as they learn to become urban scientists of many kinds; and 5) promotes the recruitment and involvement of underrepresented minorities in all aspects of our research endeavor.

Our program management structure is inclusive, democratic, and relatively flat (Fig. 6.1). The Lead PI and Director of CAP IV is Dan Childers, founding PI and Director of the FCE LTER Program and director of CAP III for its first 2 years, while PI Grimm as working at the NSF. Childers directs all aspects of the CAP program, including communications with the NSF and University administration. He also serves as CAP's representative to the LTER Network Science Council and is currently serving on the Network Executive Board. Under Childers' leadership, CAP continues to exemplify interdisciplinary and translational research, transparent management, openness to new scientists, recruitment of underrepresented minority students, staff, and colleagues, and nimbleness in resource allocation to nurture exciting new minds and ideas. We anticipate a Lead PI leadership transition during the CAP V funding phase, and planning for this has begun (Section 6.3).

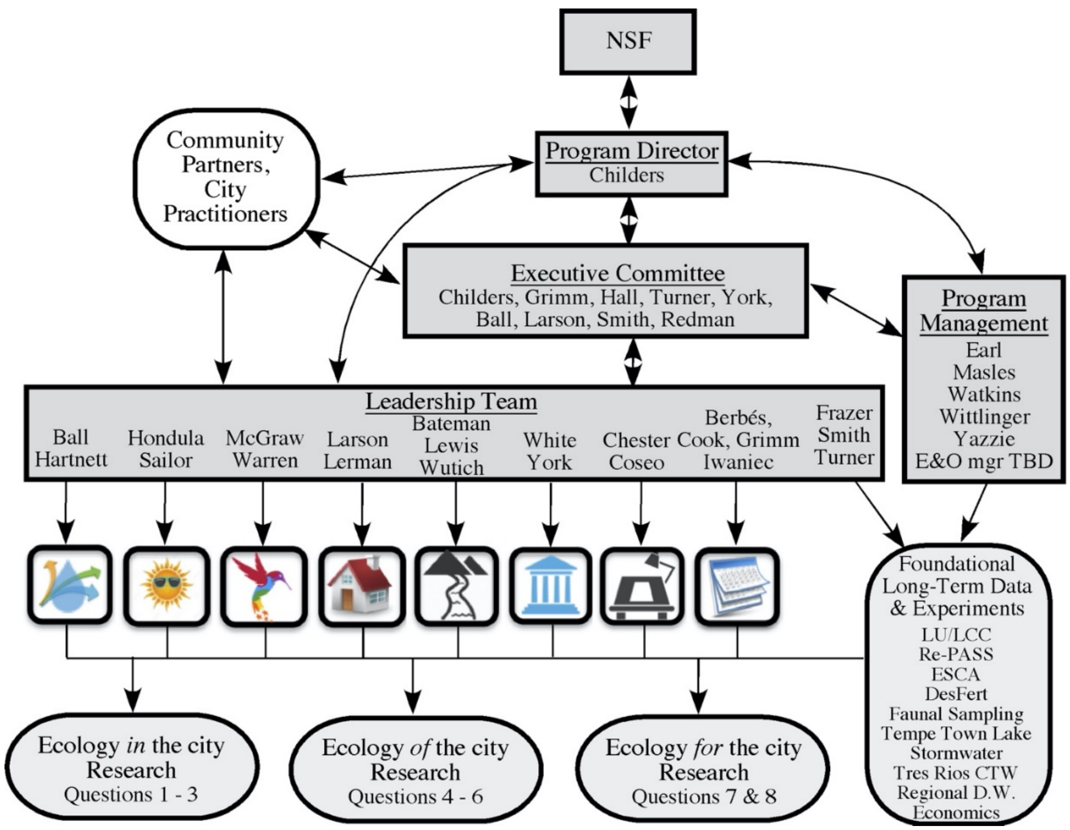


Figure 6.1: The CAP program management structure, including membership of the Executive Committee, the Leadership Team (i.e., co-leads of the eight IRTs, and management staff. The research question numbers refer to our 2018 proposal.

The CAP Executive Committee (EC) advises Childers on important programmatic decisions, per the CAP Administrative Guidelines. These decisions include substantial allocation of resources (e.g. Grad Grant awards, faculty summer salary, REU requests), the addition of new senior personnel, and new projects and experiments. The EC is composed of Childers and Co-PIs Nancy Grimm, Sharon Hall, Billie Turner, and Abigail York, plus Becky Ball, Kelli Larson, Chuck Redman, and Kerry Smith (Fig. 6.1). Ball, Childers, Grimm, and Hall are ecosystem ecologists; Larson and Turner are geographers; York and Redman are interdisciplinary social scientists; and Smith is an environmental economist. The EC meets roughly every other month or more frequently when needed (any member of the EC may call a meeting). The EC is, in turn, advised by the CAP Leadership Team, which is composed of the Co-Leaders of the eight Interdisciplinary Research Teams (IRTs; Fig. 7.1). The IRT Co-Leaders are: David Hondula and David Sailor (Climate & Heat); Kevin McGraw and Paige Warren (Adapting to City Life); Larson and Susannah Lerman (Residential Landscapes & Neighborhoods); Dave White and York (Governance & Institutions); Heather Bateman, Jesse Lewis, and Amber Wutich (Parks & Rivers); Ball and Hilairy Hartnett (Water & Fluxes); Mikhail Chester and Paul Coseo (Urban Design); and Marta Berbés-Blázquez, Elizabeth Cook, Grimm and David Iwaniec (Scenarios & Futures). Of the 24 members of the EC and/or the CAP Leadership team, eight are junior scientists (i.e., pre-tenure), eight are associate professors, and three are members of the National Academy of Sciences. In keeping with CAP's interdisciplinary reputation, the EC and Leadership Team are composed of eight ecologists, eight interdisciplinary social scientists, three geographers, two engineers, one economist, one geochemist, and one landscape architect.

The Program Management Team is responsible for the day-to-day operations of research activities and oversight of technical staff (Fig. 7.1). The team is composed of: 1) Mark Watkins, Program Manager, who leads program-wide planning, communications, integration of CAP with other campus research centers, and coordination with community partners; 2) Sally Wittlinger, Site Manager, who leads field and laboratory operations for all long-term sampling, experiments, and much of the question-based research efforts, and who supervises CAP's field and laboratory staff; 3) our new and yet-to-be-hired Education & Outreach Manager, who directs Ecology Explorers (CAP's Schoolyard LTER Program) and other education and outreach initiatives; 4) Marisa Masles, Lab Manager, who directs all CAP chemical analyses; 5) Sherry Yazzie, Financial Manager, who manages our accounts and budgets; and 6) Stevan Earl, Information Manager, who is responsible for information management, data access, working with CAP researchers and students on experimental design and IM issues, and coordinating with the GIOSI Information Management Team. Most members of CAP's Program Management Team have been with us for many years, and their collective experience, institutional memory, and hard work are critical to the success of CAP IV's research enterprise.

6.2. Demographics of the CAP Community

As an urban social-ecological research program, CAP studies the places where people live, work, and play. This situation presents us with exciting opportunities, but also with unique responsibilities. To meet these responsibilities, yet take advantage of these opportunities, we continue to foster sensitivity and awareness in the CAP community about the multiple facets of diversity encountered in the Greater Phoenix region every day. Per our Diversity and Inclusion Plan (Section 1.7), we are committed to sustaining and enhancing diversity among all participants in the CAP scientific endeavor. We recognize that diversity includes, but is not limited to, race, nationality, ethnicity, gender, age, sexual orientation, gender identification, language, religion, disability or health status, socio-economic status, veteran status, and geographic origin. *Our DEI goal is to maintain an environment that is open to all, and where individual differences are understood and valued and are integral to our collective empowerment as a scientific and academic community.*

In CAP IV, we have continued to strengthen our commitment to diversity and to providing opportunities for women and underrepresented minorities in all aspects of our research enterprise. Our 24-

strong leadership group includes 12 women, four LGBT members, and two Hispanic members. We continue to benefit from the ESA's SEEDS Partnerships for Undergraduate Research (SPUR) Fellowship Program as recruitment vehicles for our REU Program; we endeavor to provide REU support to as many under-represented students as possible. We have worked and will continue to work with ASU's Western Alliance to Expand Student Opportunities (WAESO) program, which funds faculty to recruit underrepresented minority students (undergraduate and graduate) to collaborate on research projects. Several CAP scientists are based at ASU's West Campus, which is primarily undergraduate and is home to a NSF-funded Research in Undergraduate Institutions (RUI) program. The ASU West student population is highly diverse: nearly half are minority, first-generation, or non-traditional students. Undergraduate research experiences of all kinds are an excellent pipeline into CAP-related graduate programs, and we actively recruit minority students using this pipeline. Faculty hiring is not within the direct purview of CAP, but our faculty scientists are fully cognizant of the importance of diversity in hiring decisions made by their respective academic units. ASU's reputation for inclusion and diversity is also strong; notably, ASU has more Native American students than any other institution of higher education in the U.S., including the entire University of California system. ASU's student body is 41% non-white and more than 50% of the 7000+ new freshmen that started at ASU in Fall 2019 were minority students. With a total enrollment of more than 125,000 students, we have a large minority population from whom to recruit just within our University.

6.3. CAP Transitions

In August, our former Education and Outreach Manager, Lisa Herrmann, retired from ASU. This unfortunately happened very quickly, and even with an expedited hiring process we were unable to hire her replacement before Lisa left town. At the time we submitted this report to the NSF, we had just made an offer to our new E&O Manager, Monique Franco. We anticipate that Monique will still be very much in the "training wheels" phase of learning her/his new job in October. We will also be losing our Site Manager, Sally Wittlinger, to retirement later this year. Fortunately, Sally agreed to put off this transition until after our site review and she agreed to work part-time for several months after that to help get her replacement secure in her/his new job.

As we noted in Section 6.1, we also anticipate a Lead PI/Director leadership transition during our next round of funding (CAP V). Transitions in top leadership in LTER programs are never easy, and extensive experience with these all across the Network indicates that best practice is to make these transitions roughly midway through a 6-year funding cycle and to include several years of ramp-up experience for the new Lead PI/Director. Childers will continue to lead the CAP program through the submission of our 2022 renewal proposal, and once CAP V funding is secure he will begin to transition leadership to Becky Ball, who has agreed to be our next Lead PI and Director. We anticipate that this transition will be complete in time to prepare for our 2025 mid-term site review. An important ambition with this transition is that we are able to also bring in an experienced social scientist to co-lead CAP with Ball. In spring 2021 we will formally add Ball and, hopefully, this new lead social scientist, to the cover page of CAP IV--replacing Hall and York. This change is necessary per NSF rules about LTER leadership transitions: The new lead PI must be on the cover page of the most recent grant, and cover page co-PI changes must be made and approved well in advance of submission of a renewal proposal.

6.4. Leveraged Funding

In keeping with our history, our scientists and students continue to be successful with leveraging CAP to win additional research funding. Since December 2016, a large number of CAP scientists have brought in nearly $10 Million in leveraged funding from a variety of governmental and foundation sources. This means that we have effectively leveraged the $4.5 Million investment in CAP by the NSF by more than two-fold.

6.5. Institutional Commitment to CAP

ASU's Global Institute of Sustainability and Innovation (GIOSI) is administrative home for CAP, supporting grant administration, accounting, human resources, communications and web development, meeting and event planning, and technical support. GIOSI supports portions of the salaries of several members of our Program Management Team and provides offices for our Program Management Team in Wrigley Hall. Our analytical lab facilities are located primarily in ASU's Metals, Environmental and Terrestrial Analytical Laboratory, a shared-use recharge facility, and we have separate lab and office space for staff and sample processing. Besides GIOSI, all nine academic units on ASU's campus that are represented by our Leadership Team support both graduate and undergraduate students in their respective units. Finally, the Office of Knowledge Enterprise (ASU's sponsored research office) makes a substantial returned indirect costs investment in CAP, funding our postdoc salaries, the CAP Grad Grants, travel, and meeting logistics. The CAP research endeavor gets remarkable institutional support from ASU, for which we are very grateful.

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