PROJECT SUMMARY

Overview:

Phase IV of the Central Arizona-Phoenix LTER (CAP) continues to focus on the question: How do the ecosystem services 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? The overarching goal is to foster social-ecological urban research aimed at understanding these complex systems using a holistic, ecology of cities perspective while contributing to an ecology for cities that enhances urban sustainability and resilience. This goal is being met through four broad programmatic objectives: 1) use long-term observations and datasets to articulate and answer new questions requiring a long-term perspective; 2) develop and use predictive models and future-looking scenarios to help answer research questions; 3) employ existing urban ecological theory while articulating new theory; and 4) build transdisciplinary partnerships to foster resilience and enhance sustainability in urban ecosystems while educating urban dwellers of all ages and experiences. CAP IV research is organized around eight interdisciplinary questions and ten long-term datasets and experiments, and researchers are organized into eight Interdisciplinary Research Themes to pursue these long-term research questions.

Intellectual Merit:

Homo sapiens is becoming an increasingly urban species, pointing to the profound importance of understanding urban ecosystems. Cities are concentrated consumers of energy and resources and producers of various wastes, but they are also centers of social networks, innovation, efficiency, and solutions. Understanding urban ecosystems has always been central to the CAP enterprise. By its very nature, the CAP IV central question articulates the interconnectedness of human motivations, behaviors, actions, and outcomes with urban ecosystem structure and function. This focus only makes sense given that Homo sapiens is the dominant species - the ecosystem engineer - of urban ecosystems. A new theoretical focus for CAP IV is on Urban Ecological Infrastructure (UEI) as a critical bridge between the system's biophysical and human/social domains. UIE is thus central in the conceptual framework that guides all CAP IV activities. CAP IV research is exploring new social-ecological frontiers of interdisciplinary urban ecology in residential landscapes, urban waterbodies, desert parks and preserves, the flora, fauna, and climate of a "riparianized" desert city, and urban design and governance. CAP will continue to grow urban systems theory, knowledge, and predictive capacity while helping Phoenix and other cities cope with an increasingly uncertain future.

Broader Impacts:

CAP IV now includes research in its broader impacts, with a theoretical focus on the nexus of ecology and design to enhance urban sustainability and resilience. This focus, combined with ongoing CAP scenarios work, is the translational and transdisciplinary link between social-ecological research outcomes and city institutions, ultimately making Phoenix, and cities in general, better places to live. In addition to these research endeavors, CAP's Schoolyard LTER - Ecology Explorers - continues to connect teachers and students with CAP scientists through urban ecology protocols and learning modules based on CAP research. Ecology Explorers hosts summer professional development programs for K-12 teachers and offers internships for undergraduate students to reach low socio-economic status
K-12 students. CAP is expanding its citizen science projects around Phoenix through collaborations with community partners such as the McDowell Sonoran Conservancy, the Central Arizona Conservation Alliance, the Desert Botanical Garden, and numerous municipal agencies. The successful CAP REU Program continues to use the ESA SPUR Fellowship Program to recruit underrepresented students, as CAP grows its leadership on - and strong commitment to - diversity and inclusion. CAP continues to support graduate students with the Grad Grants program, by providing extensive research infrastructure and services, and by direct support from all of the academic units at ASU that house CAP scientists. Finally, CAP's large, diverse, and rich database, and nearly 200 datasets in the LTER NIS, is a valuable and growing resource for LTER scientists and students, for urban researchers worldwide, for urban practitioners, for teachers, and for the general public.

PROJECT DESCRIPTION

I. Intellectual Merit – Introduction

a. General Introduction: In this proposal, we present research and activities of the Central Arizona–Phoenix LTER program (CAP) that began in late 2016 with our fourth round of funding, as well as new research that our Spring 2016 proposal review stimulated. We begin with a short history of CAP's first 20 years, followed by our central question and conceptual framework (throughout the proposal, we show papers that acknowledged CAP support in blue). Key results from CAP III and Year 1 of CAP IV lay the backdrop for the research plan that follows. We wrap-up with a description of the broader impacts that, for the first time, includes two transdisciplinary and translational research questions (convergence research; NSF AC-ERE 2018). By including fundamental research in our broader impacts, we highlight interactions with the city that we study as integral to our overall research endeavor.

b. Historical Overview of CAP LTER: CAP, one of the two urban LTER sites, has been the hub for studies of complex social-ecological systems in the Phoenix metro area (Fig. 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 (e.g., past agriculture increased soil nitrogen and carbon; Lewis et al. 2006; Zhu et al. 2006) and that other social variables help explain ecological patterns (e.g., the "luxury effect," whereby biodiversity is higher in wealthier neighborhoods; Hope et al. 2003; Kinzig et al. 2005; Walker et al. 2009). Our regional-scale research showed a high degree of heterogeneity in atmospheric deposition (Lohse et al. 2008), soil nutrients (Kaye et al. 2008), the nitrogen budget (Baker et al. 2001), exposure to toxic hazards (Bolin et al. 2000), and landscape pattern (Luck and Wu 2002). We also conducted historic analyses of land use/land cover change (LULCC; Keys et al. 2007) and of development and impact of the urban heat island (UHI) effect (Baker et al. 2002; Brazel et al. 2007). 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:

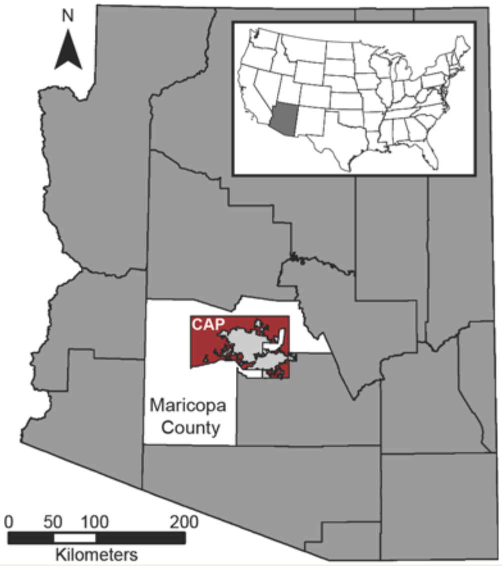


Figure 1.1: The 6400 km^2 CAP IV study area in central Arizona (red) that includes the Phoenix Metro Area (light gray within the red). Dark lines are county boundaries.

> ***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 (Grimm et al. 2013) and CAP IV (Fig. 1.2) are based on ecological disturbance theory, but with human/social elements representing 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 impact ecosystem structure and function. Internal presses and pulses (per Collins et al. 2011) 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 infrastructure (Fig. 1.2). 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 (Grimm et al. 2000; Childers et al. 2015; McPhearson et al. 2016; Pickett et al. 2016); that is, to understand the city as a complex, adaptive social-ecological system and to bring our knowledge to action in the transition of cities to a more sustainable trajectory.

Text Box 1: What Do We Mean by Urban Ecological Infrastructure (UEI)?

Cities are designed 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 (*sensu* Neuman and Smith 2010). We define UEI as the environmental/ecological features of cities; UEI thus includes everything from urban streams and street trees to parks and residential yards—all but the built environment. As such, most UEI is designed or managed to some degree (Steiner 2006; others). Recent literature has referred to UEI as Urban Green Space (UGS; e.g., Aronson et al. 2017). However, this nomenclature de-emphasizes non-terrestrial features, whereas our definition explicitly includes the terrestrial (green), aquatic (blue), and wetland (turquoise, per Childers et al. 2015) ecological features found in cities. Notably, our definition is distinct from the enviro-political definition of green infrastructure that includes, for example, solar panels and recycling programs; our definition expands on the green infrastructure definitions of Keeley (2011) and Larsen (2015).

c. CAP IV Central Research Question: *Homo sapiens* is becoming an increasingly urban species (Wigginton et al. 2016; NSF AC-ERE 2018), a global shift that underscores the profound importance of understanding urban ecosystems. Cities, concentrated consumers of energy and resources, are producers of various wastes, but are also centers of social networks, innovation, efficiency, and solutions (David 1995; Grimm et al. 2008; Bettencourt et al. 2009; Pickett et al. 2013: Grimm and Schindler 2018). Understanding urban ecosystems has motivated CAP since its inception in 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, are integrated within the system—a central tenet of social-ecological theory. This interconnectedness only 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 (Text Box 1). Our **overarching goal** is to foster interdisciplinary social-ecological urban research aimed at understanding these complex systems using a holistic, ecology *of* cities perspective (Grimm et al. 2000), while contributing to an ecology *for* cities to enhance urban sustainability (per Childers et al. 2014, 2015) through transdisciplinary partnerships with city practitioners.

We are meeting this goal in **four ways**. We will continue to: 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.

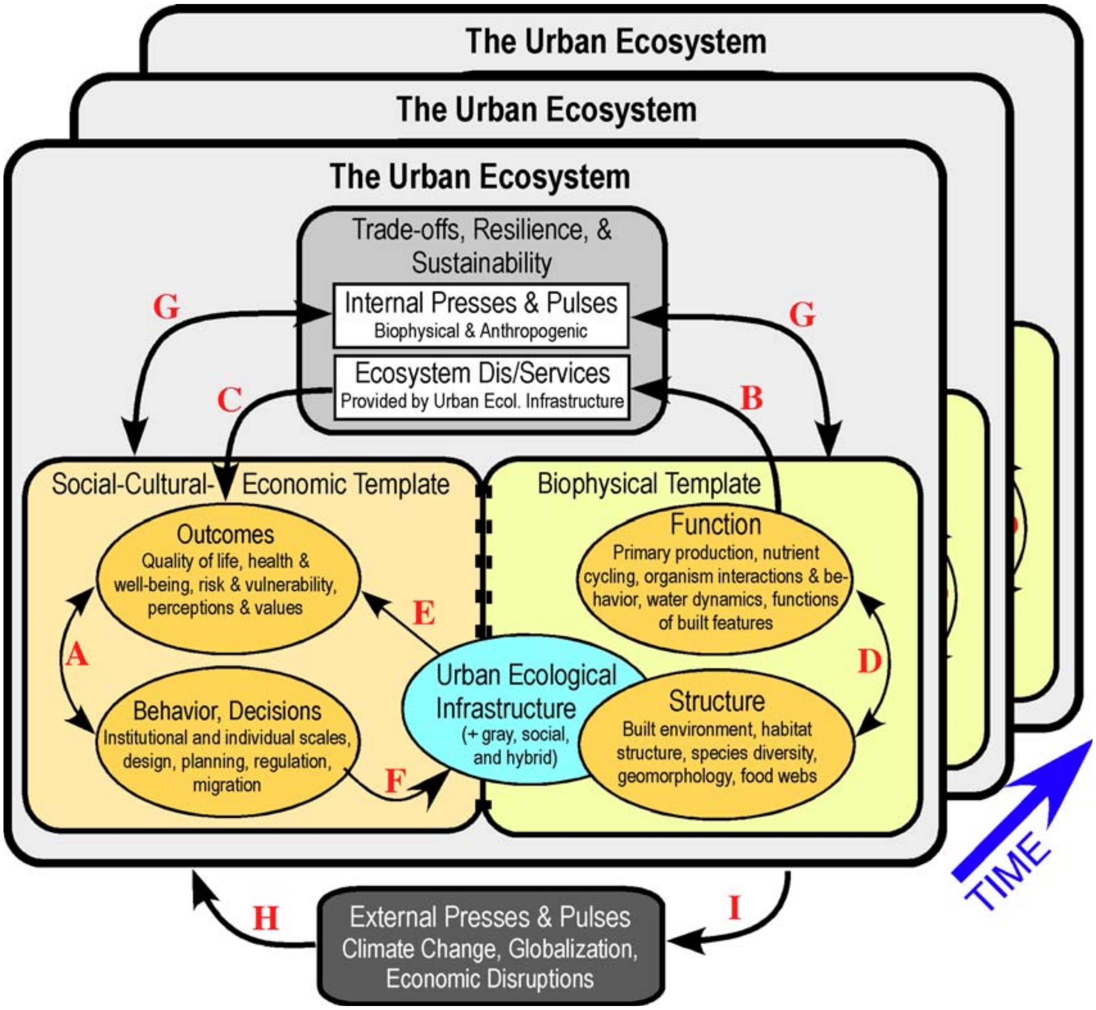


Figure 1.2: CAP IV central conceptual framework. See text for details and descriptions of the red letters.

d. Central Conceptual Framework: The CAP IV conceptual framework (Fig. 1.2) 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.

II. Intellectual Merit: Results of Prior Support

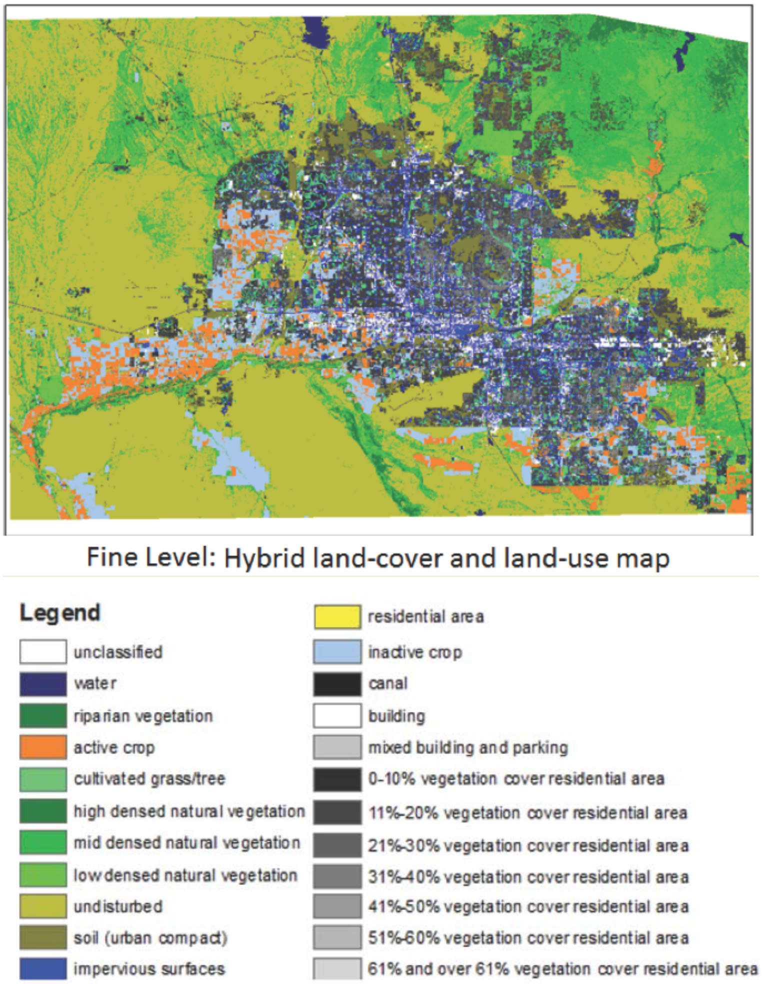


Figure 2.1: 2010 Land-cover classifications for the CAP study area at 1-m resolution. Our object-based imagery process approach employs the spectral, textural, geometrical, and spatial information to hierarchically refine basic land-cover mapping into an ecologically useful and hybrid LULCC mapping.

a. CAP III and CAP IV (Year 1) Significant Findings and 10 Most Significant Publications:

The last seven years of CAP research have yielded key insights (in *italics*) that synthesize findings across research themes and long-term datasets and that led to the new research questions in Section III. Of the more than 300 publications originating from CAP III and IV, we selected 10 that reflect the strong interdisciplinarity, and intellectual and theoretical impact, of our long-term research endeavor (these 10 citations are in **bold** font).

LULCC: *The most profound effect of urbanization is land-cover change,* accompanied by changes in economics, ecological and hydrological systems, infrastructure, and population growth and demography. Shrestha et al. (2012) analyzed 20th-century land-fragmentation patterns in the Phoenix metro area and found that five social-ecological drivers explained changes in urban geography: population dynamics; water provisioning; technology and transportation; institutional factors; and topography. We developed sub-m resolution, object-oriented classified imagery for the 6400 km^2 CAP study area using National Agricultural Imagery Program (NAIP) data (X. Li et al. 2014; Fig. 2.1). We analyzed changes in urban form at a 30m resolution from 1970–2010, using compactness measures developed by W. Li et al. (2013, 2014) and found reduced sprawl in post-1990 growth compared to the previous two decades. We have begun to explore the landscape configuration, at individual parcel and neighborhood levels, as well as new measures of that configuration (X.Li et al. 2016). This work directly links to our climate research and is being used for other ecological assessments (Myint et al. 2015; X.Li et al. 2017; Zhao et al. 2017). Finally, we have developed methods to identify vacant land and its clustering, providing an empirical base to explore design options for placing UEI features to help ameliorate the UHI (Klaiber et al. 2017; Zhang et al. 2017). CAP IV builds upon on these accomplishments as we conduct change analysis on the high-resolution land-cover data from 2010 and 2015.

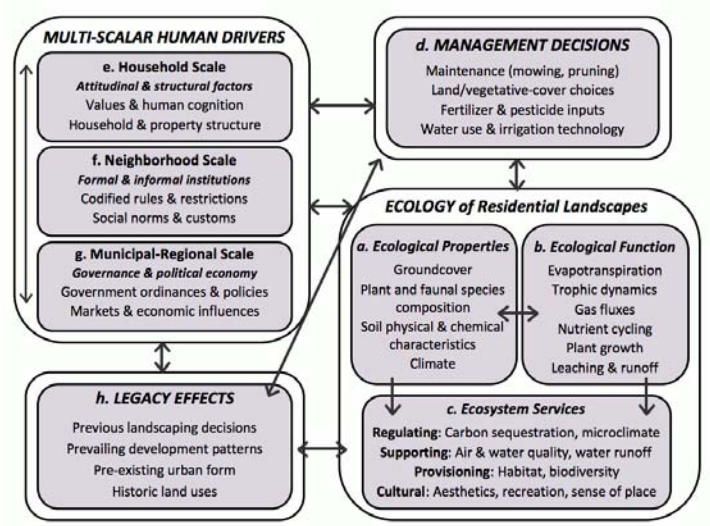


Figure 2.2: Social-ecological framework for residential landscapes showing feedbacks among ecological properties, human drivers, legacies, and management decisions (from **Cook et al. 2012**).

URBAN SOCIAL-ECOLOGICAL THEORY: Linkages between social and ecological dynamics are complex because they often are offset in scale, feature unknown feedbacks, and change over time. CAP has been a strong contributor to evolving theory about *urban social-ecological systems* and *cities as ecosystems,* and CAP continues to be a leader in integrating the social and natural sciences (Grimm et al. 2000; Grimm et al. 2008; Collins et al. 2011; Roy Chowdhury et al. 2011; Grimm et al. 2013; Childers et al. 2014, 2015; Wu 2014; McPhearson et al. 2016; Fishman and Smith 2017; Groffman et al. 2017; Grimm and Schindler 2018). For example, **Cook et al. (2012)** developed a framework for social-ecological research centered on residential landscapes, in which ecological properties, functions, and services influence, and are influenced by, management decisions, legacies, and human drivers at household, neighborhood, and municipal scales (Fig. 2.2). We continue to use this framework to guide our CAP IV residential landscapes research.

ECOLOGY OF RESIDENTIAL LANDSCAPES: Our residential landscapes and neighborhoods research has shown that *perceptions about the local environment relate to residential landscape decisions, parcel-to-neighborhood ecological properties, and property values.* Coupling this work with our Phoenix Area Social Survey (PASS), we related perceptions to ecological variability and to people's actions. PASS has revealed that attitudes and perceptions about the environment influence human behavior, sometimes in surprising ways. For example, residents with relatively strong environmental values tended to water their yards more frequently than those with relatively anthropocentric values (Larson et al. 2010). Residential landscape types did not substantively change between 2006 and 2011 but, where changes did occur, residents were more likely to modify their backyards than their front yards. Changes to front yards were largely conversion of mesic to xeric landscaping, and this conversion to more water-efficient landscaping led to increases in soil nitrogen (Heavenrich & Hall 2016). We found that drivers at multiple scales—from household to neighborhood to municipality—and broader political/economic factors influence landscape management (Roy Chowdhury et al. 2011), with informal institutions (e.g., norms) being more influential than formal ones (e.g., codified

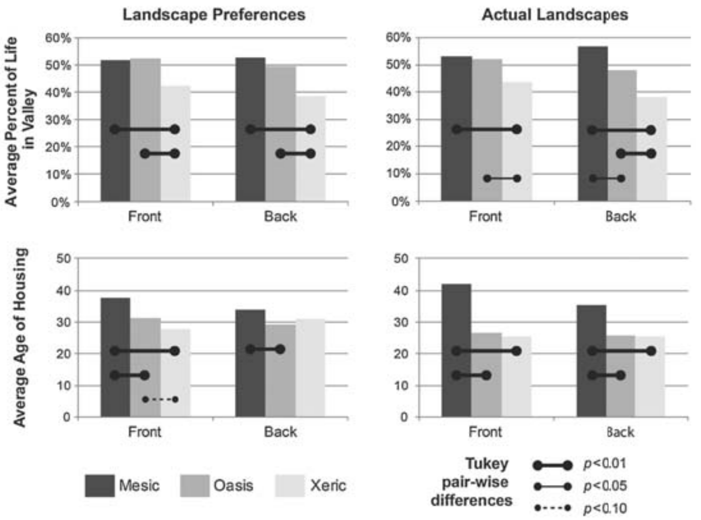


Figure 2.3: Patterns for yard preferences (left) vs. actual landscape type (right), for front and back yards, based on how long residents have lived in Phoenix (top) and the age of their homes (bottom). From Larson et al. (2017).

rules; Brumand and Larson 2012; Larson and Brumand 2014). For example, people who have lived in Phoenix for longer were more likely to prefer, and maintain, mesic turf yards than relative newcomers (Fig. 2.3; Larson et al. 2017). Our economic modeling showed that many homeowners are willing to pay for proximity to amenities, such as artificial lakes and parks (Abbott and Klaiber 2013; Larson and Perrings 2013; Fishman and Smith 2017; Klaiber et al. 2017) and our CAP IV research is focusing on both types of features. Finally, we have studied the effects of the 2008 Great Recession on plant communities in residential landscapes. **Ripplinger et al.** (2016; **2017**) found that widespread loss of management (irrigation, weeding, planting) drove an increase in post-recession plant species richness and community homogeneity, as abandoned yards were taken over by annual weedy species when people were forced to leave their homes (Fig. 2.4).

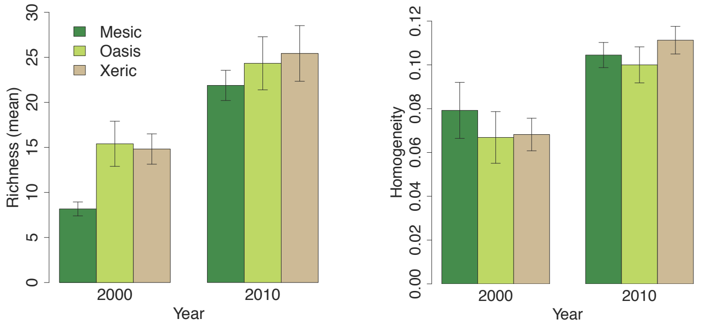


Figure 2.4. Plant species richness (left) and community homogeneity (right) in residential landscapes from ESCA data before (2000) and after (2010) the Great Recession, showing how widespread foreclosures and home abandonment altered the plant communities found in yards throughout CAP (from Ripplinger et al. 2016; **2017**).

CLIMATE, ECOSYSTEMS, AND PEOPLE: Our integrated social-ecological research has shown that *climate, vegetation, social equity, and biodiversity are linked in arid cities.* We continue to document relationships between neighborhood income and biodiversity driven by vegetation differences (Faeth et al. 2011; Lerman and Warren 2011; Ackley et al. 2015). These differences explain variation in neighborhood-scale temperatures. More research on the UHI has been done in Phoenix than any other city (Chow et al. 2012); our research on extreme heat is significant, given that urban heat affects human health and well-being in many ways (Petitti et al. 2016), and given the likelihood that heat-related impacts on human well-being will increase under most climate-change scenarios (Hondula et al. 2015). **Jenerette et al. (2016)** and Klaiber et al. (2017) analyzed remotely sensed temperature and land cover at parcel and neighborhood scales and included PASS data to show spatial disparities in human-health impacts and environmental perceptions. We also have uncovered relationships among urban vegetation, outdoor water use for irrigation, spatial variation in the UHI, personal incomes and property values, and disproportionate vulnerability to extreme heat (Ruddell et al. 2013; Harlan et al. 2014). These disparities may be mitigated with vegetation choices that modify microclimate (Chow et al. 2011; Chow and Brazel 2012; Declet-Barreto et al. 2013; Fan et al. 2015), with the tradeoff of increased water use (Jenerette et al. 2011; Jia et al. 2015). Finally, recent analysis and modeling of long-term trends in land-surface temperature confirmed the role of vegetation, and of the water that irrigates it, in reducing temperatures. Areas with a lower proportion of vegetated land had higher daytime and nighttime temperatures, and vice versa (Fig. 2.5; Harlan et al. 2014; **Jenerette et al. 2016**; Wang et al. 2016).

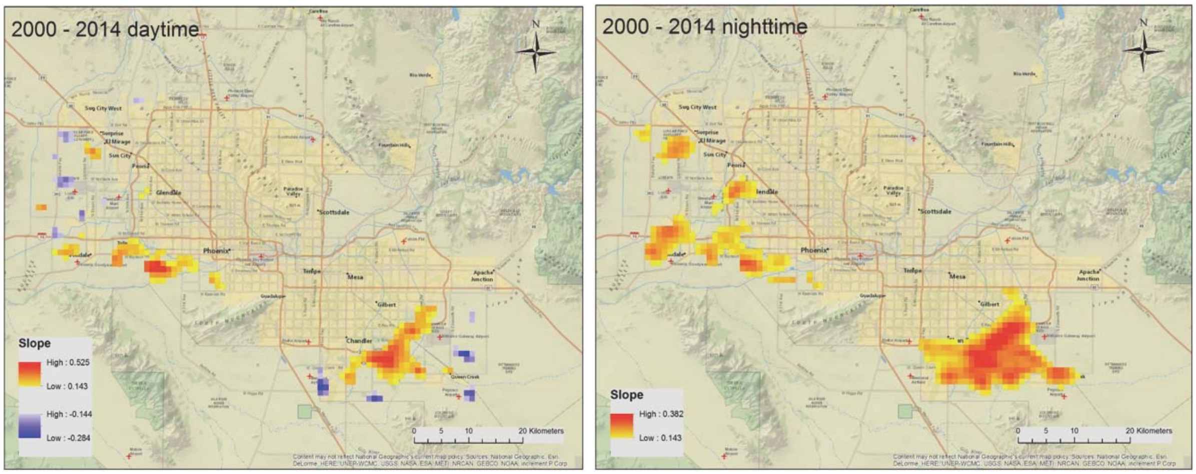


Figure 2.5: Relative values of slope of change in daytime (left) and nighttime (right) land surface temperature from 2000 to 2014 for developing areas within the CAP region. Yellow-red colors indicate increasing land surface temperature; blue-purple colors indicate decreasing temperature.

WATER DYNAMICS IN A DESERT CITY: Water is integral to nearly every aspect of the CAP ecosystem, as illustrated by the vegetation-heat studies above. Without water, much of the vegetation in residential landscapes would not survive. Water is also a disturbing force (i.e., stormwater flooding), a limiting resource to desert productivity (Sponseller et al. 2012), and a vector for waste removal (Sanchez et al. 2016). **Hale et al. (2015)** found that changes in stormwater infrastructure type over the past 50 years strongly influenced hydrological retention, and thus nutrient retention, during storms.

To determine optimal irrigation regimes for mesic and xeric residential landscapes, **Volo et al. (2014)** modeled soil moisture dynamics using soil moisture data from the long-term experimental landscapes at our North Desert Village experimental neighborhood. They showed that the relationship between irrigation schedules and plant stress differed by landscape type. Finally, a novel discovery of plant-mediated control of surface hydrology comes from our long-term research at the Tres Rios constructed wastewater treatment wetland (Weller et al. 2016). Marsh plants in this wetland are highly productive and transpire large volumes of water, particularly in the hot, dry summer. A plant-driven "biological tide" from open water into the marshes brings in new water and nutrients to replace these transpiration losses, making this treatment wetland more effective than if it was located in a cooler or more mesic climate (Fig. 2.6; Sanchez et at. 2016; **Bois et al. 2017**).

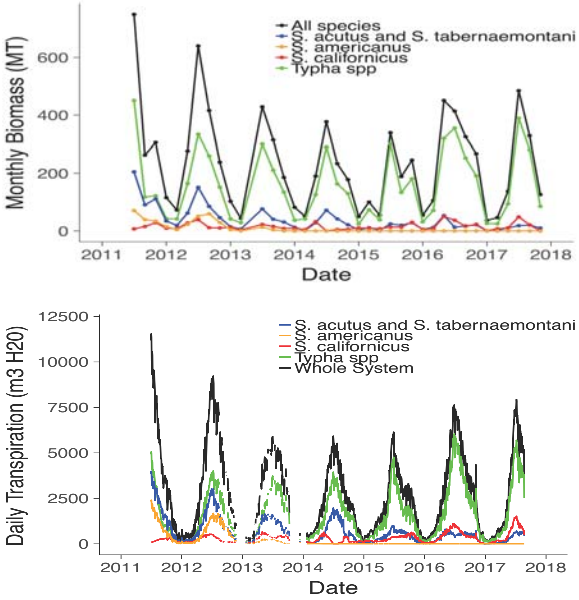


Figure 2.6: Temporal patterns of marsh plant biomass (top) and daily plant transpiration (bottom), which creates a "biological tide" drawing water and nutrients into the vegetated wetland.

A general insight from our research on infrastructure is that *designed and built* *components dominate urban ecosystems, yet the functions and services they produce are not always as intended*. For example, we found that urban riparian areas can and do provide habitat for wildlife (**Banville et al. 2017**), that stormwater infrastructure design determines water and nutrient retention and transport (Hale et al. 2014; **2015**) and can provide unintended ES such as denitrification (Roach and Grimm 2011); that unplanned or "accidental" urban riparian wetlands are more faunally diverse than designed ones (Bateman et al. 2015; Palta et al. 2017) and they provide critical ES to the homeless (Palta et al. 2016); and that designed systems such as treatment wetlands perform better than expected in this arid city (Sanchez et al. 2016; **Bois et al. 2017**).

Biogeochemical Patterns and Processes: Our biogeochemical work has focused on material fluxes and their impacts on people. Phoenix is a hot, dry city where dry deposition dominates over precipitation. Eagar et al. (2017) found that dust storms, or haboobs, account for nearly 75% of this dry deposition. As part of our long-term fertilization experiment at desert sites in urban and non-urban parks, driven by an interest in atmospheric deposition of nitrogen, **Hall et al. (2011)** reported that creosotebush (*Larrea tridentata*) growth was relatively insensitive to nitrogen addition but strongly responsive to summer rainfall, whereas winter-spring annuals responded to nitrogen addition in wet years in a climate-driven cascade of resource limitation. **Zhang et al. (2013)** used our ecological survey (ESCA) and LULCC data to develop and parameterize a model that quantifies ecological pools and processes, such as net primary production, soil organic matter and nutrients, carbon fluxes, and spatial structure of carbon storage. This model is foundational for our analysis of long-term change in ecological patterns at multiple scales (e.g., the CAP carbon budget; McHale et al. 2017) and for our future scenarios work.

Long-term water-quality data from Tempe Town Lake, an artificial lake constructed in the bed of the previously dry Salt River, showed variable impacts of extreme events, climate variability, and management decisions. The lake is an exciting model system for the many artificial lakes constructed in dryland cities (Steele et al. 2014) because management decisions lead to its occasional disappearance: It is drained, or the dams are lowered, to allow the river to flow through during floods, after which it is re-established as a lake. Patterns in dissolved organic carbon quantity and quality suggest that carbon cycling in the lake responds both to meteorological/climatological events and to anthropogenic activity, while the long-term pattern of dissolved oxygen concentration suggests that the lake is autotrophic and thus is a sink for atmospheric carbon (Fig. 2.7).

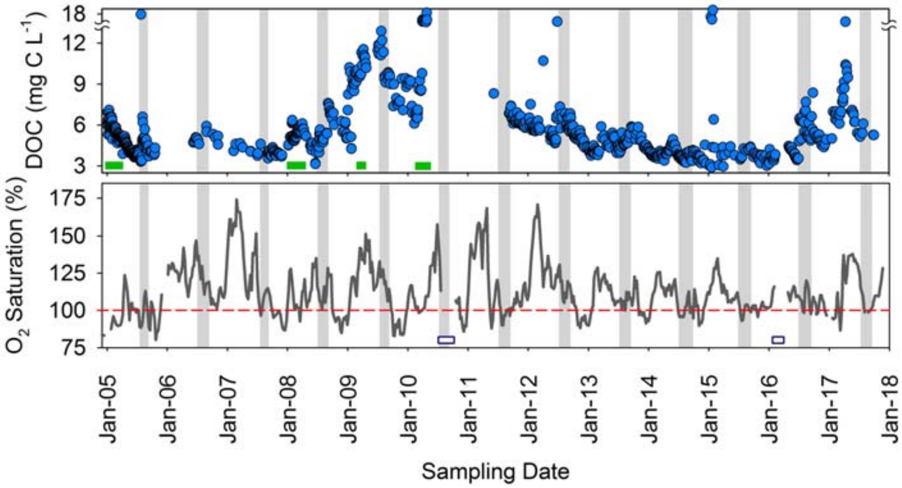


Figure 2.7: Dissolved organic carbon (DOC; top) and oxygen saturation (bottom) for Tempe Town Lake (2005-2018). DOC shows strong seasonal and inter-annual variation and responds to climate events and anthropogenic activity. Dissolved oxygen (presented as a 3-wk moving average) is nearly always supersaturated (note red line at 100%); the lake is highly productive. The summer monsoon seasons are shown with gray bars. Green boxes are periods when the lake has emptied and refilled, either accidentally or deliberately.

Biodiversity in the City: Bird, arthropod, and plant communities were the original focus of our population and community research because they represent different degrees of attractiveness to and control by people. Our population/community research on has gone beyond documenting the impacts of urbanization on biotic diversity to explore the mechanisms behind those changes. In an experiment manipulating food resources and predation, **Bang et al. (2012)** showed that bottom-up factors strongly regulated plant-associated arthropod communities in desert habitats while urban arthropods responded to a complex set of relationships among climate, plant growth, and predation. Lerman and Warren (2011) explored how bird diversity—particularly native species—varied across the city. They found that native vegetation in desert-like landscapes, proximity to large desert tracts (including urban mountain parks), and neighborhood median income explained nearly 50% of variation in the bird community. They found fewer native birds in poorer, ethnic minority neighborhoods. In addition, our long-term work at 12 riparian sites along a hydrologic and urbanization gradient has shown that engineered sites supported more broadly distributed generalists while native desert sites supported more specialists. Bird abundance, species richness, and diversity decreased across all riparian types from 2001–2015, and the riparian bird community is shifting towards one characteristic of more engineered sites with less water (**Banville et al. 2017**; Fig. 2.8). We have also tracked bird communities in PASS neighborhoods, along with satisfaction with bird diversity, and relationships of bird species to yard types. Resident satisfaction with the variety of birds in their neighborhood declined more than 10% between 2006 and 2011. Bird species richness and occupancy also decreased, with only four species increasing occupancy, indicating that residents accurately perceived bird diversity and abundance (Warren et al. in review). In CAP IV, we are exploring whether these downward trends will continue or reverse after The Great Recession of 2008.

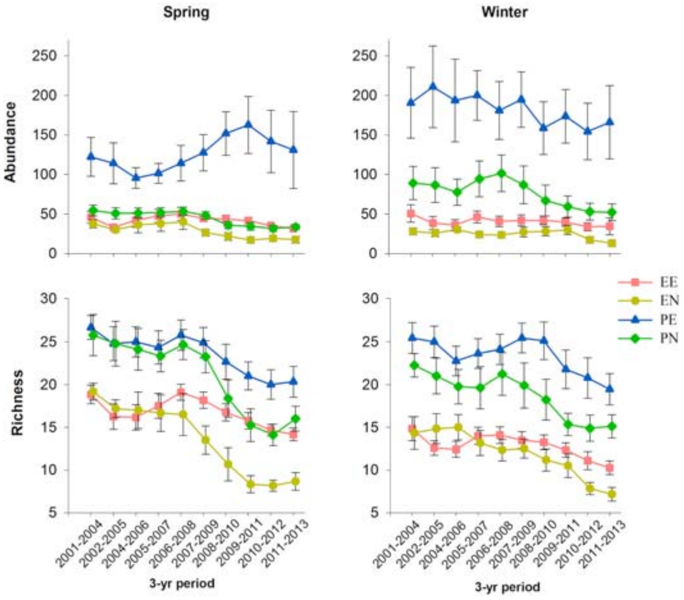


Figure 2.8: Spring (left) and winter (right) bird abundance (top) and richness (bottom), as 3-year running averages for each riparian habitat type. EE, ephemeral engineered; EN, ephemeran natural; PE, perennial engineered; PN, perennial natural.

A key insight that crosses our research themes is that *structural and functional differences between urban and desert habitats are not always as predicted.* Birds are not food-limited in the city, yet they experience much greater interspecific competition relative to desert habitats (Shochat et al. 2010; Lerman et al. 2012). The UHI accelerates phenology in both plants and animals (Buyantuyev and Wu 2012; Davies and Deviche 2014), and we have found other physiological differences related to urban environment stresses (Deviche et al. 2011; Giraudeau and McGraw 2014). Finally, community and ecosystem processes in urban desert parks differ from those of native desert, even though these two environments appear similar (Hall et al. 2009; **Hall et al. 2011**).

SUSTAINABLE FUTURE SCENARIOS: For several years, CAP scientists have engaged with representatives of over 20 governmental and nongovernmental organizations and the public to envision the future of the Phoenix metro area. This work includes workshops to identify issues of concern, then to construct increasingly useful and specific visions, and finally to evaluate tradeoffs among those visions (Iwaniec et al. 2014). We based these tradeoffs on modeled output of future climate, population, land use, and spatial distributions of resources and infrastructure. Outcomes from this work have informed the City of Phoenix General Plan and Sustainability Plan (Iwaniec and Wiek 2014). We presented the results of this ongoing process at public events and on a website and worked closely with city practitioners to integrate these co-produced visions into future planning efforts. These activities are continuing in CAP IV. This translational research aligns well with the recent NSF AC-ERE report (2018) on urban systems.

b. Broader Impacts: The broader impacts of CAP III and IV (Year 1) include: 1) developing and maintaining a comprehensive, spatially explicit, long-term database on social-ecological variables (see Text Boxes in Section III for details); 2) creating awareness of cities as social-ecological platforms for solving sustain-ability challenges; 3) co-producing knowledge with decision-makers (*sensu* Ostrom 1996; Grove et al. 2016); and 4) integrating education and outreach into our work. Our Information Management (IM) program is well-developed; datasets are archived, documented, up to date, and accessible. We work closely with regional NGOs and environmental groups to promote appreciation and understanding of urban challenges and solutions (Section IV e & f), and we have leveraged major new grants in support of decision-making on water challenges and resilience to extreme events under climate change (Section IV d). The co-production of knowledge is a major success of our scenarios and futures work. We have continued to support education at all levels: K-12 education with our award-winning Ecology Explorers program; 39 undergraduate students supported through our REU program; 58 students funded since 2010 through our novel Grad Grants program; and funding of several postdocs.

c. Products of CAP III Supplements: The CAP III and IV REU Programs provided integrated research and teaching experiences where students followed the entire cycle of scientific research. REU supplements (2011–2015) supported 27 students; 22 graduated and five are completing their degrees. Of these 22 students, eight attended graduate school (five in traditional STEM fields, two in sustainability, and one in public health) and eight have gone into the workforce (six are in STEM jobs). Our REU participants have co-authored 13 journal articles. Many REU students were women or minorities, and in Summer 2016 and 2017 CAP partnered with the ESA SEEDS program to recruit more underrepresented students. In 2011, CAP received a RAHSS supplement that supported three Hispanic high school students who continued their research with faculty and graduate students beyond the summer; all went on to college. Remaining RAHSS funds supported a high school senior in Summer-Fall 2017. Since Summer 2016, CAP has partnered with other urban-focused projects to run a summer meeting series for REU students; this collaborative program will continue in 2018.

The 2010–2015 Schoolyard Supplements trained 93 teachers through summer and academic-year workshops and reached over 2000 children through classroom visits. Twenty after-school programs and camps hosted Ecology Explorers presentations and curricula, and 11 undergraduate and graduate students were trained in education and outreach. We developed a curriculum module on the UHI to accompany an issue of *Chain Reaction*, a magazine produced for teachers and students, and an online course on Urban Ecology for ASU's Teachers College. Most students served through our K-12 programs are members of groups underrepresented in STEM. We also partnered with Homeward Bound, a transitional housing community that serves homeless families and those at risk of being homeless. Our graduate and undergraduate interns engaged Pre-K through 5th grade students in interactive lessons on urban ecology several times a year in Homeward Bound's after-school program.

In 2011, the CAP IM team received an IM Supplement to develop and test datasets for the GeoNIS. The NIS migration activities resulted in repackaging of CAP's data inventory, updating the metadata, and submitting new data inventory to the NIS (see Supplemental Documents). A 2015 CAP supplement to support LTER Network IM activities funded travel and registration for a small group to attend the 2015 summer Earth Science Information Partnership meeting. Lastly, we used a 2015 Equipment Supplement to purchase a new field vehicle and contribute to a new gas chromatograph for trace-gas analysis.

d. Response to Previous Review (Spring 2016 CAP IV Proposal): As a result of the 2016 review of our first CAP IV renewal proposal, CAP is on probation. This review provided constructive advice about our research plan and identified problems with the clarity of programmatic integration. We have modified our research plan to address the reviews. Because reviewers affirmed our conceptual framework (Fig. 1.2) and overall long-term approach, we have not instituted major changes in these elements. However, we did use the reviewer comments to reshape how we present the CAP IV program in this proposal. Thus, much of the Research Plan is a presentation of ongoing CAP IV activities, which explains why Section III is written largely in the present tense. The following summarizes the major reviewer/panel criticisms and how we have addressed them:

i. *The proposal needs to be better integrated; including social-ecological integration and across the Research Questions. Map each research question to the central question and conceptual framework.* Response: We start Section III by briefly introducing our ten long-term observational and experimental datasets with a cohesive narrative. We have modified many of our long-term observations to better integrate them over space and time, allowing us to map our research questions more cohesively to our long-term datasets and to each other. These long-term datasets are described in more detail, in Text Boxes, in our Research Question narrative (Section III). We have reconstituted the original 13 research questions into eight, each of which is being led by a specific research team. We present these questions using our conceptual framework to show how they are interconnected while telling a steadily more-integrated story about our entire research endeavor. In each case, we explicitly discuss the theoretical logic motivating our research and the connections to the central question, to our long-term data, and to the seven LTER Core Areas. Finally, we have added a new figure that maps articulation of the eight research questions with each other and with our central themes (Fig. 3.2).

ii. *The transdisciplinary "ecology for the city," actionable-knowledge Research Questions seem too much like we are "messing with" the system we are studying, and do not belong in the Research Plan.* Response: These two questions, about urban design and future scenarios, are integral to the CAP research endeavor because knowledge generated by CAP is unavoidably a part of our study system. Rather than hide this fact, we address how our social-ecological knowledge affects the study system. A central theme of all we have done, and continue to do, recognizes people as integral to the city as an ecosystem. Also, these two fundamental questions share broadly integrative and synthetic missions. We moved these two questions to the Broader Impacts section (Section IV a), and use them to expand the importance and relevance of our broader impacts, making outreach and interaction with the community even more integral to the CAP research endeavor.

iii. *The implications of our findings beyond CAP were not clear; strengthen cross-site plans with the BES LTER program.* Response: Throughout the proposal, we emphasize the implications of our social-ecological research beyond the Phoenix region. These include generic, transferrable lessons about the interactions between people and the modifications of the ecosystems where they live. We have a strong plan for cross-site collaborative research with BES and other urban research networks and groups that includes a diverse array of existing and future comparative social-ecological projects (Section IV b).

iv. *Clarify the importance of CAP's long-term datasets to answering the research questions, and how various models are being used.* Response: Our eight research questions all require a long-term perspective, and we clearly articulate which long-term datasets and models are used to answer them. We use simple abbreviations for each long-term dataset or experiment to map out these connections throughout the proposal (Table 3.1) and detail them in Text Boxes in Section III.

v. *Some reviewers had difficulty locating some long-term datasets through the CAP website, and some datasets that back up our "top 10" papers were difficult to find.* Response: We have simplified the data portal of our website, confirmed that all data are readily available per NSF policies, and highlighted our 10 long-term datasets and experiments on the CAP website (Data Table, Supplemental Documents).

III. Intellectual Merit: Proposed Research - CAP IV Integrated Research Plan

a. Study Area and CAP IV Organization: The CAP study area includes 6400 km^2 of rapidly urbanizing Central Arizona—effectively the entire Phoenix metro area (Fig. 1.1). The region is home to nearly 4.5 million residents, and this population swells by more than 1 million 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 below). 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.

INTERDISCIPLINARY RESEARCH TEAM (IRT) ICONS

= CLIMATE & HEAT
= ADAPTING TO CITY LIFE
= RESIDENTIAL LANDSCAPES & NEIGHBORHOODS
= GOVERNANCE & INSTITUTIONS
= PARKS & RIVERS
= WATER & FLUXES
= URBAN DESIGN
= SCENARIOS & FUTURES

b. Long-Term Datasets and Experiments: The foundation for all CAP research remains our long-term observational datasets and experiments, many of which began with CAP I (Table 3.1; Fig. 3.1). The original intent of 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*. We discuss these re-designs in text-box presentations of our long-term datasets and experiments throughout the Research Question narrative (Section III c).

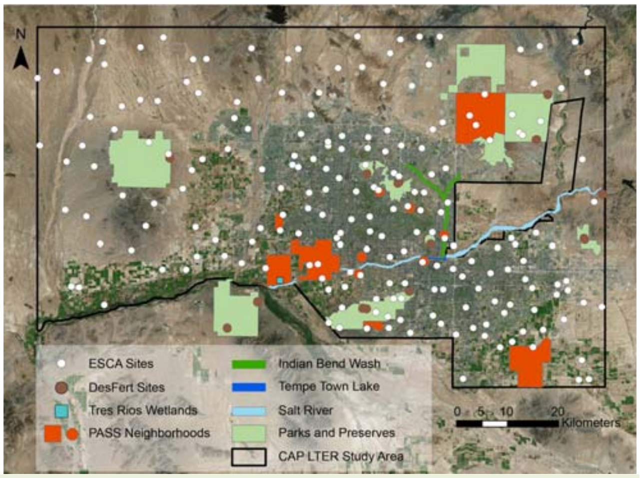


Figure 3.1: CAP study area (shown in red in Fig. 1.1) showing the specific locations of many long-term observational and experimental sites and where much of the CAP IV place-based research is taking place.

Arguably, the single most important metric of urbanization and evolving urban ecosystem structure is LULCC (Text Box 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. The first of these is the Ecological Survey of Central Arizona (ESCA, formerly Survey 200; Text Box 5), 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 PASS (Text Box 4). 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; Text Box 6). Finally, we focus on long-term spatiotemporal variability in key non-human communities through our Faunal Sampling (Fauna; Text Box 3).

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. 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

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

Table 3.1: Long-term datasets and experiments + abbreviations for each that are used throughout the proposal.

Quality program (Drinking Water Quality; Text Box 7). 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; Text Box 9) 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 (Larson and Grimm 2012). Perhaps the most iconic of these is Tempe Town Lake, and since 2005 we have measured water quality in this lake (TTL; Text Box 10*)*. We also track water leaving our desert city. We know from our whole-ecosystem nutrient budgets (e.g.; Metson et al. 2012) 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 at since 2011 (Tres Rios; Text Box 11). 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; Text Box 8). The DesFert experimental design is also a CAP-wide urban-rural gradient based in protected areas, allowing for research beyond the fertilization experiment itself.

c. CAP IV Research Plan: Over the course of two decades, CAP research has made many contributions to urban ecology. Treating cities as complex social-ecological systems requires a holistic, ecology *of* cities perspective. We are now expanding this thinking to an ecology *for* cities approach that enhances urban sustainability through transdisciplinary partnerships with city practitioners (per NSF AC-ERE 2018). We have found that climate, vegetation and water use, biodiversity, and social equity are linked, and that environmental perceptions relate to residential landscape decisions, neighborhood-scale ecological characteristics, and property values. We will further articulate these linkages by investigating variations of climatic conditions across the region, with an emphasis on heat as the dominant stressor (**Research Question 1**), animal adaptation to urban environments (**Research Question 2**), human adaptation to city life through their design and management of residential landscapes and neighborhood UEI (**Research Question 3**), the effects of broader urban governance and institutions on UEI (**Research Question 4**), the management of—and the ES provided by—park, desert preserve, and river UEI (**Research Question 5**), and movement of water and materials into, within, and out of the city (**Research Question 6**). Finally, we have found that the functions and ES provided by UEI are not always as intended, which argues for more iterative and participatory design processes that integrate the perspectives of decision-makers and residents alike. We address this challenge with transdisciplinary questions focused on urban design (**Research Question 7**) and future scenarios (**Research Question 8**). Some of our research questions are largely about ecology *in* cities (Research Questions 1, 2, and 4) while the holistic approaches needed for Research Questions 3, 5, and 6 make these focused on an ecology *of* cities. The future-oriented nature of Research Questions 7 and 8 are clearly about ecology *for* cities. Because of the translational nature of these last two fundamental questions, and their broadly integrative and synthetic power, we are using them to expand our Broader Impacts to include substantial research endeavors (Fig. 3.2 demonstrates how these eight questions link with each other and with our central themes of UEI and ES).

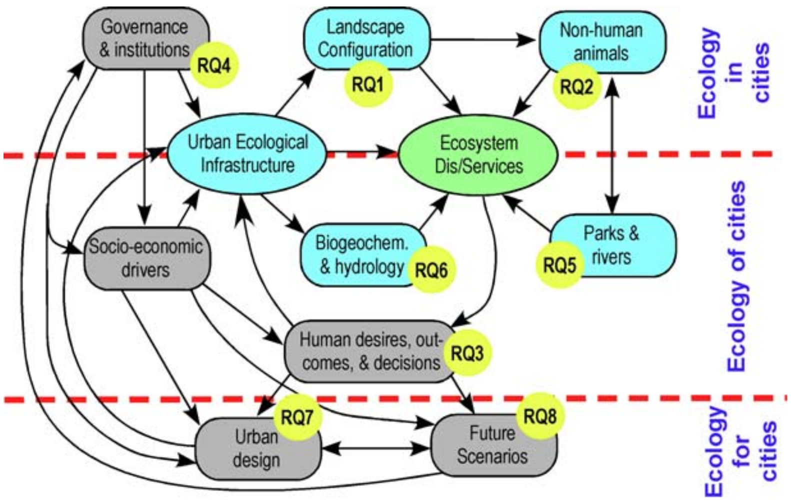


Figure 3.2: Depiction of how key components of the CAP research endeavor are linked to each other, to the eight Research Questions (yellow circles), and to the central themes of CAP IV: Urban Ecological Infrastructure (components shown in blue) and Ecosystem Services (shown in green). The "ecology in cities" Research Questions are at the top of the figure, the "ecology of cities" questions are in the middle, and the "ecology for cities" questions are at the bottom. Note that this is not a conceptual framework; rather, it maps how the eight Research Questions map to each other, and to key elements of Fig. 1.2.

We organize our Research Plan around these eight broad research questions, which progress from largely ecological or social in nature (ecology *in* cities) to being more broadly social-ecological (ecology *of* cities), and ultimately to a larger focus on urban sustainability (ecology *for* cities). For each research question, we use the icons shown on page 12 to identify the IRT—and thus the researchers—that will address the question (see the Project Management Plan for more on the CAP IV leadership structure). We identify the long-term data that justify each question, the long-term data and models that we will use to answer each question, how each question addresses the seven LTER core areas (Table 3.2), and connections to other research questions (Fig. 3.2). Under each question, myriad hypotheses may be tested and detailed analyses involving long-term data may be conducted. However, we use research questions rather than hypotheses for consistency and to highlight relationships among the questions. Finally, we also explicitly map each question to our central conceptual framework (Fig. 1.2) using miniature versions of the framework itself.

Research Question 1 (RQ1): In hot desert cities such as Phoenix, heat is a major driver of many social-ecological phenomena. Organisms, including people, respond to thermal environments at a variety of spatiotemporal scales. Human responses include decisions about how to design and manage UEI, especially vegetation, how to mitigate heat as well as decisions about where to live, how to cool one's home, or where to find shade when walking in the summer. There is a large, mesoscale urbanization effect on climate in Phoenix, as demonstrated by decades of observational and modeling research (Balling and Brazel 1987; Brazel et al. 2007; Georgescu et al. 2011; Chow et al. 2012; Georgescu et al. 2014; Grossman-Clarke et al. 2014). Urbanization has been the dominant driver of regional climate change over the past several decades and will continue to drive change through mid-century and beyond as the region grows and expands. The regional temperature effect is among the largest observed or modeled anywhere in the world and this has provided us with an opportunity to study the causes and impacts of temperature variability across time and space. Additionally, high spatiotemporal variability in precipitation characterizes Phoenix and many dry regions. This variability provides opportunities to examine how social-ecological systems cope with the stresses associated with having too little water on a regular basis or, at times, far too much.

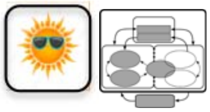
Urban infrastructure, and UEI in particular, influences a wide suite of climatic variables—

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

Table 3.2. Research Questions from the Section III.c narrative, lead Interdisciplinary Research Team (IRT) for each, and how each relates to the seven LTER Core Areas.

temperature, rainfall, evaporation, short and long wave radiation, humidity, and wind speed—at smaller, ecologically relevant scales (meters to kilometers; Georgescu et al. 2012; Middel et al. 2014; Sailor 2014; Lenzholzer 2015; Vanos et al. 2016). As in many other cities, spatiotemporal variability at this microclimatic scale can dwarf the already large regional effect. Our knowledge of the physical drivers of microclimate variability continues to grow, demonstrating a strong connection to parcel-level decisions. Microclimate variability imposes significant consequences on the health, well-being, and productivity of urban organisms, including humans, in ways we are only beginning to understand. However, cities across the world, including in Phoenix, are implementing intentional UEI modifications to minimize adverse effects of climatic hazard exposure, and these plans present a range of mostly unknown consequences for the inhabitants of urban ecosystems. To address these myriad challenges, we ask **Research Question 1**: *How do current and future configurations of UEI influence socially and ecologically relevant climatic variables, at what scales are (dis)services realized, and how are these (dis)services impacted by external presses and pulses?* (IRT lead and mapping to the conceptual framework are identified to the right)

RQ1 IRT Lead & Framework Mapping



RQ1 Approach: To answer this question, we will continue to build knowledge of the urban climate system through observations and modeling, especially at scales and locations relevant for humans. Our expanding work on small-scale climatic variability is providing both greater knowledge of the physical dynamics of the urban climate and useful information to decision-makers. We continue to concentrate our efforts on environmental heat as a major variable of concern in the region for people and other organisms. In CAP IV, we expanded our environmental heat research by placing new emphasis on the entirety of the thermal environment rather than focusing on only air temperature. We are using observations and modeling of short- and long-wave radiation, humidity, and wind conditions along with continued measuring and modeling of air temperature. This new emphasis on the entire thermal environment is important because air temperature alone represents only a portion of the energy balance that determines heat stress for urban organisms. We are systematically collecting microclimate data at a suite of locations

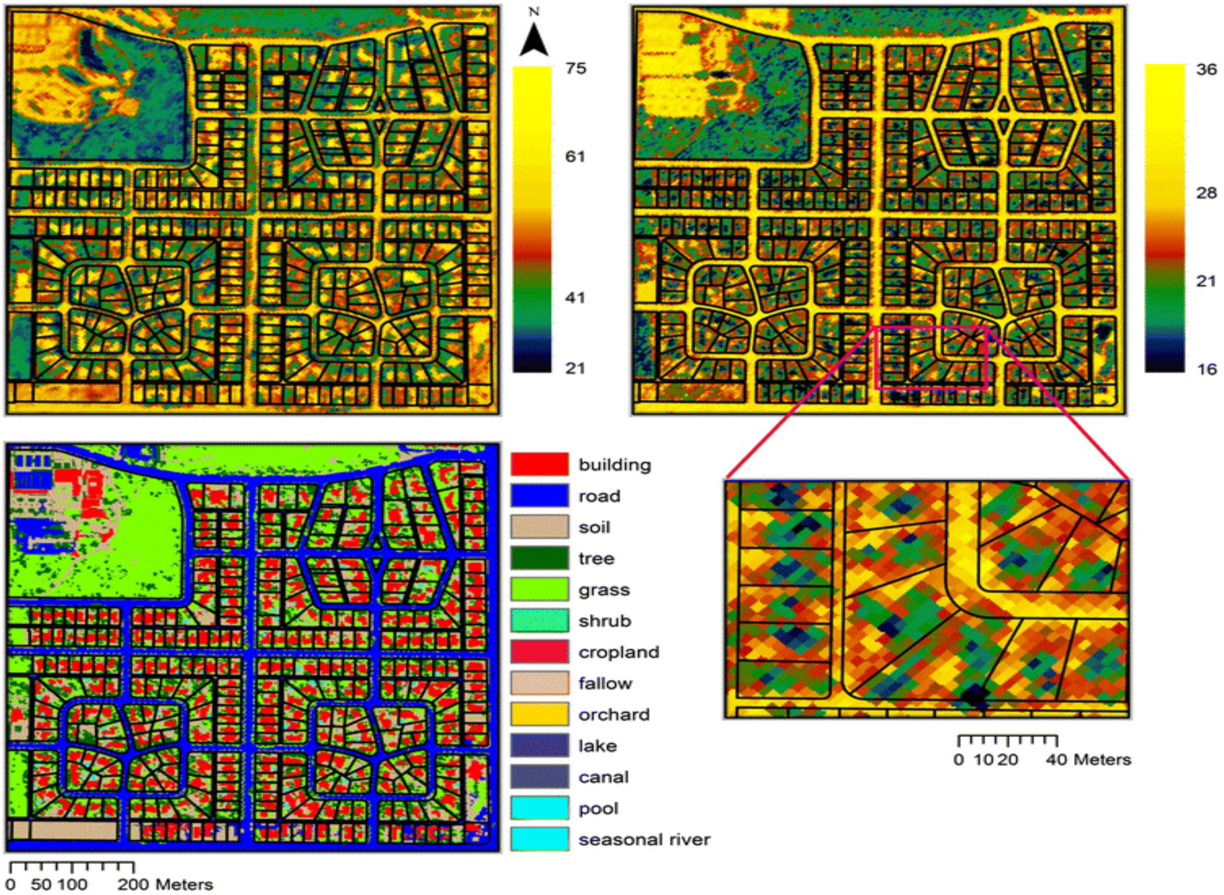


Figure 3.3: Representative overlay of land cover data, parcel boundaries, and MASTER land surface temperature (LST) data for a well-vegetated neighborhood. Day and night LST (°C) and parcel boundaries (top panels), land cover classifications and parcel boundaries from the long-term LULCC data(lower left), and a detailed subset of the nighttime LST and parcel delineations (lower right).

across the region, in collaboration with city planners, and integrating these with remotely sensed imagery and LULCC data (Text Box 2; Fig. 3.3). We are also refining a protocol for assessing microclimate that will be used to evaluate the impact of long-term urban change on thermal variables. Modeling work using the Weather Research and Forecasting Model (WRF), ENVI-MET, RayMan, and new software that we are developing will enable us to explore the consequences of alternative and future urban configurations. This work is being done in close coordination with Research Question 8. We are particularly interested in green UEI, because it is the subject of ambitious public policy goals throughout the region and in many other cities (e.g., doubling the tree canopy cover in Phoenix by 2030). We are also continuing our long tradition of social-ecological research related to heat, integrating multiple long-term datasets to evaluate linkages within and between ecological and social systems. This includes using the PASS data (Text Box 4) to understand household risk perceptions, experiences, and mitigative/adaptive behaviors related to heat, and observations of behaviors, by humans and other organisms, coincident with *in situ* meteorological monitoring. We are concurrently exploring heat as an acute stressor, with immediate consequences for health and behavioral choices, and as a chronic stressor that has more indirect causal pathways. We are also continuing an emerging line of research focused on comparing regional- to global-scale influences, versus localized and microscale impacts, on climatic conditions in the Phoenix region (*sensu* Georgescu et al. 2014). Finally, the Climate & Heat IRT will support the rest of CAP by producing annual climatological assessments of the Phoenix region, modeled after the U.S. National Climate Assessment.

Text Box 2: Long-Term Land Use/Land Cover Change Data

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 NAIP (National Agricultural Imagery Program) data that employed an object-based imagery assessment method, coupled with cadastral data, to generate 12 land classes (Fig. 2.1; X. Li et al. 2014); 2) a 30-m resolution land cover classification based on 2010 Landsat TM data that employed a similar approach to generate 21 land classes from the percentage of land cover per parcel and; 3) 30m resolution land-cover classifications for 1985, 1990, 1995, 2000, and 2005 based on Landsat ETM data that employed a systematic land classification consistent with the 2010 product but that has 9 land-cover classes because of a lack of cadastral ancillary data. Thus, our 1m resolution LULCC data inform our 30m resolution time-series data. We are continuing this work in CAP IV, including completing the 2015 1m land-cover classification and hierarchically integrating our LULCC information such that the 1m land-cover classes may be aggregated to 30m and the 30m may be aggregated to 250m. In addition, we are developing a series of specific data products, including: 1) 1-m resolution land-cover change from 2010 to 2015, and to 2020 when imagery is available; 2) 1m resolution "open" or "vacant" land cover for 2010 and 2015; and 3) alignment of the 1m resolution coverage to address CAP IV research questions (Fan et al. 2015; X. Li et al. 2016; Wentz et al. in review).

Research Question 2 (RQ2): Non-human organisms—an often-charismatic part of UEI—must respond to a range of potential stressors associated with city life (e.g, urban heat, pollution; Kight and Swaddle 2011). However, people also intentionally and unintentionally provide an array of resources to urban animals (e.g. food/water subsidies; Oro et al. 2013; Bateman et al. 2015). Thus, anthropogenic modifications to the biotic and abiotic environment can be disruptive or beneficial. Surprisingly little work in urban ecology has considered the breadth and depth of these effects across a range of organisms or of fitness-determining life-history traits within particular taxa (Alberti et al. 2017a). These responses need not all be adaptive; they may be rapid, plastic, or non-heritable adjustments to phenotype that allow organisms to cope with or exploit novel city conditions (Sol et al. 2013). A recent meta-analysis argued, in fact, that the dominant response by organisms to anthropogenic environmental change is acclimation (Hendry et al. 2008), but as with many large-scale analyses, data gaps remain (Alberti et al. 2017b). To that end, we ask **Research Question 2**: *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?*

Datasets on urban animal ecology tend to be from relatively short studies (2–3 years) and restricted mostly to long-lived organisms, all of which biases analysis towards uncovering plastic responses as opposed to putative adaptive ones (Sol et al. 2013). Our long-term faunal observations (Text Box 3) provide taxonomically broad, spatially explicit datasets that we will continue to build to test the balance of positive vs. negative impacts of particular anthropogenic modifications (e.g., LULCC, water availability, food provisioning) and the speed and intensity with which they impact organisms with different ecologies and life histories. Long-term data are essential to answer Research Question 2 because short-term fluctuations in resources may mask the effects of anthropogenic modifications or provide misleading findings. We predict that urban pressures will have clade-specific effects due to organismal variation in: 1) intrinsic factors, including degree of vagility (e.g., dispersal distances) and generation time (Fig. 3.4); and 2) the pace of urban development. We further expect that organisms inhabiting portions of CAP that are undergoing rapid LULCC will respond more strongly (either positively or negatively) than those in more stable areas. Among these rapid changes, we highlight the potentially broad ramifications of anthropogenic resource subsidies. Urban ecosystems constitute a type of natural experiment, with

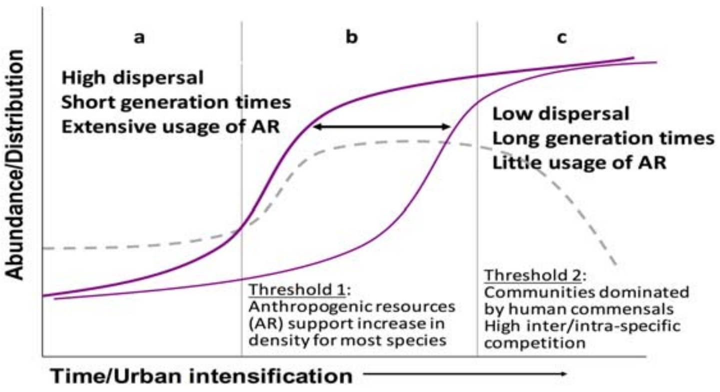


Figure 3.4: Hypothesized community effects of variation in speed at which different species adapt to city life (from Shochat et al. 2010). Long-term data allow for exploration of delays in responses to altered resources by native and exotic species (solid lines) as a function of intrinsic factors such as vagility, generation time, and exploitation of anthropogenic resources (AR). At high levels of urbanization, native specialists decline (dashed line).

humans supplementing food and water resources (Goddard et al. 2013, Oro et al. 2013, Bateman et al. 2015). We predict that species that exploit food and water subsidies in cities will benefit and increase in local abundance and distribution in direct association with recent changes in these resources. We have found decadal declines in avian abundance and diversity broadly across CAP, with the strongest declines in species that do not typically exploit anthropogenic resources (Banville et al. 2017; Warren et al. in review). Predictable hotspots of UEI resource inputs, such as bird feeders, fruiting garden plants, or "accidental wetlands," may become loci for heightened human-animal interactions, with either positive feedbacks in the presence of preferred species (Dallimer et al. 2012) or negative feedbacks if species diversity is reduced or pests thrive (Pauw and Louw 2012; Galbraith et al. 2015). Thus, we expect that there are clade-specific effects of species abundances on the attitudes of residents about their neighborhoods and the environment. Higher perceived levels of biodiversity are associated with higher environmental satisfaction among residents (Dallimer et al. 2012, Lerman and Warren 2011). Analyses of our long-term PASS (Text Box 4) and Fauna data have shown this correlation to be remarkably stable over time, despite species losses (Fig. 3.5; Warren et al. in review.). But species are not equally preferred (Cox and Gaston 2015), and people are not always accurate in their perceptions of actual biodiversity (Fuller et al. 2007, Shwartz et al. 2014). Our research is now focused on examining how attitudes in urban systems (e.g., environmental satisfaction at the neighborhood level, positive views of the desert environment) are influenced by experiences with local wildlife, both positive and negative. This work builds on previous analyses of our long-term bird, plant, and arthropod data (Ripplinger et al. 2016; Andrade et al. 2017; Banville et al. 2017; Warren et al. in review) and will produce new results on the effects of stressors and human-provided resources. We are also complementing our long-term faunal data with mechanistic, single-species studies across multiple taxa (per Trubl et al. 2012; Giraudeau et al. 2014; Davies et al. 2015; Hutton and McGraw in review), including a new large mammal initiative.

Text Box 3: 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 (Lerman and Warren 2011). We will continue to quantify species abundance/distribution for birds (Banville et al. 2017), ground-dwelling arthropods (McIntyre et al. 2001; Shochat et al. 2004; Bang and Faeth 2011), and riparian herpetofauna but have redesigned the sampling to align more closely with the ESCA, PASS, and DesFert long-term datasets and to our question-driven research. In CAP III, bird censuses included biannual sampling at 63 locations throughout the region and in the 44 original PASS neighborhoods in the year of, and the year following, the survey. Because we have re-designed PASS, we refocused our residential bird sampling on these 12 PASS neighborhoods. We consolidated many of our desert bird and arthropod sampling locations to the DesFert sites, to other desert parks/preserves where we are pursuing question-driven research, and to the Salt River—where we are also sampling herpetofauna (Bateman et al. 2015). These changes have enhanced synergies among our long-term data collection efforts and our question-driven research.

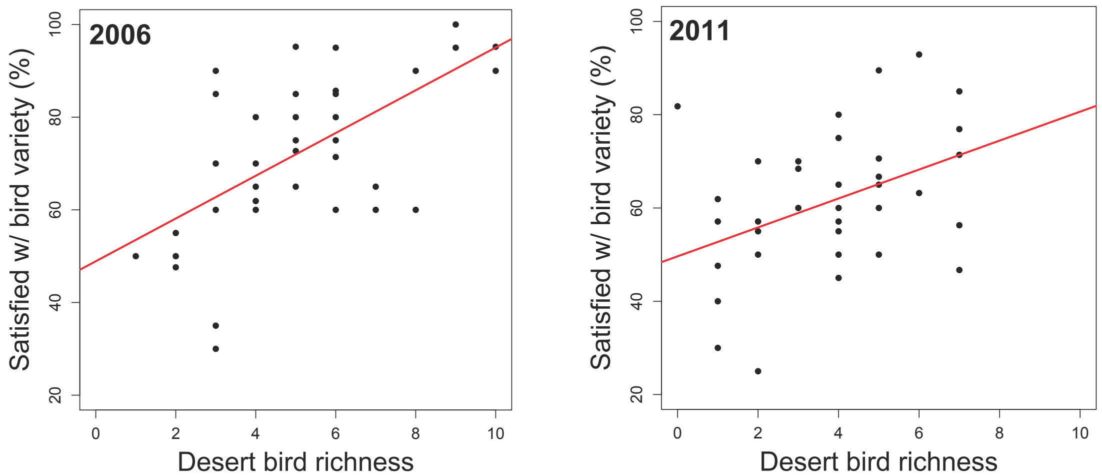


Figure 3.5: Relationship between bird species richness and resident satisfaction, by neighborhood, from PASS. Neighborhood satisfaction with local bird communities was positively and significantly correlated with actual species richness of desert birds, although the correlation was weaker in 2011 than in 2006 (Warren et al. in review)

Text Box 4: Long-Term Phoenix Area Social Survey Data

The PASS surveyed 44 discrete neighborhoods in 2006 and 2011. In this configuration, PASS quantified the social and spatial heterogeneity of a host of variables, including heat stress and vulnerability (Harlan et al. 2012), water-risk perceptions and consumption rates (Larson et al. 2011a,b; 2013a), and landscape preferences and practices (Larson et al. 2009a; 2010; 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 other CAP IV research. This new PASS surveyed 12 neighborhoods (Fig. 3.1) with a minimum of 65 respondents per neighborhood. Nine of these 12 PASS neighborhoods were also surveyed 2006 and 2011. This new design, which will repeat in 2021, allows for multilevel modeling to test for neighborhood effects (Sampson et al. 2002; Sampson 2003) and enables more integrated social-ecological analysis of focal areas, including those that have always been CAP research sites (e.g., the Salt River, Tempe Town Lake, Indian Bend Wash, and urban mountain parks and preserves). This approach capitalizes on existing PASS data to delve more deeply into our CAP IV research questions. PASS will continue to capture constructs and variables that have long been central to CAP: LULCC, and UEI management choices coupled with expressed and observed ES (Larson et al. 2009a; 2016); heat stress and vulnerability along with mitigation and adaption strategies (Jia et al. 2015); as well as risks, perceptions, and environmental satisfaction related to various biophysical factors (Larson et al. 2009b; Lerman and Warren 2011). Thus, LULCC, environmental risks, and implications for urban ecology, social vulnerability, and well-being remain central to our PASS research.

RQ2 Approach: We are using the long-term Fauna data for birds and arthropods, newer data on herpetofauna, a recently-started mammal sampling effort, and LULCC data to address large-scale spatiotemporal changes in species abundance and distribution. Data relevant to understanding these changes include measures of disturbance (e.g., LULCC; Luck and Wu 2002, Baker et al. 2004), resources (e.g. bird feeders, water; Lerman and Warren 2011), and factors predicted to mediate the effects of such anthropogenic activities (e.g., temperature, plant phenology; Neil et al. 2010, Buyantuyev and Wu 2012). We have recently initiated new investigations into: 1) mammals that have known interactions with humans (e.g., raccoons, skunks, coyotes, bobcats) using camera traps in urban parks as part of the DesFert experiment (Text Box 8) and in nearby PASS neighborhoods; 2) the effects of nighttime light exposure on birds (Hutton and McGraw in review) and; 3) the urban and peri-urban soundscape. We classify species according to their intrinsic characteristics, based on published literature and ongoing species-specific studies (Fig. 3.4). These categories are being included in statistical models of abundance and diversity, following methods from Banville et al. (2017), as well as other relevant time-series analyses (Ripplinger et al. 2016; Andrade et al. 2017). We use these findings as a basis for species-specific studies on particular animal communities (arthropods, birds, herpetofauna, mammals) to address individual-level responses to environmental stressors.

For analyses of anthropogenic resource subsidies, we are using long-term Stormwater (Text Box 9), TTL (Text Box 10), and Tres Rios (Text Box 11) data and our PASS and ESCA data (Text Box 5; Lepczyk et al. 2012) to map changes in the type and composition of organismal communities onto these shifts in the presence and density of urban water and food subsidies. To assess risk perceptions and attitudes about nearby wildlife, we added key questions to the 2016/17 PASS, along with questions about the impact of homeowner management of UEI (e.g., land cover and vegetation choices, food and water provisioning) on animal abundances.

Text Box 5: Long-term Ecological Survey of Central Arizona Data

With ESCA, we have documented environmental heterogeneity at 204 re-visit sampling sites every five years since 2000. We have used these data to quantify spatial variation in soil black carbon (Hamilton and Hartnett 2013), soil microbial communities (Cousins et al. 2003; Rainey et al. 2005), biogeochemistry (Hope et al. 2005; Oleson et al. 2006; Zhu et al. 2006; Zhuo et al. 2012), and various flora (Hope et al. 2003; 2006; Stuart et al. 2006; Dugan et al. 2007; Walker et al. 2009) and fauna (Bang and Faeth 2011). We have also developed innovative statistical approaches to assess biophysical and social controls on spatial patterns of biophysical variables (Kaye et al. 2008; Majumdar and Gries 2010; Majumdar et al. 2008; 2010; 2011).

In CAP IV, we will more closely integrate the 2021 ESCA survey with our other long-term sampling efforts and question-based research. We will use ESCA to enhance this research synchrony by redistributing a subset of the previous 204 sites to align them with other long-term data collection efforts and with the place-based focal areas of CAP IV. We will: 1) consolidate some desert sites into regional desert parks that coincide with the DesFert experiment; 2) add new sampling locations in the Indian Bend Wash watershed to support our stormwater research; 3) add new sites in and near the Salt River to support our place-based research there and; 4) consolidate some urban sites into the PASS neighborhoods such that at least five parcels will be surveyed in each neighborhood. Both PASS and ESCA will be sampled in the same year (2021). This re-design will retain roughly half of the original 204 sites, maintaining the long-term integrity of the dataset.

Research Question 3 (RQ3): Residential landscapes are a dominant form of UEI and provide many ES to residents (Fig. 2.2; Cook et al. 2012). Arguably, the daily decisions that people make about their yards and gardens have a stronger cumulative impact on the structure and function of urban ecosystems than those made at city hall. Our research has pioneered theory on the social-ecological drivers of residential plant biodiversity (Kinzig et al. 2005; Walker et al. 2009; Ripplinger et al. 2017), microclimate and heat stress (Harlan et al. 2006; Chow et al. 2012; Middel et al. 2014; Hall et al. 2016; X. Li et al. 2016), soil properties and nutrient cycling (Kaye et al. 2008; Hall et al. 2009; Davies and Hall 2010; Heavenrich and Hall 2016), and water consumption (Wentz and Gober 2007; Klaiber et al. 2014). We have also explored the multifaceted factors that drive homeowner landscape preferences (e.g. Larsen and Harlan 2006; Larson et al. 2009a; Klaiber et al. 2017) and how fine-scale LULCC affects "human-scale" climate (Research Question 1; X. Li et al. 2016). Current research is also addressing the effect of local-scale human decisions on distributions of birds and other wildlife (Research Question 2). We are pursuing an integrated understanding of how people respond to local UEI, wildlife, and other environmental conditions of their neighborhoods by asking **Research Question 3**: *How do the environmental and socio-economic settings of residential landscapes affect UEI services and disservices, environmental risks and perceptions,* *management decisions, and tradeoffs at the household and neighborhood scales? Moreover, how do these factors vary in the long term across space?*

In this research, we are testing theory related to ES tradeoffs (Raudsepp-Hearne et al. 2010) using the social-ecological conceptual model of Cook et al. (2012) by co-developing and integrating long-term monitoring of human management drivers and outcomes (PASS), associated ecological patterns (ESCA, Fauna), and spatial change (LULCC) in residential landscapes. By working across known social-ecological gradients (e.g., income, land use, vegetative cover), we will learn how and why people make decisions about their yards and neighborhoods, and how alternative futures (Research Question 8) related to residential UEI will affect the provisioning of ES. We predict that land cover and perceptions of neighborhood UEI will correlate to ecosystem properties and to perceived and actual tradeoffs in ES at multiple scales. We are also quantifying changes in residential land cover and management as well as ecological outcomes, such as bird and arthropod diversity (Research Question 2; Lerman and Warren 2011). Our research on residential landscapes is central to CAP research, as it relates closely to wildlife adaptation and movement across the city (Research Question 5), to climate and heat (Research Question 1), and to the institutional drivers of LULCC and yard management decisions (Research Question 4).

RQ3 Approach: We continue to use the Cook et al. (2012) social-ecological framework for residential landscapes (Fig. 2.2) to guide our Research Question 3 research. We are assessing patterns of residential landscape change using our LULCC data and parcel-scale assessments of green UEI from ESCA. We are using PASS data to assess decisions about, and outcomes of, residential UEI design and management, including homeowner attitudes about yard/ neighborhood features, local wildlife, and various types of UEI (e.g., for wildlife, heat, or stormwater mitigation). We predict that long-term changes in residential landscape cover will continue to be towards desert-like yards with less turf area, and that predictable social forces that occur across spatial, temporal, and institutional scales will drive residential landscape change. The PASS data will also reveal homeowner perceptions about ES and risks, such as stormwater mitigation and flooding. To increase social-ecological integration, we will co-locate new ESCA plots in the parcels of PASS survey respondents, and both surveys will take place in the same year (2021). Additionally, we will gather local microclimate (Research Question 1) and biodiversity (Research Question 2) data on a recurring basis from the yards of participating homeowners.

Research Question 4 (RQ4): Broader and larger-scale decisions are strong drivers of urban ecosystem structure and function as well. Governance by elected officials, planners, designers, and managers affects UEI in numerous ways, and these effects are manifest through social institutions (defined as the rules, norms, and shared strategies that govern human behavior; Ostrom 2005). They both inform and constrain decision making in social-ecological systems (Anderies 2015). Characteristics of a particular social-ecological system, such as preferences and resources (including tax base, wealth, or social capital; Ostrom and Ostrom 1999), the nature of the social networks (Janssen et al. 2006), and political leadership (Schoon and York 2011) drive decisions about UEI, but systemic perturbations also influence decisions and policy. Climate change (Marsden et al. 2014), extreme weather events (Howlett 2014), and flooding (Driessen et al. 2012; Lubell et al. 2013) are examples of disturbances that drive policy adoption and diffusion. However, uncertainty about disturbances may mediate adaptation (Larsen 2015). While incremental change often dominates policy making (Arentsen et al. 2000), dramatic institutional change may occur after extreme events (Baumgartner et al. 2014) or shifts in coalitions (Ellison 1998). Infrastructure failures may necessitate investment in new technologies (Tompkins and Eakin 2012), including shifts from engineered to UEI features (Pincetl 2010; Research Questions 6 and 7). Infrastructure itself mediates the opportunities for policy change by constraining the decision space (Johnston 2010). Although society often focuses on state and federal policy making, local-level governance often determines UEI design. In short, formal government actors are responsible for only a fraction of decisions about UEI design and management (Wiek and Larson 2012; Larson et al. 2013a,b).

Pulse events and abrupt change are not the only drivers of change in urban ecosystems. Press disturbances, such as climate change and socio-demographic shifts occurring in neighborhoods (Lees 2000), cities (York et al. 2013), and regions (Kahn 2002) also influence local policy and infrastructure design and management. But there are feedbacks among policy, people, and environment (per Fig. 1.2), and changes to urban infrastructure, such as improved UEI, may actually drive demographic changes, such as gentrification (Eckerd 2011). To address these social complexities, we ask **Research Question 4**: *How do long-term socio-economic and institutional dynamics affect and control UEI and associated ecosystem services, and do infrastructure failures and/or concerns for services induce societal actions regarding infrastructure and its governance?*

Text Box 6: 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 (Abbott and Klaiber 2010, 2011; Klaiber et al. 2017). We also link parcel-scale records for housing sales and residential UEI use to metered household water use in select municipalities (Klaiber et al. 2014; Smith and Zhao 2015). 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 socio-economic demographics data so valuable.

RQ4 Approach: Cadenasso and Pickett (2008) demonstrated how increased use of UEI to manage urban stormwater has resulted from environmental change that informed federal regulation and legislation. Building upon this foundation, we are analyzing long-term datasets to document UEI design and management decisions by both governmental and private actors using analytical, qualitative, and quantitative methods for policy change analysis (Sabatier and Weible 2014). We are also using PASS data to evaluate public opinions on various environmental policies and to link these perceptions to changes in socio-economic patterns (Text Box 6), water (Stormwater; TTL; Tres Rios; Drinking Water Quality, Text Box 7), heat (Research Question 1), and LULCC, at an individual level (York and Munroe 2013). We are developing tools and strategies to understand policymaking under uncertainty within social-ecological systems that include mathematical modeling (Anderies 2015), institutional analysis (Ostrom 2005), and participatory modeling (Larsen 2015).

Research Question 5 (RQ5): Government agencies, via the institutions studied in Research Question 4, make most decisions about the design and management of public UEI, including urban and near-urban parks, green spaces, and preserves. However, knowledge of how these areas relate to city inhabitants does not often drive those decisions. Urban and near-urban parks, green spaces, and preserves provide important ES to people, but the demand for and quantification of those ES are poorly understood (Bagstad et al. 2014). Frequently cited benefits include increases in psychological health and quality of life by providing places for physical activity and recreation, mitigating floods and climate extremes, purifying air and water, and enhancing biodiversity and nutrient cycling (Chiesura 2004; Kinzig et al. 2005; Hall et al. 2011; Haase et al. 2014; Ibes 2015). In Arizona, parks created $2.1 billion in economic activity in 2013 (NPRA 2015). Phoenix is a river city, and a major project (Rio Salado 2.0) is being planned that will create a corridor of green, blue, and turquoise UEI along 60 km of the Salt River, with the societal goal of enhancing resident satisfaction and stimulating economic activity (Tyrväinen 1997; Jim and Chen 2006). As urban areas expand worldwide, the need increases to identify sustainable ways to protect and rehabilitate urban rivers and open space parks so they continue to provide ES to people (Bernhardt and Palmer 2007; Everard and Moggridge 2012). We are coordinating our DesFert observations in local and regional open space parks and along the Salt River (Fauna) to identify the social-ecological drivers and outcomes of community and ecosystem processes. We have expanded our previous long-term work quantifying non-human animals and plants (DesFert) to explore the recursive relationship between human actions and the ES provided by open spaces and preserves. With this work, we ask **Research Question 5**: W*hat 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 and pulses, and how do humans respond to these ES with respect to their perceptions and uses of these areas?*

Text Box 7: Long-Term Drinking Water Quality Data

Our long-term data on water quality have improved the understanding of taste and odor occurrence, control, and treatment (Bruce et al. 2002; Hu et al. 2003; Westerhoff et al. 2005), dissolved organic carbon and algal dynamics (Westerhoff and Anning 2000; Nguyen et al 2002; Baker et al. 2006; Westerhoff and Abbaszadegan 2007), and disinfection byproducts (McKnight et al. 2001; Yang et al. 2008; Hanigan et al. 2015). For example, methyl-isoborneol is an algal metabolite occurring mainly in winter (Fig. 3.6) 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 sample drinking water quality monthly at 20 lake, river, urban canal, and finished drinking water sites. 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. We have used these long-term data to document the impacts of severe weather events (Barry et al. 2016) and the inability of quagga mussels to infest the Salt and Verde River watersheds (Sokowloski and Fox 2016). 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.

To answer this question, we are coordinating ongoing long-term observations in local and regional parks (ESCA, DesFert) and along the Salt River (Fauna) to identify social-ecological drivers and outcomes of ecosystem processes in urban and near-urban open space areas. Using a comparative gradient approach (Boone et al. 2012), we are exploring the recursive relationship between human actions and the ES provided by park UEI. Critical to this effort are our long-term datasets on plant communities (Bateman et al. 2015; Stromberg et al. 2015), animals (Banville et al. 2017), soil and water biogeochemistry and primary productivity (Hall et al. 2009; 2011; Sponseller et al. 2012; Marusenko et al. 2015; Davis et al. 2015; Palta et al. 2017), visitor perceptions of and payments for regional parks (Budruk et al. 2015), and unplanned and illicit human uses of rivers and accidental wetlands (Palta et al. 2016; 2017; DeMyers et al. 2017). Additionally, we will use questions in the 2021 PASS to identify how perceived ES or

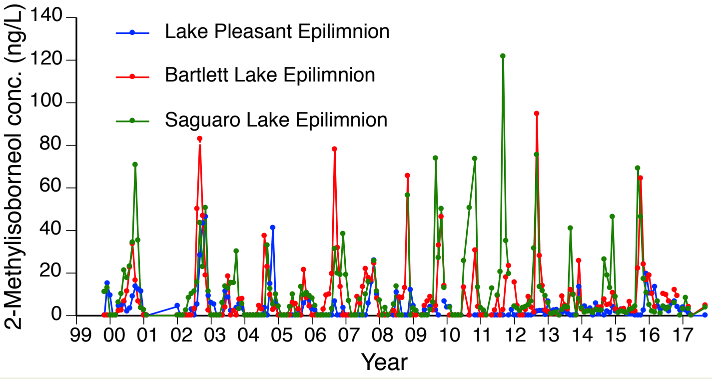


Figure 3.6: Monthly MIB concentrations in surface water of three reservoirs that supply the Phoenix region with water.

disservices of open space UEI vary across a range of socio-economic communities. Humans have long used the Salt River, from the early pre-history of Hohokam canal systems to the modern-day canal system. In post-WWII Phoenix, the river and its diversions have been profoundly underused to spark economic development. Yet, the river is beginning to be recognized for its value as an intermittent desert stream, its constructed "working" wetlands (Tres Rios), the iconic and economically important Tempe Town Lake, and flows from stormwater outfalls that support "accidental" wetlands (Bateman et al. 2015; Palta et al. 2017). These areas can have important, but often unexpected, impacts on ES provisioning (Abbott et al. 2015). Our work along the Salt River enables us to address relatively less-explored questions within these literatures.

RQ 5 Approach: We will continue to quantify nutrient cycling, animal communities, primary production, and vegetation structure, composition, and distribution through our bird surveys and Salt River (Fauna) surveys, ESCA, and with the DesFert experiment. We recently began using new approaches to monitoring ecological variables, including camera traps and acoustic monitoring, and we will incorporate these data into modeling frameworks developed for our system (e.g., the Zhang et al. 2013 ecosystem model). We will use PASS data to identify how proximity to and visitation of parks and rivers affects perceptions of ES across diverse neighborhoods. We will also expand our collaborations with community partners (Section IV e and f) to monitor invasive plant species and animal distributions in desert park and preserve UEI, identifying the role of residential landscapes as potential sources of invasion and wildlife habitat and connecting this work with Research Questions 2 and 3.

Text Box 8: Long-Term Desert Fertilization Experiment Data

Since 2006, the DesFert experiment has simulated how atmospheric enrichment from the city affects nearby native desert ecosystems using a fully factorial nitrogen and phosphorus fertilization design. DesFert doubles as an urban-rural gradient experiment in which we can explore the impacts of the urban environment and nutrient enrichment on biotic and abiotic ecosystem properties in protected desert areas (Fig. 3.7; Hall et al. 2011; Kaye et al. 2011; Sponseller et al. 2012; Ball and Guevara 2015; Davis et al. 2015). Parameters include plant community composition, primary production, soil biogeochemistry, and atmospheric deposition. We are continuing our experimental protocols at all 15 sites, but as this experiment is a labor-intensive, we will discontinue most of our work at several remote sites to free up critical resources. The result will be a balanced experimental design (six outlying desert park sites and six urban desert park sites), that will better integrate the experiment into our question-driven research.

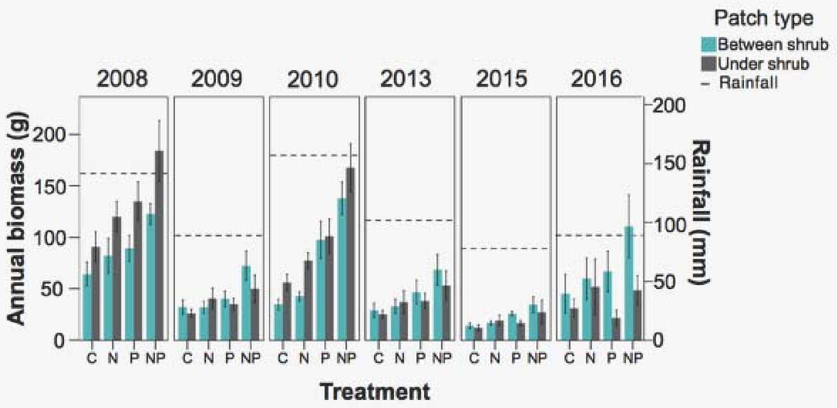


Figure 3.7: Annual biomass, as a proxy for annual net primary production (ANPP), of desert annual plants across the 15 DesFert sites beneath and between shrubs. Patches beneath shrubs support higher rates of annual plant ANPP only when winter rainfall exceeds > 150 mm (i.e. 2008, 2010). In years with lower winter rainfall, ANPP is highest in patches between shrubs. C=control, N=nitrogen addition; P=phosphorus addition; NP=nitrogen + phosphorus addition.

We will continue to quantify ecological characteristics of Salt River and mountain park UEI, including faunal meta-community dynamics, habitat connectivity, biogeochemical connections to nearby urban areas, and human use. In the Salt River, we are documenting the importance of adjacent LULCC types and different hydrologic regimes (perennial versus intermittent flows; Fig. 2.8). Different reaches along the Salt River form a gradient of management intensity, from highly managed and planned (e.g., Tempe Town Lake) to areas forming "accidental" wetlands (Bateman et al. 2015; Palta et al. 2017). We are evaluating how social-ecological processes vary along this gradient and affect ecological characteristics (per Palta et al. 2017). Inputs from groundwater, stormwater, and local precipitation support vegetation in these urban riparian ecosystems, and we are researching how different water sources affect riparian plant and animal communities (Banville et al. 2017). As Phoenix becomes more water-efficient (due to increased demand for water, reduced supply, or both), we will evaluate how stormwater runoff into the Salt River changes by coupling long-term trends in LULCC with our stormwater quality and flow data, in coordination with Research Question 6.

To assess controls on faunal dynamics, we are using the LULCC and Fauna data to address large-scale spatiotemporal changes in species abundance and distribution (birds, herpetofauna, ground-dwelling arthropods, mammals). We are quantifying drivers of species dynamics by ranking multiple regression models using a multi-model inference approach (Burnham and Anderson 2004). Abundances of medium-sized and large carnivores tend to be lower in urbanized areas, although their prey species may be abundant (Lewis et al. 2015). Using remote-sensing techniques, we are estimating carnivore use of corridor habitats along the Salt River, Indian Bend Wash, McDowell Mountain Preserve, and across our urban-rural gradient of mountain parks (DesFert). Finally, we are evaluating how humans perceive and use these various forms of UEI (e.g., water-based areas, urban mountain parks, desert preserves) using PASS data focused on perceptions, self-reported uses of UEI, and place-based sampling of sites in the river and mountain parks (e.g., Palta et al. 2016).

Text Box 9: Long-Term Stormwater Data

Our long-term stormwater quality and hydrology monitoring focuses on urban watersheds with different types of infrastructure (Hale et al. 2015). We focus on how LULCC, type and configuration of storm-water infrastructure, and climate variability control hydrological and biogeochemical retention and stormwater transport (Grimm et al. 2005; E. Larson et al. 2013; Hale et al. 2015). Our study site, Scottsdale's Indian Bend Wash, is a ~500 km^2 catchment that is almost completely urbanized (Fig. 3.1). It follows a gradient of development age from its southern confluence with the Salt River to its northern headwaters in the McDowell Mountains (Roach et al. 2008). Concurrent with this oldest-to-newest development gradient, stormwater infrastructure includes infrastructure types with varying effectiveness at retaining water and nutrients (Fig. 3.8; Hale et al. 2015). We sample chemical constituents of stormwater during all runoff-producing storms. Our southernmost sampler is co-located with a USGS streamflow gauge, and we have added sites further upstream to better compare total watershed output with output from smaller subwatersheds that have different types of stormwater UEI (Hale et al. 2015).

Research Question 6 (RQ6): Understanding the movements and transformations of abiotic constituents is also critical. Both water and air move biogeochemically-active constituents throughout the city. The pathways and movement of water is one of the most highly controlled aspects of urban systems, and yet flooding can be one of the greatest risks. Our four long-term, water-related datasets focus on the infrastructure for water delivery, stormwater management, blue UEI, and wastewater treatment; together, these define the urban template for water and material fluxes. The generation of air pollutants and air movements within and beyond the city also affect biogeochemical processes, and the activities of urban inhabitants profoundly influence soil biogeochemistry. All these factors are subject to presses and pulses of LULCC, climate change, and disturbance. To encompass the influence of UEI, climate variability and change, and disturbance on the fate and transport of materials in urban ecosystems, we ask **Research Question 6**: *How does the design and landscape configuration of UEI interact with presses and pulses to influence urban hydro-biogeochemical patterns and processes over space and time, and how do people respond to these changes?*

The watershed approach is a useful framework to unite biogeochemists and hydrologists in the study of fluxes and flows of water and materials in ecosystems. Managed land configurations typically dominate urban watersheds. In cities, hydrologic flowpaths are altered both intentionally and inadvertently, including water delivery infrastructure, stormwater management infrastructure, and constructed treatment wetlands. Increased watershed connectivity due to storm pipes and street runoff results in large inputs of water, nutrients, and pollutants to recipient systems. Such connectivity can be seen in Phoenix, where much of the domestic water used is delivered, after treatment, to the Tres Ríos treatment wetland and, ultimately, to the Salt River. Cities are sinks for many materials, such as nutrients and water (Metson et al. 2012), and UEI is a key component of urban design that regulates hydro-biogeochemical function (Larson and Grimm 2012; Hale et al. 2015), promotes ES, and ameliorates stormwater impacts (Askarizadeh et al. 2015). For example, stormwater UEI in Indian Bend Wash increases nutrient retention and decreases runoff while providing recreation and aesthetic ES, relative to gray infrastructure (i.e., pipes) or native desert washes and drainages (Roach et al. 2008; E. Larson et al. 2013; Hale et al. 2015). Thus, the composition and configuration of infrastructure, particularly UEI, across the urban landscape greatly influences hydro-biogeochemical processes (Fig. 3.8).

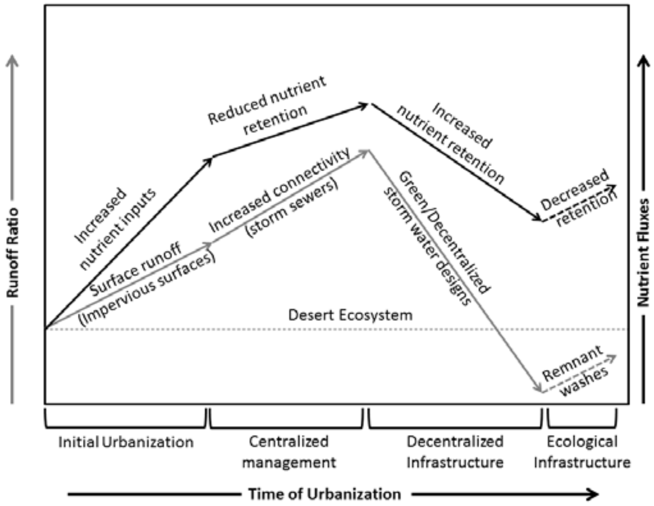


Figure 3.8: Depiction of how different types of stormwater infrastructure in Scottsdale AZ have changed over time, with a parallel move from overly gray infrastructure to more UEI-based infrastructure. Effects on hydrologic connectivity and nutrient retention are also shown (from Hale et al. 2015).

Urban airsheds are areas affected by materials produced in the city, including gases, particles, and aerosols. Many studies have documented impacts of increased atmospheric nitrogen deposition on ecosystems (Lovett 1994; Baron et al. 2000; Pardo et al. 2011; Ladwig et al. 2012), although little of that research has focused on arid lands (Hall et al. 2011; Collins et al. 2014). Spatiotemporal patterns of pollutant generation and properties of the pollutant material interact with land configuration and mesoscale air movement patterns to determine the extent of the urban airshed for any given constituent.

Text Box 10: Long-Term Tempe Town Lake (TTL) Data

Since 2005, we have measured temperature, pH, conductivity, dissolved oxygen, dissolved organic carbon concentrations and quality, and total nitrogen in TTL. 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 all rain events. Storm-event sampling allows us to evaluate the effects of extreme events on aquatic biogeochemistry (Fig. 2.7). 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 and endogenous drivers control biogeochemical processes. For this reason, we recently installed *in situ* datasondes to measure water quality, including optical dissolved organic carbon characteristics, at high temporal resolution. Initially, we have been supplementing the sensor data with twice-weekly samples. We are developing calibrations that relate optical characteristics to bulk organic carbon concentrations and statistical models that will allow us to reduce the number of discrete samples needed over time.

CAP research has focused on the impacts of nitrogen and organic carbon deposition (e.g., the DesFert experiment) which includes long-term deposition measurements (Lohse et al. 2008; Cook et al. in press) and ecosystems impacts (e.g., Kaye et al. 2011; Sponseller et al. 2012). Thus, atmospheric deposition represents a long-term press resulting from transportation infrastructure, with potential impacts on unmanaged desert systems (*sensu* Research Question 5).

Disturbance frequency and magnitude are variable in the desert Southwest (Baker 1977; Grimm et al. 1997; Swetnam and Bettancourt 1998; Shen et al. 2008). This variability is superimposed on an underlying trend of climate change (increased temperature, change in precipitation seasonality; Garfin et al. 2014). Beyond the city proper, we found that desert plant responses to fertilization vary among years depending upon precipitation (Hall et al. 2011). Long-term data are essential to tease out the impacts of internal and external perturbations (per Fig. 1.2) on the fluxes of water and materials within the urban ecosystem. For example, Hale et al. (2015) found that the drivers of, and responses to, disturbance in cities were both social and ecological and may involve technological change (i.e., construction of new infrastructure; Grimm et al. 2017). As our long-term Stormwater database grows, we will continue to link various magnitudes events to both ecohydrological and social responses. We have documented water-quality variation, on both short and long time scales, in the Drinking Water Quality and TTL datasets. We have shown that water leaving the city via river discharge from constructed treatment wetlands tends to be among the cleanest surface water in the region (Tres Rios; Sanchez et al. 2016). To further link the biophysical and social templates in our conceptual framework (Fig. 1.2), we are investigating whether people's enjoyment of urban lakes and wetlands, of desert wildflowers, or their perceptions of their drinking water, vary on time scales that are similar to, or different than, these climatic and disturbance events.

Text Box 11: Long-term Tres Rios Constructed Treatment Wetland Data

We have been conducting research, mostly with student volunteers, at Tres Rios since 2011. This 42 ha "working" wetland (21 ha of vegetated marsh, 21 ha of open water) was built in 2010 to remove nutrients from effluent being discharged into the Salt River. Our regular bimonthly sampling measures marsh plant productivity and nutrient uptake, whole-system and within-marsh water quality, whole-system nutrients, and water budgets. We have also measured greenhouse gas fluxes from this system. Our budgets have shown near-complete uptake of nitrogen by the marsh (Weller et al. 2016), and we have demonstrated, for the first time, plant mediation of surface water hydrology in this wetland (Fig. 2.6; Sanchez et al. 2016; Bois et al. 2017). We continue to host research charrettes with the City of Phoenix Water Services Department to communicate findings to their managers and staff.

RQ6 Approach: Answering this question relies upon the interpretation and continued collection of long-term hydrological and biogeochemical data from green UEI (using our PASS, Stormwater, and DesFert datasets), blue UEI (using our Drinking Water Quality and TTL datasets), and turquoise UEI (using our Tres Rios datasets). In coordination with Research Question 5, we will continue to evaluate the impacts of atmospheric deposition on desert ecosystems through DesFert and of stormwater pulse events on the Salt River wetlands and TTL. For the latter, we have used time-series analyses to link biogeochemical changes with specific events. We also have quantified the spatial extent of contributing areas to the Salt River stormwater outfalls (i.e., pipesheds) and are exploring the impact of different LULCC configurations in each pipeshed on stormwater chemistry. We are taking advantage of the development-age gradient and associated UEI gradient in the Indian Bend Wash (Fig. 3.8; Hale et al. 2015) to permit a more rigorous evaluation of the effects of UEI design and landscape configuration on stormwater hydro-biogeochemical patterns. To perform this evaluation, we are comparing stormwater chemistry of three sites along the Indian Bend Wash: a near-natural, headwater desert wash; a larger subwatershed dominated by retention basins; and the most-downstream site that integrates the first two basins plus areas with pipe and street drainage infrastructure. We will add selective measurements of stable isotopes of water (deuterium and ^{18}O) and nitrate (^{15}N and

^{18}O) in past-preserved samples from Tempe Town Lake and new samples from Indian Bend Wash to identify water and nutrient sources (per Hale et al. 2014).

Our research on ecosystem impacts of presses and pulses as mediated by UEI configuration and design continues to explore impacts on plant productivity (Sponseller et al. 2012), desert soil crusts (Ball & Guevara 2015) and decomposition (Ball et al. in review) in desert parks, and on metabolism in Tempe Town Lake and water supply canals. We recently began measurements of oxygen concentrations in Tempe Town Lake and canals, allowing us to continuously model metabolism in these aquatic ecosystems. We expect that, given the abundant sunlight and high year-round temperature, these ecosystems are frequently autotrophic, but that disturbances (floods, dust storms) will result in transient shifts to heterotrophy. To address temporal variability in human perceptions of drinking water taste and odor and enjoyment of lakes, wetlands, Indian Bend Wash, and desert parks, we will analyze PASS results from nearby neighborhoods and correlate public complaints about water quality to the Drinking Water Quality data. We will conduct “use surveys” immediately following disturbance events and during intervals between disturbances at specific public locations (e.g., Tempe Town Lake, Indian Bend Wash parks, desert parks) in collaboration with Research Question 7. We predict that people will have different experiences of the same disturbance that are a function of the types of UEI they encountered (e.g., Indian Bend Wash vs. Tempe Town Lake).

IV. Broader Impacts

a. Transdisciplinary and translational ecology *for* cities research:

Our last two Research Questions involve us working closely with practitioners, decision-makers, and residents in Phoenix. These fundamental questions are critical to the CAP research endeavor but, because these transdisciplinary activities go beyond the realm of traditional research questions and are synthetic and integrative across all of CAP, we present them in our Broader Impacts. We posit that these transdisciplinary activities considerably enhance the scientific rigor and breadth of our Broader Impacts.

Research Question 7 (RQ7): We are using social-ecological knowledge from CAP to make the region a better place to live through the urban design process. We define design in the broadest possible sense (*sensu* Childers et al. 2015). For example, when a homeowner decides how to manage the UEI in their yard, they are “doing” design. Our focus on urban design addresses knowledge gaps in operationalizing the co-production of UEI projects with practitioners. Co-production differs from collaborative processes in that it emphasizes the contributions of residents in producing and managing UEI ES that impact them (Ostrom 1996; Grove et al. 2016). The co-production of UEI design supports knowledge-to-action processes that enhance social fit (Armitage et al. 2011; Albrechts 2013; Voorberg et al. 2014; Childers et al. 2015). City officials that pay for and manage UEI are increasingly interested in measuring ES benefits, but they often have insufficient resources or staff time to support empirical research. Additionally, a knowledge gap exists in our understanding of how organizations and institutional processes can foster better design and management of UEI to address challenging—or wicked—social-ecological problems (Armitage et al. 2011). In light of these gaps, we are asking **Research Question 7**: *How can governance and institutions support the co-produced design and management of sustainable and resilient UEI projects?*

Co-production design processes—a research and practice approach increasingly used in ecological work (Turner et al. 2016)—will enhance the ES provided by UEI. Co-production links scientists, planners, designers, city residents, and students to collaborate on: 1) design documents; 2) management practices and; 3) monitoring protocols for improved social-ecological outcomes (Childers et al. 2015). It also addresses a key disconnect with UEI in that urban ecologists typically have not been involved with the planning, design, management, and monitoring of UEI projects (Steiner et al. 2013). To address this translational disconnection, Felson & Pickett (2005) proposed the concept of designed experiments*,* or co-produced urban design projects as ecological tests. To answer this question, we are testing and refining the Childers et al. (2015) Urban Design-Ecology Nexus model using designed experiments. These experiments create a societally-relevant feedback loop that integrates CAP data and findings into new UEI projects at the design, construction, and management stages, enhancing both biophysical and social outcomes (Fig. 4.1). Our premise is that research must move from examining current ecological conditions to participating in creating and managing sustainable and resilient UEI (Lawton and Jones 1995; Felson et al. 2013; Steiner et al. 2013; NSF AC-ERE 2018).

***RQ7 Approach*:** Our designed experiments are being co-produced through service-learning design studio courses at ASU. As part of these experiments, we are measuring both biophysical and social outcomes. To document the biophysical outcomes, we use a Before-After–Control-Reference-Impact (BACRI) experimental design similar to Walsh et al. (2015), a research design extension of the Beyond-BACI approach (Underwood 1991). The BACRI design uses multiple, randomly selected control and reference locations and at least one case location to isolate design impacts. To document the social outcomes, we use IRB-approved survey, interview, and focus group instruments to measure changes in adaptive capacity and social learning as a result of the designed experiment process, and as a mechanism to manage CAP research adaptively. We use three criteria to select our designed experiment projects: 1) projects where organizations are willing to collaborate; 2) projects focused on UEI and; 3) projects that leverage CAP datasets and research sites. We select control locations from existing PASS neighborhoods or sites where ESCA, Fauna, or DesFert data are being collected. Finally, to integrate these new sites into existing CAP efforts, we are using the LULCC data to provide a spatial context to the design process. We have launched three UEI designed experiments: 1) a low-impact development master plan for the Maricopa County Flood Control District headquarters; 2) Cooler Neighborhoods Phoenix; and 3) the regional Rio Salado 2.0 project (Fig. 4.1). Notably, the Rio Salado 2.0 project includes Tempe Town Lake, Indian Bend Wash, the Tres Rios treatment wetlands, and more than 60 km of the Salt River—all locations of much CAP research. We collect data on the project and reference locations before and after construction, targeting both the design process and the outcomes. Our analysis of the design process is being coordinated with efforts in Research Question 6 to compare past UEI design processes with the Urban Design-Ecology Nexus model (Childers et al. 2015). All three design experiments have partnered with other translational research efforts (Section IV c.). We are also applying these evidence-based UEI design results to inform our scenario development (Research Question 8).

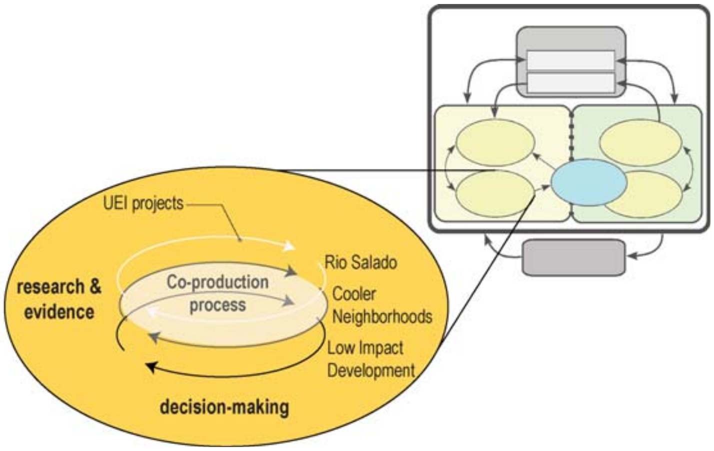


Figure 4.1: How the design co-production process fits into the central conceptual framework; ongoing design experiments and projects are shown.

Research Question 8 (RQ8): Our new focus on urban design is future-oriented, aimed at making Phoenix, and cities in general, more sustainable and resilient habitats for humans (*sensu* NSF AC-ERE 2018). Urban ecology brings useful knowledge and perspectives to the future development of cities, but this requires transdisciplinary approaches to address city planning and management needs. In CAP III, we developed participatory scenarios for the region. These scenarios allowed researchers and policy makers to explore a broad range of strategies, transition pathways, and desirable and plausible future states (Iwaniec and Wiek 2014; Iwaniec et al. 2014). In CAP IV, we ask: *What are the ES, tradeoffs, 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?*

We emphasize co-development and synthesis of evidence-based knowledge to explore the impact of potential decisions and human activities on ecosystem change, to reconcile tradeoffs among society's development goals, and to examine their implications for resilience and sustainability. Our objective is to co-develop diverse scenarios of urban futures that guide planning and policy making toward more resilient and sustainable pathways, acknowledging that resilience pathways differ from sustainability pathways and that the two may be incompatible (Redman 2014). Our scenario development explores potential responses, tradeoffs, and uncertainties associated with resilience to various presses and pulses, both internal and external (per Fig. 1.2). Resilience scenarios will lead to strategies to build capacity for the region to adapt to a "new normal:" extreme events, unpredictable changes, and uncertain futures. Scenarios also are a mechanism for practitioners and researchers to explore desirable futures that represent creative departures from the *status quo*. Transformative scenarios are those that are more likely to lead to more sustainable and livable cities.

RQ8 Approach: We are co-developing future scenario workshops, continuing our transdisciplinary research based on long-term data and partnerships with city, county, state, federal, and tribal decision-makers, diverse nonprofit leaders representing social and environmental issues, and academic researchers. This research includes participatory stakeholder mapping to ensure inclusive and representative involvement (Lang et al. 2012; Weaver et al. 2014; Kishita et al. 2016; Muñoz-Erickson et al. 2016). We explore alternative futures using three distinct methodological approaches: Adaptive futures developed in response to extreme events (e.g., drought, flood, heat); Strategic futures that project forward using existing municipal goals and targets; and Transformative futures that are backcast from radically transformed visions of sustainability developed by workshop participants. This project integrates plausibility-based futures (what is most likely to happen) with desirability-based futures (what we would like to happen). Predictive and exploratory models remain critical to this scenarios work, and we are continuing to use our spatially articulate ecosystem modeling (Zhang et al. 2013), WRF modeling of regional heat and precipitation (Georgescu et al. 2011; Georgescu 2015), microscale climate modeling (Middel et al. 2014), and the Decision Center for a Desert City's (DCDC) participatory WaterSim model of water availability and use (Sampson et al. 2016; Section IV c). We use *all* of CAP's long-term datasets plus these models to simulate press and pulse disturbances in order to evaluate a range of scenarios under different regimes of uncertainty and variability. Through synthesis of our social-cultural-economic and biophysical datasets and models, we are exploring scenarios that provide a balance of ES to enhance human well-being and ecological integrity while avoiding undesirable developments. In the first set of CAP IV workshops, we are co-developing scenarios at the neighborhood and village scale in South Phoenix, a historically disadvantaged area of Phoenix. Using the PASS data, we are identifying issues for South Phoenix residents to explore in our scenarios. This work will integrate and build upon our previous regional scenarios and upon other research at ASU and in Phoenix (Section IV c) and with LTER network-wide scenario activities—including new scenarios work at the BES LTER.

b. Related Research Projects: CAP has always had a close and collaborative relationship with the ASU-based 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 grant (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. 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; Project Management Plan and Facilities, Equipment, and Other Resources). The UREx SRN includes nine cities, 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), and the Infrastructure Management for Extreme Events Program (Lead PI: M. Chester)—all are NSF-funded.

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 we are now strengthening and formalizing this valuable connection. One example is the addition of future scenarios research at BES, in collaboration with our Scenarios & Futures IRT. Our Urban Design IRT is working closely with BES colleagues who have expertise with the ecology-design nexus (e.g., Pickett et al. 2013; Grove et al. 2016). We are also comparing the results of the PASS with the Baltimore Phone Survey, with special emphasis on cultural ES. 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. We will initiate 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. 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.

c. Diversity and Inclusion: We continue to strengthen our commitment to diversity and to providing opportunities for women and underrepresented minorities across our research enterprise. Our 20-strong leadership group includes nine women, three LGBT members, and one Hispanic member. Undergraduate research experiences are excellent pipelines into graduate programs, and we actively recruit minority students using this pipeline. We work with ASU's Western Alliance to Expand Student Opportunities (WAESO) program, which provides funding for faculty to recruit underrepresented minority students (undergraduate and graduate) to collaborate with them on research projects. ASU's 100,000+ student body is 48% non-white and more than half of the 7000+ new freshman (Fall 2017) are minority students. Several CAP scientists are based at ASU's West Campus, which is primarily undergraduate, highly diverse (nearly half are minority, first-generation, or non-traditional students), and home to a NSF-funded Research in Undergraduate Institutions (RUI) program. CAP does not control faculty hiring, but our faculty scientists are fully cognizant of the importance of diversity in these hiring decisions. ASU's reputation for inclusion and diversity is also very strong; notably, ASU has more Native American students than any other university in the U.S. Our complete Diversity and Inclusion Plan is included in the Project Management Plan.

d. Education & Outreach Activities (K-12 Schoolyard Program): Ecology Explorers, our K-12 Schoolyard program, connects teachers and students with CAP scientists through schoolyard-friendly urban ecology protocols and learning modules. We host summer professional-development programs to share our research with teachers and help implement these programs throughout the school year. This approach is the most cost-effective way to share our research and to impact classrooms (Bestelmeyer et al. 2015). 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 to develop "citizen science" protocols and to create teaching materials that use CAP data in "Data Nuggets" lessons (Bestelmeyer et al. 2015).

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.

e. Education & Outreach Activities (Citizen Science): We continue several citizen science projects across metro Phoenix while seeking more opportunities with community partners. Our most active project is with the McDowell Sonoran Conservancy (MSC) Field Institute. Citizen scientists collect data that are used to manage Scottsdale's McDowell Sonoran Mountain Preserve. The Institute manages seven arthropod pitfall trapping transects, and we are considering a new DesFert experimental site there. We continue to collaborate with the Central Arizona Conservation Alliance (CAZCA), administered by our long-time community partner, the Desert Botanical Garden (DBG), on a number of environmental initiatives. The CAZCA is a partnership among public, nonprofit, and academic entities (e.g., City of Phoenix Parks and Recreation, The Nature Conservancy, Audubon Arizona, and Maricopa County Parks and Recreation). The DBG has trained citizen botanists to document plant diversity in regional parks, and these volunteer botanists participate in our DesFert sampling. The MSC Field Institute is also interested in working with CAP and our CAZCA partners to develop citizen-science trainings/workshops for other regional parks. Finally, the Climate & Heat IRT continues to collect personal temperature data from urban dwellers using "i-buttons." We are expanding this i-button work to schools that use our Ecology Explorers UHI education module; in both cases these data are being used to address Research Question 1.

f. Education & Outreach Activities (Community Partnerships & Engagement): 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 DCDC researchers and Maricopa County water managers to track changes in residential turf landscaping, and they are working with the City of Goodyear to discern how UEI varies between HOA and non-HOA neighborhoods (Wentz et al. in review). Our Tres Rios constructed treatment wetland work is in collaboration with the City of Phoenix Water Services Department. As noted above, we have strong partnerships with the MSC Field Institute and the CAZCA (Letters of Commitment included). Ecology Explorers partners with schools and school districts in low-income, minority communities and will continue its partnership with Homeward Bound to provide STEM programming at its residential community serving homeless families and those at risk of homelessness.

g. Education & Outreach Activities (REU and other Student Support Programs): We continue our successful REU Program into CAP IV with stipend and research support for three 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 10 undergraduate researchers. This collaboration will continue. 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; we placed two such students with CAP researchers in our Summer 2017 REU Program (our Diversity and Inclusion Plan is part of the Project Management Plan).

CAP IV supports 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. 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. 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.

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blue font denotes papers that acknowledged CAP support

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