# PROJECT SUMMARY


## Overview:

Phase IV of the Central Arizona-Phoenix LTER (CAP) centers around the questions: How do the services provided by dynamic urban ecosystems and their infrastructure 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 will be met through four broad programmatic objectives. CAP IV will: 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 our 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 will be organized around eight interdisciplinary questions and 11 long-term datasets and experiments, and researchers will be organized into eight Interdisciplinary Research Themes.

## 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 will be on urban infrastructure as a critical bridge between the system’s biophysical and human/social components. Infrastructure is thus central in the conceptual framework that will guide all CAP IV activities. Another new theoretical focus will be a nexus of ecology and design to enhance urban sustainability and resilience. This focus, in combination with ongoing CAP scenarios work, will be the "knowledge to action" link between social-ecological research outcomes and city institutions, ultimately making Phoenix a better place to live. CAP IV research will explore 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 :

Ecology Explorers, CAP’s Schoolyard LTER, will continue to connect teachers and students with CAP scientists through urban ecology protocols and learning modules based on CAP research. Ecology Explorers will host summer professional development programs for K-12 teachers and will offer internships for undergraduate students to directly reach low socio-economic status K-12 students. The CAP children’s book, focused on the herpetological research along the Salt River, will be published soon. CAP will expand 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, the Valley Permaculture Alliance, and numerous municipal agencies. The successful CAP REU Program will continue to use ASU’s ESA SEEDS chapter and the ESA SPUR Fellowship Program to recruit underrepresented students, as CAP grows its leadership on, and strong commitment to, diversity and inclusion. CAP will continue to support graduate students with the Grad Grants program, by providing extensive research infrastructure and services, and by direct support from all of the major 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, researchers world-wide, urban practitioners, teachers, and the general public.

# "Design with Nature" Infrastructure in Phoenix: A Framework for Exploring Urban Ecology and Sustainability"

## PROJECT DESCRIPTION

### I. Results from Prior Support

**a. Historical Overview of CAP LTER:** The Central Arizona–Phoenix LTER Program (DEB-1026865, CAP III, 2010–2016, ~$5,960,000 including supplements), one of two urban LTER sites, has been the hub for studies of complex social-ecological systems in the Phoenix Metropolitan Area (PMA) since 1997. Research in CAP I (1997–2004) and CAP II (2004–2010) addressed the central question: *How does the pattern of development of the city alter ecological conditions of the city and its surrounding environment, and how do ecological consequences of these developments feed back to the social system to generate future changes?* From CAP I and II, we learned that land-use legacies have strong effects (e.g., past agriculture increased soil nitrogen and carbon; Zhu et al. 2006; Lewis et al. 2006) and that other social variables help to explain ecological patterns in the PMA (e.g., the "luxury effect," whereby biodiversity is higher in wealthier neighborhoods; Hope et al. 2003; Kinzig et al. 2005; Walker et al. 2009) by analysis of data collected across the broad, heterogeneous spatial extent of the 6400 km$^2$ CAP area. 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; Knowles-Yanez et al. 1999; Keys et al. 2007) and of the development and impact of the urban heat island effect (UHI; Baker et al. 2002; Brazel et al. 2007). From CAP I and CAP II research we concluded that the imprint and legacy of human action on ecosystem pattern and process within and outside the city is pervasive. Yet the mechanisms and even direction of change are not always obvious or as expected. In CAP III (2010–2016), we more explicitly addressed feedbacks between the ecological and social systems as mediated through ecosystem services and we investigated human behavior and outcomes in addition to ecological change, asking: *How do the services provided by evolving urban ecosystems affect human outcomes and behavior, and how does human action (response) alter patterns of ecosystem structure and function and, ultimately, urban sustainability, in a dynamic environment?*

CAP research adopts a long-term perspective to understand how continued urbanization (e.g., population, demographic, land, and infrastructure change) interacts with external forces (e.g., climate change, economic change, human movements) to determine urban social-ecological system structure and function. The central conceptual framework of CAP III (Grimm et al. 2013)—a modified version of the LTER Integrated Science for Society & Environmental framework (Collins et al. 2011)—was based on ecological disturbance theory but with human/social elements as both drivers and responders. Key elements of our framework include: 1) how structure and function interact; 2) how human outcomes are conditioned by the delivery of ecosystem services (i.e., benefits that people derive from ecosystems) or disservices; and 3) how human outcomes in turn affect human decisions and behavior that have implications for ecosystem structure and function, via press and pulse events. Internal presses and pulses that we study include LULCC (e.g., housing development), the UHI, storms and urban flooding, atmospheric deposition of nutrients, pollution of water, air, and soil, and the management and reorganization of urban infrastructure (a key addition to the CAP framework and central question in CAP IV; see Section II). External presses and pulses include climate change (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 philosophy (Grimm et al. 2000; Childers et al. 2015; McPhearson et al. in press); that is, to document how urban stressors alter ecological phenomena, to understand the city as a complex, adaptive, social-ecological system, and to bring our knowledge to action in the transition of the PMA, and other cities, to a more sustainable trajectory. The framework, themes, and datasets of CAP I–III form the basis for our CAP IV research.

**b. CAP III Significant Findings and 10 Most Significant Publications:** CAP research has yielded key insights (in *italics*) that synthesize our findings across the CAP III research themes and our long-term datasets and lead to the new questions in Section II. Of the 258 publications originating from CAP III research (Fig. 1.1), we have selected 10 that reflect broad subject matter and the diversity of journals in which we publish (these citations are in **bold** font, and we show papers that acknowledged CAP support in blue). In this section, we also highlight recent and ongoing analyses of our long-term datasets. These analyses directly respond to the midterm site-review recommendations that we better articulate and promote the use of long-term data; many are ongoing and, as yet, unpublished.

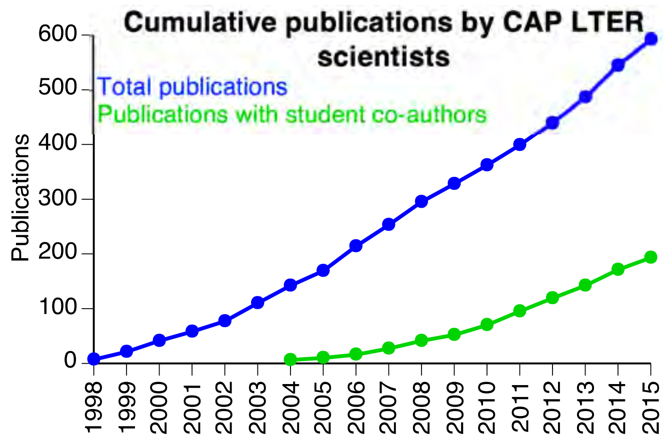



**Figure 1.1.** Total number of publications attributing CAP support, with those co-authored by students shown in green.

LULCC: *Rapid urbanization is the core dynamic in this large and complex system,* accompanied by changes in land use and cover, economics, hydrological systems, infrastructure, and population growth and demography. Supporting CAP I–II findings, Wu et al. (2011) showed that 20$^{th}$-century urbanization patterns in Phoenix and Las Vegas were similar, with increasing diversity in land use, fragmented structure, and shape complexity over time. **Shrestha et al. (2012)** analyzed land-fragmentation patterns in the PMA over a similar period and determined that five social-ecological drivers explained changes in urban geography: population dynamics; water provisioning; technology and transportation; institutional factors; and topography. The conversion of land from desert or farmland to urban uses had slowed following the 2008 housing crash but continued apace during the CAP III period. We developed sub-m resolution, object-oriented classified imagery for the entire CAP study area using National Agricultural Imagery Program (NAIP) input data (X. Li et al. 2014), which supports research on impacts and drivers of these changes. Our new land-cover classification scheme, related to existing schemes but scalable from this high-resolution dataset to regional extents, was completed in 2010 (Fig. 1.2). We also have analyzed changes in urban form from 1970–2010 for major PMA municipalities, using compactness measures developed by W. Li et al. (2013, 2014), and found that post-1990 growth has reduced sprawl compared to the previous two decades.

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 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. in press). For example, **Cook et al. (2012)** developed a framework for social-ecological research centered on residential landscapes, in which ecology (e.g., properties, functions, and services) influences and is influenced by management decisions, legacies, and human drivers at household, neighborhood, and municipal scales (Fig. 1.3).

ECOLOGY OF RESIDENTIAL LANDSCAPES: The Cook et al. (2012) model will guide the residential landscapes and neighborhoods research that we will pursue in CAP IV. This research to date has shown that *perceptions about the local environment are related to residential landscape decisions, parcel-to-neighborhood ecological properties, and property values.* We have coupled this work with the Phoenix Area Social Survey (PASS)—a longitudinal survey conducted every five years in socially and ecologically distinctive neighborhoods—to relate perceptions to ecological variability and to the actions that people take. PASS has revealed that people's attitudes and perceptions about the

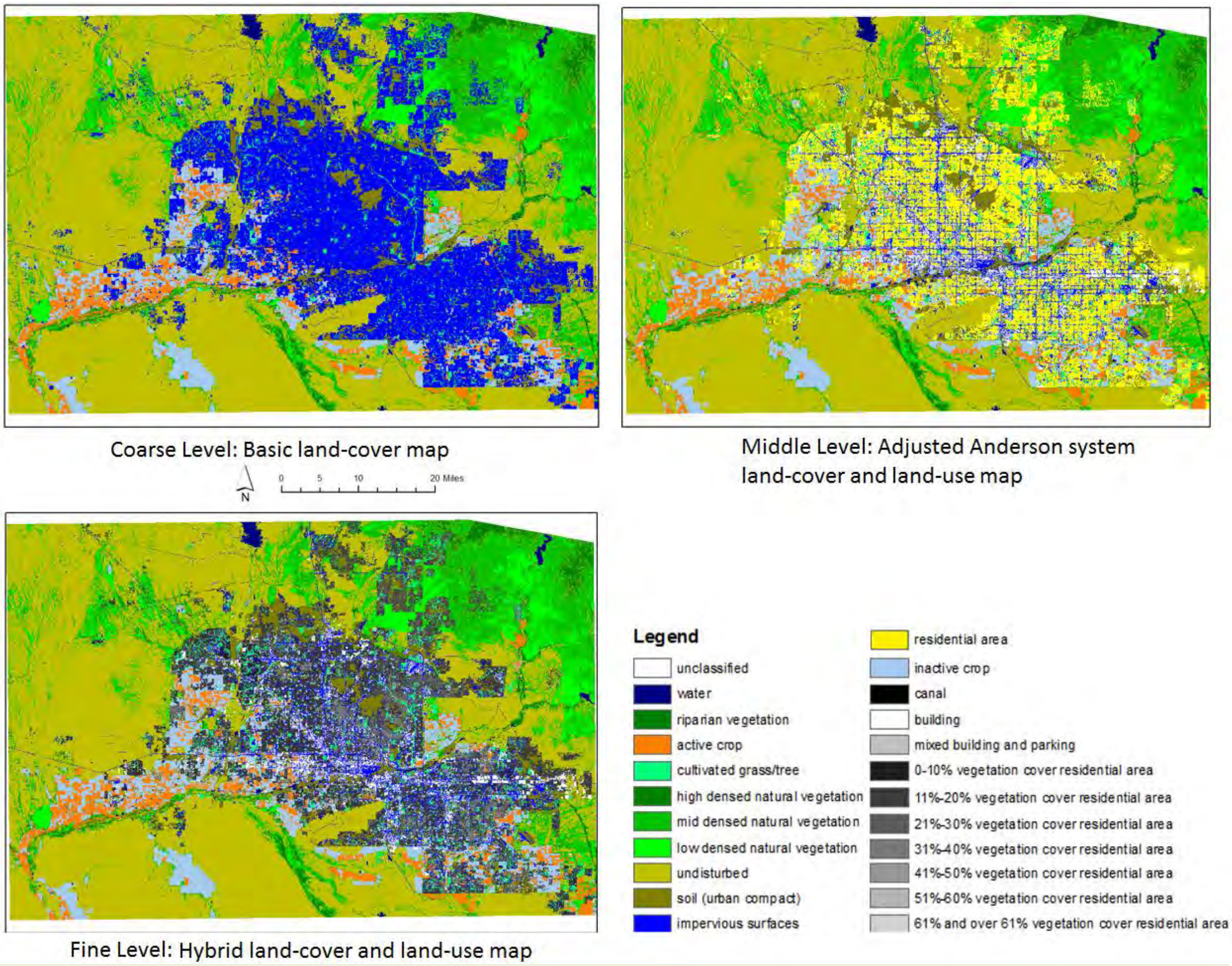



**Figure 1.2.** 2010 Land-cover classifications for the CAP study area at three scales. Our object-based imagery process approach employs the spectral, textural, geometrical and spatial information to classify Landsat images and achieve high accuracy land-use and land-cover (LULC) results. A newly developed 3-level LULC classification framework hierarchically refines basic land-cover mapping to an ecologically useful and hybrid LULC mapping.

environment influence their behavior, sometimes in surprising ways. For example, we found that residents with relatively strong environmental values tended to water their yards more frequently (Larson et al. 2010). Analyses of the PASS data also have revealed that 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 and changes in front yards were largely conversion of mesic to xeric landscaping (Fig. 1.4; Larson et al. 2015a; Hoffman and Larson 2016). In CAP IV, we will use PASS data to study why this shift occurred. Through other research on residential landscapes and neighborhoods we have 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; Brumand and Larson 2012; Larson and Brumand 2014). 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 in press; Klaiber et al. in review) and our CAP IV research will focus on both types of features.

CLIMATE, ECOSYSTEMS, AND PEOPLE: Our integrated social-ecological research has shown that, *in arid cities, climate, vegetation, social equality, and biodiversity are linked.* We continue to document relationships between neighborhood income and biodiversity that are driven by vegetation differences (Faeth et al. 2011; Lerman and Warren 2011; Ackley et al. 2015). These same vegetation differences explain variation in heat exposure. More research on causes and impacts of the UHI has been done in Phoenix than any other city (Chow et al. 2012); our research on extreme heat is significant given the likelihood that heat-related mortality will increase under most climate-change scenarios (Hondula et al. 2015). **Jenerette et al. (in press)**—a recent excellent example of fully interdisciplinary research—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), but with the tradeoff of increased water use (Jenerette et al. 2011; Jia et al. 2015). **Chow and Brazel (2012)** used the ENVI-MET model to show that xeric vegetation can ameliorate extreme heat, implying a solution that reduces the water-use tradeoff. Finally, our recent analysis of the long-term trend in land-surface temperature (LST) confirmed the role of vegetation, and of the water that irrigates it, in reducing LST. Where the proportion of land with vegetation decreased, daytime and nighttime LST increased, and where daytime LST decreased, vegetation increased (Figs. 1.5 & 1.6; Harlan et al. 2014; Jenerette et al. in press).

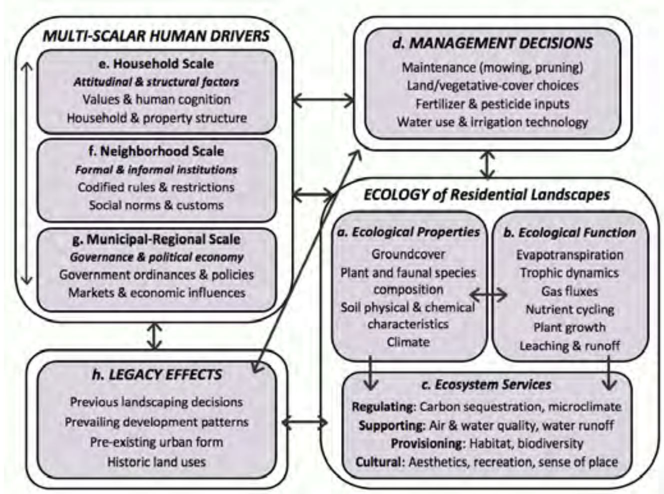
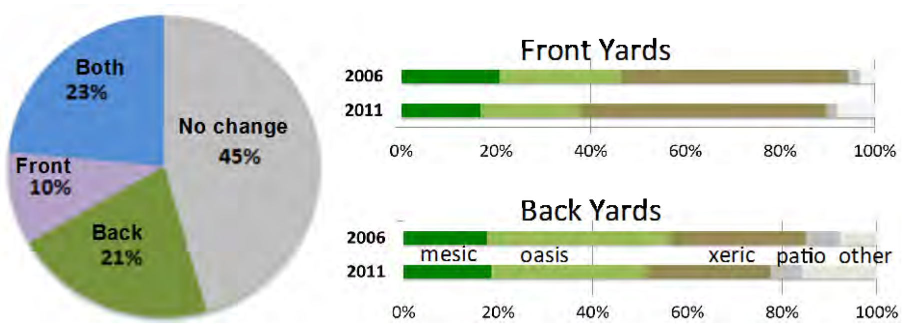



**Figure 1.3.** Social-ecological framework for residential landscapes showing feedbacks among ecological properties, human drivers, legacies, and management decisions (from Cook et al. 2012).

**Figure 1.4.** Changes from 2006 and 2011 in residential landscapes for houses resampled by PASS (n=365). Pie chart shows proportion changing, and bar charts show types of change in front and back yards.




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 vegetation in residential landscapes would not survive. Water also is essential for life, is a disturbing force (i.e., stormwater flooding), is a limiting resource to desert productivity (Sponseller et al. 2012), and is a vector for waste removal. **Hale et al. (2015)** found that changes in predominant stormwater infrastructure type over the past 50 years strongly influenced hydrological retention, and thus nutrient retention, during storms. The retention of both stormwater and nutrients are services mediated by built infrastructure, underscoring the importance of including the designed and built environment in urban ecosystems research (see Section II).

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 xeric and

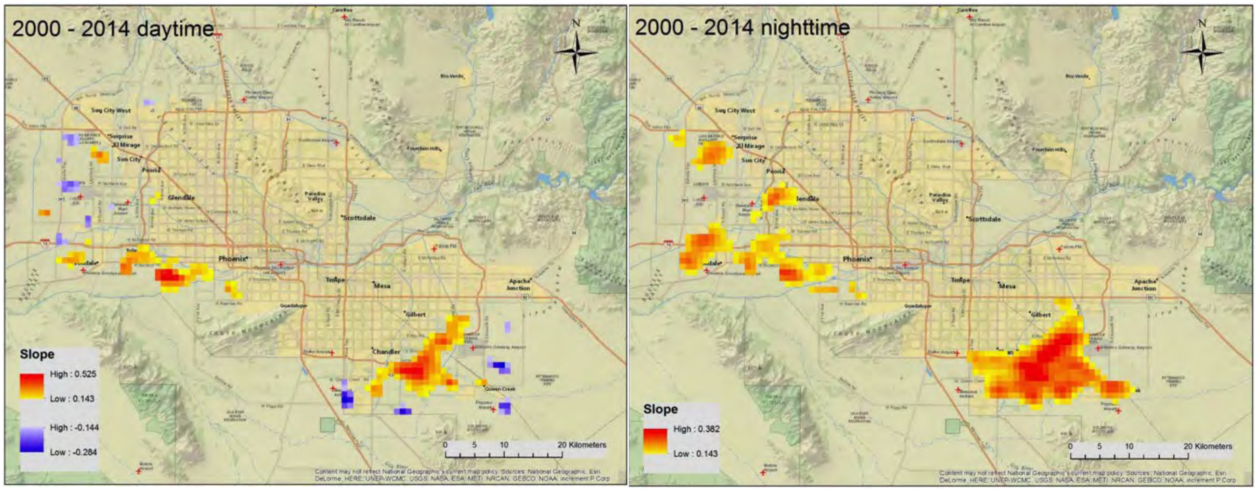



**Figure 1.5.** Relative values of slope of change in daytime (left) and nighttime (right) land surface temperature (LST) from 2000 to 2014 for developing areas within the CAP region. Yellow-red colors indicate increasing LST; blue-purple colors indicate decreasing LST.

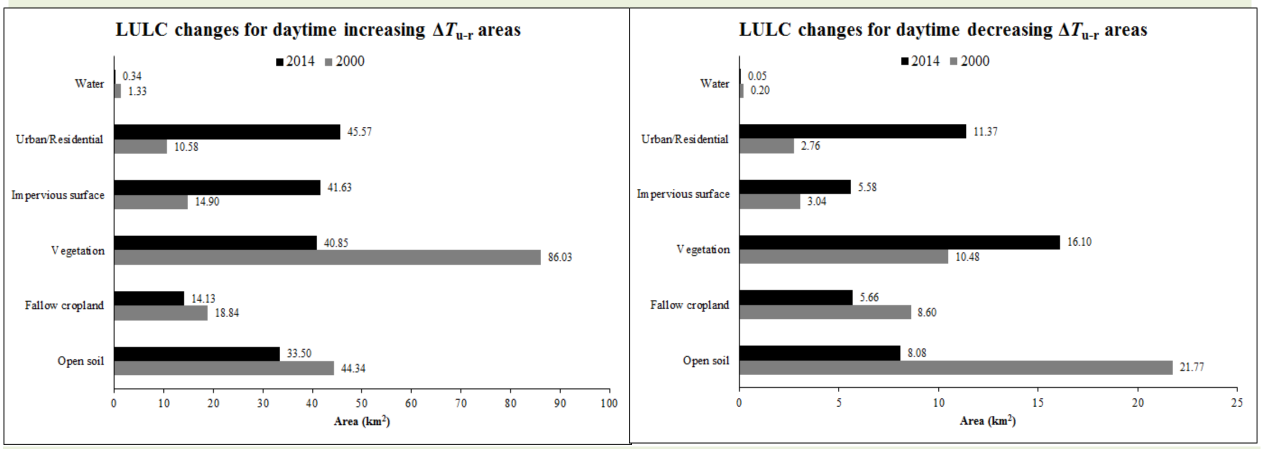



**Figure 1.6.** Comparison of total area for various land use and cover types from 2000 (light shading) to 2014 (dark shading) for regions that have experienced significant LST changes (Note: No significant decreasing LST has been observed for the nighttime).

mesic landscapes at our North Desert Village experimental neighborhood. They showed that the relationship between irrigation schedules and plant stress differed for the two landscape types. Finally, a unique discovery of plant-mediated control of surface hydrology comes from long-term research begun during CAP III at the Tres Rios constructed wastewater treatment wetland (Weller et al. in press). Marsh plants in this wetland are highly productive and transpire large volumes of water, particularly during 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 much more effective than if located in a cooler or more mesic climate (Fig. 1.7; Sanchez et at. in press).

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 areas can and do provide habitat for wildlife (Banville and Bateman 2012), that stormwater infrastructure design determines water and nutrient retention and transport (Hale et al. 2014, 2015) and can provide unintended services such as denitrification (Roach and Grimm 2011), that

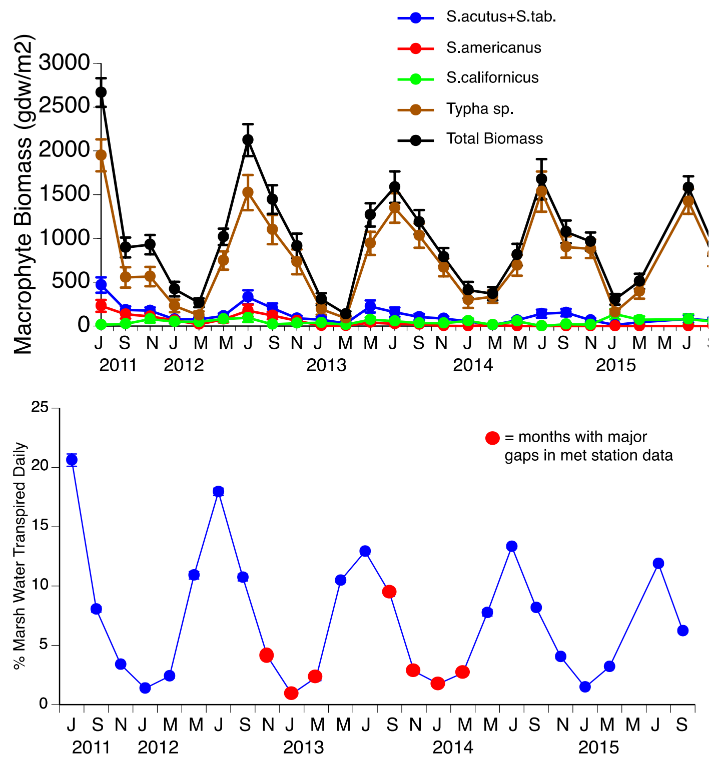



**Figure 1.7.** Temporal patterns of marsh plant biomass (top) and the fraction of total water overlying the marsh that is lost to plant transpiration daily (bottom), which creates a “biological tide” drawing water and nutrients into the vegetated wetland.

unplanned or “accidental” urban riparian wetlands are more faunally diverse than planned ones (Bateman et al. 2015; Palta et al. in review), and that designed systems such as treatment wetlands perform better in this arid city than expected (Sanchez et al. in press).

BIOGEOCHEMICAL PATTERNS AND PROCESSES: Our biogeochemical work has focused on material fluxes and their impacts on people. As part of our long-term fertilization experiment at desert sites in urban and non-urban settings, **Hall et al. (2011)** reported that creosotebush (*Larrea tridentata*) growth was relatively insensitive to nitrogen (N) addition but strongly responsive to summer rainfall, whereas winter-spring annuals responded to N addition in wet years in a climate-driven cascade of resource limitation. **Zhang et al. (2013)** used our ecological survey and LULCC data to develop and parameterize a model that quantifies ecological pools and processes, such as net primary production (NPP), soil organic matter and nutrients, carbon fluxes, and spatial structure of C storage. Although we have not yet used this model to simulate temporal change, it is foundational for our analysis of long-term change in ecological patterns at multiple scales and will be a focus of our future scenarios work.

Long-term (2005–2015) water-quality data from Tempe Town Lake (TTL), 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 (see Section II.d). Complex seasonal and inter-annual patterns in dissolved organic carbon (DOC) quantity and quality suggest that carbon cycling in the lake responds both to meteorological/ climatological events and to anthropogenic activity. Further, our time-series analysis showed that flow into the lake and rainfall during the preceding week had a positive effect on DOC concentration and composition (Fig. 1.8a). Finally, seasonal patterns in dissolved $O_2$ concentration from 2005–2015 revealed supersaturation more than 70% of the time (Fig. 1.8b), suggesting that the lake is autotrophic and is thus is a sink for atmospheric $CO_2$.

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. Urbanization is frequently cited as driving species losses worldwide based upon a space-for-time substitution approach. Our population/community research on has gone beyond documenting human impacts on biotic diversity by exploring the mechanisms behind those changes. In an experiment manipulating food resources and predation, **Bang et al. (2012)** showed that bottom-up factors, as expected, strongly regulated plant-associated arthropod communities in desert habitats. Urban arthropods subjected to the same treatments were not top-down controlled, as hypothesized, but rather

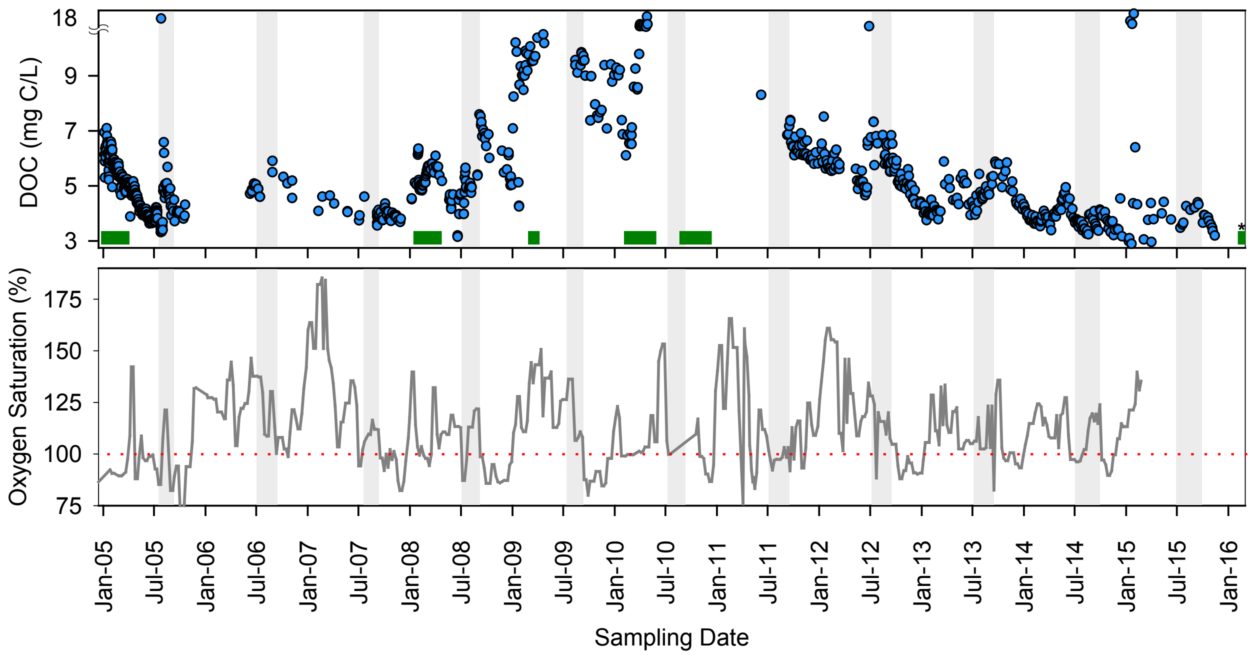



**Figure 1.8.** Dissolved organic carbon (DOC; top) and oxygen saturation (bottom) for Tempe Town Lake (2005-2015). DOC shows strong seasonal and inter-annual variation and responds to climate events and anthropogenic activity. Dissolved oxygen (presented as a 3-wk moving average) is nearly always supersaturated (note red line at 100%); the lake is highly productive. The summer monsoon seasons are shown with gray bars. Green boxes indicate periods when the lake has emptied and refilled, either accidentally or deliberately; the lake was being emptied as this proposal was being finalized (Feb. 2016, asterisk).

responded to a complex set of relationships among climate, plant growth, and predation. **Lerman and Warren (2011)** explored how species diversity varied across the city, with a focus on native bird diversity. 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, with fewer native birds in poorer, ethnic minority neighborhoods. Our long-term work at 12 riparian sites along a gradient of human modifications and water flow has also shown that

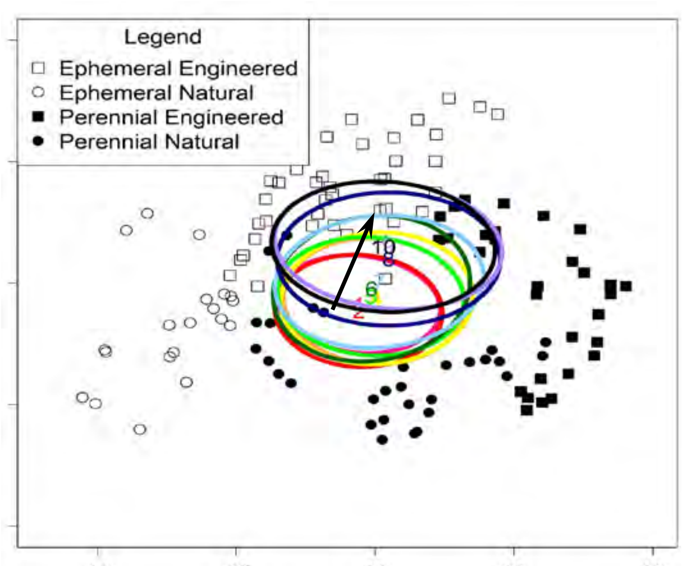



**Figure 1.9.** Temporal shifts in riparian bird community structure (NMDS) during spring from 2001 to 2013 as 3-year moving averages. Ellipses represent the core of the overall riparian bird community for each of 10 temporal periods. Trajectory of ellipses (arrow) depicts the change in bird assemblages over time.

engineered urban riparian sites supported more broadly distributed generalists while undeveloped desert riparian sites supported more specialists. Bird abundance, species richness, and diversity decreased across all riparian types from 2001–2015, and bird communities in desert riparian habitats have changed more than urban communities. Overall, the riparian bird community is shifting towards one characteristic of riparian sites with less water and more-impervious surface, such as those in the city (Fig. 1.9; Banville et al. in review). We have also tracked changes in bird communities in PASS neighborhoods, along with changes in 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, suggesting that residents accurately perceived bird diversity and abundance. We will explore whether these downward trends continue or reverse post-recession (i.e., 2011–2016–2021) with CAP IV research.

A key insight that crosses our research themes is that *differences between urban and desert habitats are both structural and functional, and not always as predicted.* Birds are not food-limited in the city yet 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 are different from those of native desert, even though these two environments outwardly appear similar (Hall et al. 2009; Hall et al. 2011).

SUSTAINABLE FUTURE SCENARIOS: For the past two years CAP scientists have engaged with representatives of over 20 governmental and nongovernmental organizations and the public to envision the future of the PMA. This work has entailed a series of workshops to first 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. We will host a public event to convey the results of this ongoing process in Fall 2016, and these activities will continue into CAP IV.

**c. Broader Impacts:** The broader impacts of CAP III include: 1) developing and maintaining a comprehensive, spatially explicit, long-term database on social-ecological variables for the PMA; 2) creating awareness of cities as social-ecological platforms for solving sustainability challenges; 3) co-producing knowledge with decision makers; and 4) integrating education and outreach into our work. Our Information Management program is well developed; datasets are archived, documented, up to date, and accessible. We work closely with a local Conservation Alliance to promote appreciation and understanding of urban challenges and solutions, and we have leveraged major new initiatives in support of decision making on water challenges under climate change and urban resilience to weather-related extreme events (Section II.g; see Fig. 1.10 for the record of CAP-leveraged grants). 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; our REU program that has supported 27 undergraduate students; a unique Grad Grants program has funded 45 students since 2010; and several postdocs.

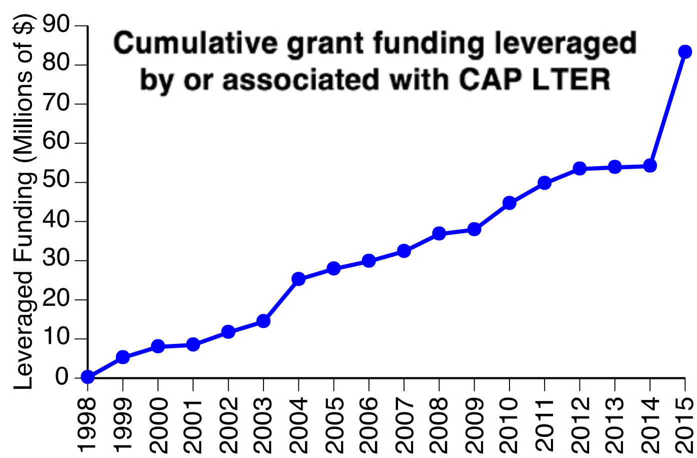



**Figure 1.10**: Cumulative grant funding that has been leveraged with CAP. The large bump in 2015 is largely attributable to the awarding of two of the three new $12 Million Sustainability Research Network programs that leveraged CAP; one of these is being led by CAP scientists Grimm, Chester, and Redman (UREx SRN).

**d. Products of CAP III Supplements:** The CAP III REU Program 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 the new field of sustainability, and one in public health—eight have gone into the workforce, and six are in STEM jobs. Our REU participants have co-authored 13 journal articles (see * in literature cited). Several REU students are women or members of minority groups, and in Summer 2016, CAP will partner with the ESA's SEEDS program to recruit more underrepresented minority 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.

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 two new products: 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 the Mary Lou Fulton Teachers College. Most students served through our K-12 programs are members of groups underrepresented in STEM. We also initiated a partnership 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, CAP received an IM Supplement to support developing and testing datasets for the GeoNIS by the CAP IM team. The NIS migration activities resulted in the repackaging of CAP's data inventory, updates to the metadata, and submission of the new data inventory to the NIS. Our full public-data inventory is now available through the NIS PASTA system (see Supplemental Documents for the list). 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 (ESIP) meeting. At the meeting, the group developed the LTER IM organizational model referred to as NIMO and interacted with other ESIP members to seek additional ideas for this model, now in the proposal stage. Lastly, we used a 2015 Equipment Supplement to purchase a new field vehicle and contribute to a new gas chromatograph for trace-gas analysis.

**e. Response to the Midterm Site Review:** Our review in September 2013 was positive and supportive. The panel's report made three main recommendations: 1) more use of long-term data to answer research questions; 2) greater linkage of our research themes to the LTER core areas; and 3) more use of existing or new theory-based models to answer questions. Our response to that review outlined our changes in course: 1) using our summer calls for faculty and student support in 2014, 2015, and 2016 to encourage analysis of long-term datasets; 2) supporting 10 Working Groups in 2015–2016 to analyze long-term datasets; 3), drawing connections to the LTER core areas throughout our work and this proposal; and 4) being explicit about developing, using, evaluating, and originating theory. As an example of the last, we have tested alternative mechanisms of organismal interaction, such as theories of top-down vs. bottom-up controls of community structure (Bang et al. 2012) or organismal responses to stress (Deviche et al. 2011; Giraudeau and McGraw 2014) that may explain lower diversity in urban areas, rather than simply assuming that "urban conditions" were to blame. Similarly, we have evaluated the applicability of the Urban Stream Syndrome in aridland cities and modified this theory to highlight infrastructure (Hale et al. 2015). CAP was a strong contributor to the Press-Pulse Dynamics conceptual framework (Collins et al. 2011) that is organizing a great deal of social-ecological research in the US and abroad (e.g., the LTSER Network in Europe). Our PASS questionnaires included the New Environmental Paradigm (NEP) scale, extensively used to differentiate underlying world views about how humans relate to nature. CAP researchers have used the NEP to test theories about influences on attitudes toward public policies (Larson et al. 2009b) and public goods (Fishman and Smith in press). Finally, we are developing new theoretical models for ecosystem services in an urban context, where the built environment and technological services dominate, for systemic inertias in urban ecosystems, and for linking urban ecology with design to enhance urban sustainability (Childers et al. 2014, 2015; Grimm et al. 2016).

## II. Proposed Research

**a. Introduction and Central Question**: *Homo sapiens* is becoming an increasingly urban species. This fact needs no attribution and underscores 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 (David 1995; Grimm et al. 2008; Bettencourt et al. 2009; Pickett et al. 2013). Understanding urban ecosystems has been the motivation behind CAP LTER since its inception in 1997 and will continue to be our inspiration in CAP IV. The CAP study area includes 6400 $km^2$ of rapidly urbanizing central Arizona—effectively all of the PMA (Fig. 2.1). The PMA is home to nearly 4.5 million residents, and this population swells by more than 1 million every winter during "snowbird season." The 6400 $km^2$ CAP study area includes 26 independent urban municipalities as well as agricultural and undeveloped Sonoran desert areas. As we continue our urban ecological explorations, the central question that will guide our CAP IV research—a logical evolution of the CAP III question—is:

***How do the services provided by dynamic urban ecosystems and their infrastructure affect human outcomes and behavior, and how do human actions affect patterns of urban ecosystem structure and function and, ultimately, urban sustainability and resilience?***

By its very nature, this central question articulates the inter-connectedness of human motivations, behaviors, actions, and outcomes with urban ecosystem structure and function—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.

A new focus for CAP IV will be on urban infrastructure as a bridge between the biophysical and human/social components of the system (see Text Box definition). Our **overarching goal** will be 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 will meet this goal through four **broad programmatic objectives**. We will continue: 1) using our long-term observations and datasets to articulate new questions that require a long-term perspective; 2) developing and using predictive models and future scenarios to address our research questions; 3) applying our broad use of existing urban

**What Do We Mean by Infrastructure?**

Cities are designed human habitats, and urban infrastructure is the result. Scientists typically define infrastructure 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). Depending on one's discipline, there are different conceptual and analytical definitions, so we view urban infrastructure broadly (Fig. 2.2): Infrastructure bridges the biophysical and social realms of the urban ecosystem. It includes various ecological features (e.g., green, blue, and turquoise infrastructure, per Childers et al. 2015), built structures (=gray infrastructure), social institutions (often called "soft" infrastructure), and hybrid infrastructures (per Grimm et al. 2016). Much of the ecological structures and functions in cities are, to varying degrees, designed or managed, and are thus part of urban infrastructure. Our CAP IV research will necessarily focus on these "design with nature" infrastructures (Steiner 2006, others) rather than on the gray, or more highly engineered, infrastructure. Notably, our definition distinguishes green infrastructure from the enviro-political definition that includes, for example, solar panels and recycling programs and expands on the green infrastructure definitions of Keeley (2011) and Larsen (2015).

ecological theory while contributing new theory from our knowledge-generating endeavor; and 4) building and using transdisciplinary partnerships to foster resilience and enhance sustainability in urban ecosystems while contributing to the education of urban dwellers of all ages and experiences.

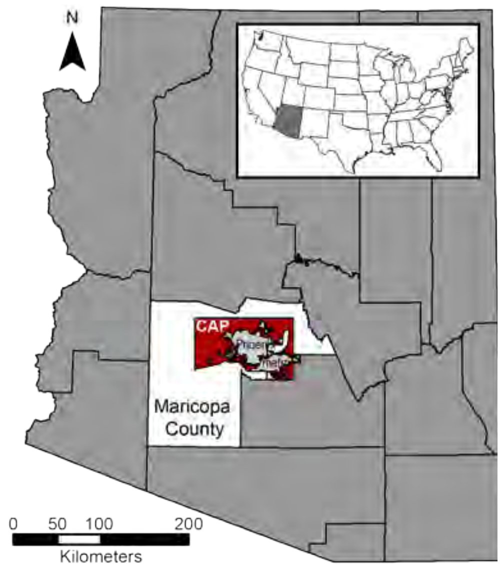



**Figure 2.1**: The 6400 km$^2$ CAP IV study area in central Arizona (red) that includes the Phoenix Metro Area (light gray area within the red). Dark lines are county boundaries.

**b. CAP IV Conceptual Framework:** The CAP IV conceptual framework (Fig. 2.2) is based upon the CAP III framework, with key modifications. Our definition of the urban ecosystem still includes 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. 2.2). The biophysical and human/social templates join with a porous, "zipper-like" boundary, demonstrating that they are not actually separate. Myriad human behaviors and decisions lead to a host of outcomes that, in turn, affect future decisions and behaviors. The functional and structural components of the biophysical template link to human outcomes through the purveyance of services and their benefits (Fig. 2.2). The various forms of urban infrastructure are part of, and overlap with, these components, and infrastructure bridges the porous boundary between the biophysical and human templates. Our CAP IV research necessarily focuses on non-gray infrastructure (Text Box), with the caveat that we do not include unmanaged or non-designed features in our broad definition of urban infrastructure. For example, vacant lots or "accidental wetlands" have ecological functions and structures and do provide urban services, but we do not consider them to be infrastructure. Human decisions affect the design and management of infrastructure and infrastructure influences outcomes, via its various functions, by providing a wide range of urban services to city dwellers. These services directly affect human outcomes (Fig. 2.2). The double-headed arrows that connect the two templates with internal presses and pulses demonstrate that these environmental and human-sourced disturbance-type events operate in both directions. For example, the biophysical template produces pulse perturbations, such as floods, while the human template produces press perturbations, such as land cover change. In both cases, presses and pulses affect

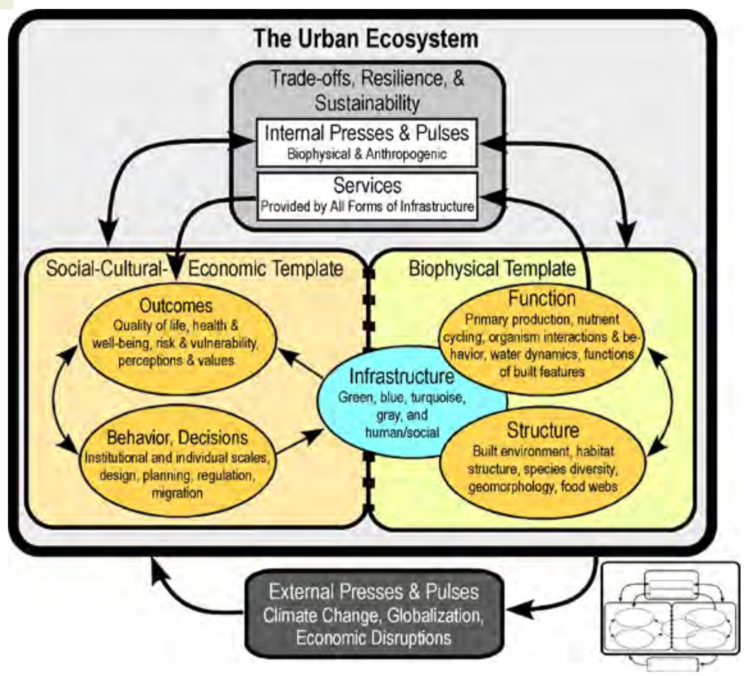
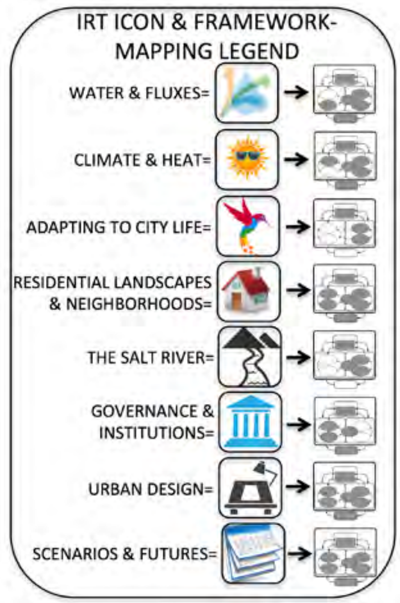



**Figure 2.2**: The CAP IV central conceptual framework for understanding urban social-ecological systems. This framework is applicable to individual people, households, neighborhoods, municipalities, or the entire poly-centric PMA. See text for details. We will use the miniature version shown to the right to map our long-term datasets, IRTs, and each Research Question to components of this framework.

both templates regardless of their source. Finally, a number of external presses and pulses influence the urban ecosystem (dark box at bottom of Fig. 2.2), while cities also influence beyond their boundaries. Our long-term datasets, research questions, and programmatic structure map to this central conceptual framework; it is the glue that will bind CAP IV together.

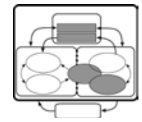
In our conceptual framework, the services that infrastructure provide that benefit people link the biophysical and social templates (Fig. 2.2). We do not call these ecosystem services for a reason: In our broad, holistic definition of the urban ecosystem, all urban infrastructure is capable of providing services and benefits, including the built or "gray." For example, trees in a park provide obvious ecosystem services of shade, transpirational cooling, and air purification, but park benches, playgrounds, and restrooms provide services as well. Our definition of the urban ecosystem includes all these services, and we recognize that calling them ecosystem services might engender confusion. For this reason, throughout this proposal we refer to the infrastructural services and their benefits in Figure 2.2 as "urban services," per Grimm et al. (2016). We argue that this new focus on urban infrastructure and new consideration of ecosystem services in cities represents an important theoretical expansion of urban social-ecological theory.

**c. CAP IV Organization:** The foundation on which the entire CAP IV enterprise rests is composed of four components: 1) our long-term datasets and experiments; 2) the seven LTER Core Areas; 3) our education, outreach, and citizen science initiatives; and 4) the co-production of knowledge to enhance urban sustainability. Resting on this foundation are eight Interdisciplinary Research Themes (IRTs; legend to the right). Two IRTs are process-based (Water & Fluxes; Climate & Heat), some are thematic (Adapting to City Life; Governance & Institutions; Urban Design), two are locations in the PMA where we will focus a diversity of interdisciplinary research and energy (The Salt River; Residential Landscapes & Neighborhoods), and one is broadly integrative (Scenarios & Futures). All eight are highly interdisciplinary and interconnected; they all depend upon our long-term foundational datasets, resources, and activities. We created an icon for each IRT (right) and use these to map how the eight IRT groups participate in the CAP IV research questions.




**d. 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. We have used these to document land use/cover change and spatiotemporal heterogeneity in biophysical, economic, and social characteristics of the PMA. Water is critical for all life and is particularly important to a desert city such as Phoenix. For this reason, our long-term datasets have tracked water supply to the city, and its quality—from reservoirs to tap, the quality of wastewater leaving the city, the ecohydrologic dynamics of urban stormwater, and aquatic features of the urban Salt River, including Tempe Town Lake and "accidental" wetlands in the riverbed. We have also used a long-term fertilization experiment to articulate how the city affects its surrounding desert landscape. All these long-term datasets or experiments are detailed below.

The original intent of these long-term datasets was to document the heterogeneity and changing heterogeneity of our 6400 km$^2$ study area. In many cases, we have met this goal and have re-designed our observational data collection to allow more direct testing of our central conceptual framework (Fig. 2.2) and to better reflect the research activities of our eight IRT groups. While the power to detect trends is marginally higher in "always revisit" sampling designs, these designs may produce less precise estimates of status and trends at specific sites or locations (Urquhart 2012). We are thus comfortable with these redesigns, which will also free up critical resources (technician time, driving time, supplies, sample analysis) and allow us to explore new questions and research while taking full advantage of our long-term data to answer those questions. Where we have re-thought our long-term data collection, the re-designed sampling schemes will now more closely articulate with our specific research questions *while maintaining the long-term integrity of our existing datasets*.



• *Documenting land use/land cover change*: Arguably, the single most important metric of urbanization and evolving urban ecosystem structure is land use/land cover change (LULCC). In CAP IV, we will continue to document LULCC at multiple spatial and temporal scales, including spatial resolutions of 1m, 30m, and 250m and a temporal resolution of the 30m data of five-year intervals beginning in 1985 (Fig. 1.2). Some of these data are integrated with Maricopa County Cadastral data (land-use parcels) and ASTER temperature data. The following LULCC products are available through the CAP data portal: 1) 1-m resolution land-cover classification 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 (Li et al. 2014); 2) 30m resolution land cover classification based on 2010 Landsat TM data that employed an object-based imagery assessment method, coupled with cadastral data, to generate as many as 21 land classes from the percentage of a 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 will continue this work in CAP IV, including developing 250-m resolution coverages using MODIS data and hierarchically integrating our LULCC information such that the 1-m land-cover classes may be aggregated to 30m or 250m, and the 30m may be aggregated to 250m. In addition, we propose to develop a series of specific data products, including: 1) 2010 NAIP-based 1-m resolution "open" or "vacant" land covers; 2) 2010 Landsat-based 30m land classifications for specific watersheds where CAP IV research will take place; and 3) alignment of the 1m resolution NAIP-based coverage to address CAP IV questions related to urban heat and water use (e.g., Fan et al. 2015; X. Li et al. 2016; Wentz et al. in review).

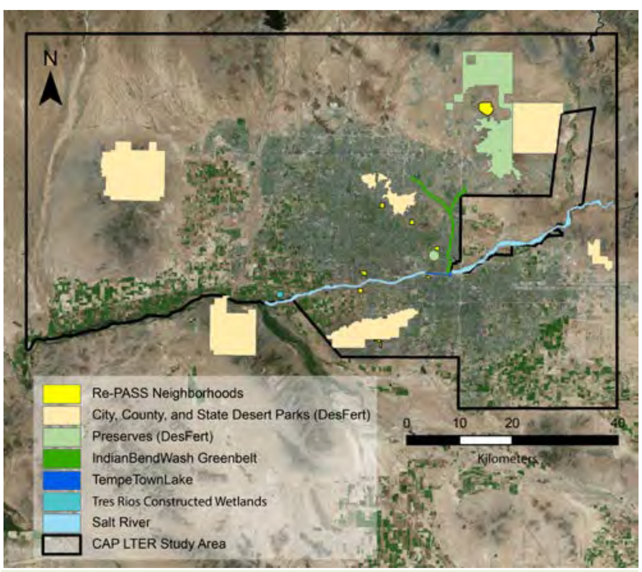
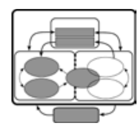
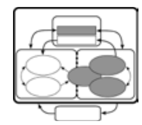



**Figure 2.3**: CAP study area and the PMA showing the specific locations of many long-term observational and experimental sites and where much of the CAP IV place-based research will take place.



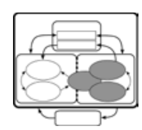
• *Phoenix Area Social Survey*: The Phoenix Area Social Survey (PASS) has been conducted every five years, beginning with a pilot survey in 2001 and extended to more than 40 neighborhoods in 2006 and 2011. In this configuration, PASS was able to quantify the social and spatial heterogeneity of a number of variables, including heat stress and vulnerability (Harlan et al. 2012), water risk perceptions and consumption rates (K. Larson et al. 2011a,b; 2013a), and landscape preferences and practices (Larson et al. 2009a; 2010). For the 2016 survey, we re-designed our sampling strategy to focus on a more robust/reliable characterization of residents per neighborhood while focusing on fewer neighborhoods, many of which are strategically located near where CAP IV research will be concentrated. This restructured "Re-PASS" is surveying 12 of our long-term study neighborhoods (Fig. 2.3) with the goal of approximately 65 respondents per neighborhood (as opposed to only about 20 in the past). Notably, all Re-PASS neighborhoods have been surveyed two to three times in the past. This new design—with a sufficient number of individuals to represent neighborhoods—allows for multi-level modeling to test for neighborhood effects (Sampson et al. 2002) on risk perceptions, landscape practices, and household-level outcomes (Sampson 2003). It will allow us to more substantively test the [general] social norms theory and the [more specific] value-belief-norm theory. This new experimental/sampling design will also facilitate more integrated social-ecological analysis of focal areas, including those that have served as research sites over the history of CAP (e.g., the Salt River, Tempe Town Lake, Indian Bend Wash, urban mountain parks and preserves, and South Phoenix).

The re-PASS survey approach will capitalize on the long-term data from the three previous surveys, in addition to delving more deeply into our new question-driven research. The longitudinal surveys in 2016 (CAP III) and 2021 (CAP IV) will capture constructs and variables long central to CAP: Land-cover and management choices coupled with expressed and observed ecosystem services (Larson et al. 2009a; 2015b); heat stress and vulnerability, along with mitigation and adaption strategies (Jia et al. 2015); and risks, perceptions, and environmental satisfaction in relation to ecological and other biophysical factors (e.g., biodiversity, proximity to open water; Larson et al. 2009b; Lerman and Warren 2011). In this way, landscape change (e.g., LULCC), environmental risks, and implications for urban ecology and social vulnerability/satisfaction will remain central to Re-PASS.

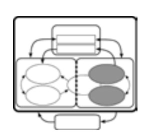


- *Ecological Survey of Central Arizona (ESCA)*: The Survey 200 has been the stalwart of CAP's biophysical observations, documenting the environmental heterogeneity of our 6400 $km^2$ study area every five years since 2000. We have used these data to document spatial variation in soil black carbon (Hamilton and Hartnett 2013), soil microbial communities (Cousins et al. 2003; Rainey et al. 2005) and 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) of the PMA. We have also developed innovative statistical approaches to assess biophysical and social controls on spatial patterns of many biophysical variables (Kaye et al. 2008; Majumdar and Gries 2010; Majumdar et al. 2008, 2010, 2011). For CAP IV, we have more closely integrated this biophysical survey with our other long-term sampling efforts and question-based research while maintaining the long-term integrity of the Survey 200 dataset. In this re-design, we have renamed it ESCA.

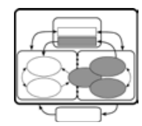
We will use ESCA to enhance this research synchrony by redistributing a subset of Survey 200 sites to align them with other long-term data collection efforts and with the place-based focal areas of CAP described below. We will: 1) consolidate desert sites into regional desert parks and to coincide with the DesFert experiment; 2) add sampling locations in the Indian Bend Wash watershed to support our urban stormwater research; 3) add sites in and near the Salt River to support our place-based research there; 4) consolidate urban sites into the Re-PASS neighborhoods such that at least five plots/parcels will be surveyed in each PASS neighborhood (Fig. 2.3); and 5) conduct both Re-PASS and ESCA sampling in the same year (2021). This re-design retains a minimum of 50 existing Survey 200 sites.



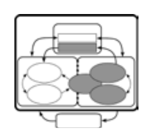
- *Long-Term Desert Fertilization Experiment:* Our long-term desert fertilization experiment (DesFert) began in 2006 with a NSF grant (N.Grimm, Lead PI) and has been incorporated into our long-term observational and experimental network. In this experiment, we are exploring the impacts of the urban environment and nutrient enrichment on biotic and abiotic ecosystem properties across an urban-rural gradient in protected desert areas (Fig. 2.3; Hall et al. 2011; Kaye et al. 2011; Sponseller et al. 2012; Ball and Guevara 2015). DesFert park sites will be the focus of CAP IV question-driven research, and we will continue our experimental protocols at these locations, allowing findings to link to our other research. This is a labor-intensive experiment, though, so we will discontinue our work at several sites to free up critical resources. This will make a balanced experimental design with six outlying desert park sites and six urban desert park sites. This strategic decision will more closely link the DesFert experiment with our question-driven research.



- *Other Faunal Sampling:* We have learned a great deal about how human activities and behaviors influence urban biodiversity from our long-term sampling of faunal communities and, in turn, how biodiversity links to human perceptions, values, and actions (e.g., Lerman and Warren 2011). We will maintain these datasets (e.g., Banville et al. in review), ground-dwelling arthropods (McIntyre et al. 2001; Shochat et al. 2004; Bang and Faeth 2011), and riparian herpetofauna (Banville and Bateman 2012) in CAP IV, but will redesign the sampling to align more closely with ESCA, Re-PASS, DesFert, and our question-driven research. In CAP III, bird censuses included biannual sampling at 63 locations throughout the PMA and biannual sampling at the 40 original PASS neighborhoods in the year of and the year following the survey. Because of the Re-PASS sampling design change to fewer neighborhoods and more respondents, we will refocus our residential bird sampling on these Re-PASS neighborhoods. We will consolidate our desert sampling locations to the DesFert sites and to other desert parks/preserves where we will pursue our question-driven research. We will also consolidate our riparian bird sampling to places where we are focusing other CAP IV research efforts, such as the Salt River where we are also sampling herpetofaunal communities (Banville and Bateman 2012; Bateman et al. 2015; Fig. 2.3). Parallel relocations will occur with a number of our arthropod monitoring sites. These changes will enhance synergies among our observational efforts and our question-driven research.



- *Tempe Town Lake Water Quality:* We have been measuring water quality (temperature, pH, conductivity, and dissolved oxygen), dissolved organic carbon (DOC), DOC quality (via 3D-fluorescence), and total nitrogen in Tempe Town Lake (TTL; Fig. 2.3) since 2005. 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 TTL biogeochemistry. The lake is unique in that it is occasionally emptied and 'refilled' after river-flow events or, once, after a dam failure (Fig. 1.8). These major disturbances are opportunities to study TTL's dynamic evolution to new limnological steady states. The TTL was being drained again as this proposal was being finalized, to replace the dam, and we will conduct additional sampling once the lake has been refilled (April–May 2016) to assess the time-evolution of biogeochemical processes. We have used ARIMA time-series modeling of our long-term TTL data to show that high-resolution sampling (at least sub-weekly) is necessary to determine how exogenous and endogenous drivers control TTL carbon and nutrient cycling. For this reason, we will install *in situ* datasondes to measure water quality parameters, including nitrate and optical characteristics (i.e., fDOM) at high temporal resolution. Initially, we will supplement the sensor data with twice-weekly samples for DOC, nutrients, and 3D-fluorescence analyses. We will also develop a statistical model that relates fDOM to DOC concentration, allowing us to reduce the number of discrete samples needed over time.



- *Stormwater Quality & Hydrology:* We base our long-term monitoring of stormwater hydrology and biogeochemistry on a detailed stormwater study in urban watersheds with different types of infrastructure (Hale et al. 2015). We will continue to focus on how land cover, type and configuration of stormwater infrastructure, and climate variability control hydrological and biogeochemical retention and transport of stormwater (Grimm et al. 2005; E. Larson et al. 2013; Hale et al. 2015). Our study watershed, the Indian Bend Wash (IBW) in Scottsdale, is a ~500 $km^2$ catchment that has become nearly completely urbanized. 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; Fig. 2.3). Concurrent with this south-to-north, oldest-to-newest development gradient, stormwater infrastructure includes different infrastructure types with varying effectiveness at retaining water and nutrients (Hale et al. 2015; Fig. 2.4). This work began in 2009 with a NSF grant (N.Grimm, Lead PI), and we have incorporated that research into our long-term observational network. We will continue to monitor chemical constituents of stormwater during all runoff-producing storms. Our IBW sampler is co-located with a USGS streamflow gauge. We will add a new site further upstream, so we can to compare the total watershed output with output from the northern portion of the watershed that contains mainly natural wash, engineered wash, and retention basin infrastructure (Hale et al. 2015; Fig. 2.4). In addition, we will leverage LTREB-based storm chemistry monitoring (N. Grimm, Lead PI) on an undeveloped catchment (Sycamore Creek) northeast of the PMA.

- *Tres Rios Constructed Treatment Wetland:* We have been conducting research at Tres Rios since 2011 (Fig. 2.3). This 42 ha "working" wetland (21 ha of vegetated marsh, 21 ha of open water) was built in 2010 to remove nutrients from effluent being discharged into the Salt River by the largest wastewater treatment plan in Phoenix. Our regular bimonthly sampling measures marsh plant productivity and nutrient uptake, whole-system and within-marsh water quality, soil nutrients, and water budgets (Fig. 1.7a); we have also measured greenhouse gas fluxes from this system. Our budgets have shown near-complete uptake of N by the marsh (Weller et al. in press).We have demonstrated, for the first time, plant mediation of surface water hydrology in this wetland (Sanchez et al. in press; Fig. 1.7b). Student volunteers have conducted much of this research. We will continue to host research charettes with the City of Phoenix Water Services Department to communicate findings to their administrators, site managers, and other staff.

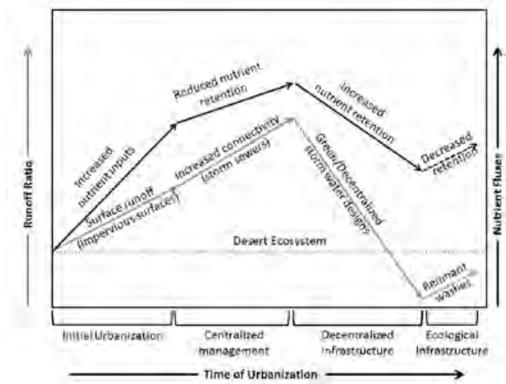



**Figure 2.4**: Depiction of how different types of stormwater infrastructure in Scottsdale AZ have changed over time, with a parallel move from overly gray infrastructure to more "design with nature" green infrastructure. Effects on hydrologic connectivity and nutrient retention are also shown (from Hale et al. 2015).

- *Regional Drinking Water Quality:* Our Regional Water Quality Center has been working with water providers and PMA cities since 1998 on issues affecting drinking water supplies, treatment, and distribution. Our long-term data have improved the understanding of taste and odor occurrence, control, and treatment (Bruce et al. 2002; Hu et al. 2003; Westerhoff et al. 2005), DOC and algal dynamics (Westerhoff and Anning 2000; Nguyen et al 2002; Baker et al. 2006; Westerhoff and Abbaszadegan 2007; Fig. 2.5), and disinfection byproducts (McKnight et al. 2001; Yang et al. 2008; Hanigan et al. 2015). For example, methyl-isoborneol (MIB) is an algal metabolite that humans can smell at 10 ng $L^{-1}$. Periphytic algal production of MIB in urban canals occurs mainly in winter. We collect these data monthly at 20 lake, river, urban canal and finished drinking water sites. MIB is noticeable to people recreating in the lakes, along urban canals, and in drinking water—it is one indicator that strongly links ecosystem processes (e.g. algal primary production) with human perceptions of the cleanliness of water (e.g. odor). We support an online forum to discuss regional water-quality issues. We have used these long-term data to document the impacts of severe weather events (Barry et al. in press) and inability of quagga mussels to infest the Salt and Verde River Watersheds (Sokowloski et al. in press). We will continue to monitor the Salt and Verde River reservoirs, and the canals and the water treatment plants that provide drinking water to the PMA. We will analyze samples for organic carbon, total N, arsenic, conductance, and taste and odor compounds; we will continue to leverage these datasets with

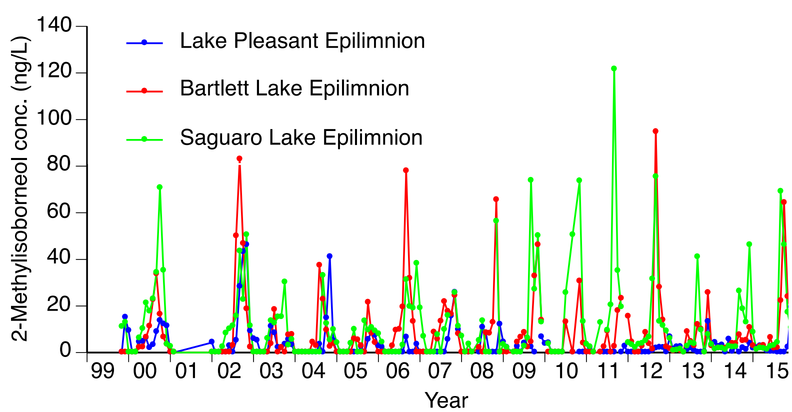
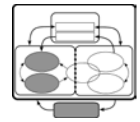



**Figure 2.5**: Monthly MIB concentrations in surface water of 3 reservoirs that supply the PMA with water.

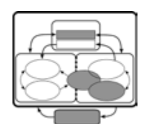
cooperation from local and federal agencies. We will also continue our quarterly sampling of upstream water supply reservoirs for limnological and water-quality characteristics. Our monthly water quality reports will continue to provide timely input to water providers for process control, reservoir and canal management, and drinking-water treatment.



- *Economic and Census Data Analysis:* The interconnections between people and ecosystems are both heterogeneous and bidirectional. Human activities affect ecosystems and these systems influence people. Unpacking these connections requires using consistent spatial scales for representing human behavior and for tracking urban services while measuring both over time. Both sources of variation were essential to the strategy we used to distinguish UHI and local landscape effects on the tradeoffs that households make to reduce summer temperatures in Phoenix (Klaiber et al. in review).

The US Decadal Census offers fundamental social-science data, and we will continue to maintain a database of these data, including the annual American Community Survey. We will match the spatial dimension of these records to records of housing sales with the parcel-level identification and to past Census and PASS surveys, allowing us to track neighborhood-scale changes in economic and demographic variables and records of environmental attitudes. We have used these datasets to understand how changes in urban services affect household locational choices (Fishman and Smith in press). Our ability to link housing-transaction records with indices of urban services and PASS data allows us to better understand the spatiotemporal differences in these services (Abbott and Klaiber 2010, 2011).

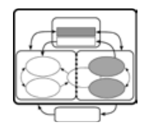
Declining response rates to household surveys have forced major changes in the way scientists collect and interpret survey data (Groves 2006). As a result, we have developed new strategies for evaluating response rates (Smith et al. in press), which will continue in CAP IV. Meyer et al. (2015) concluded that the best way to improve data quality in the face of declining response rates is to better link the surveys to administrative data. We piloted this process with the cities of Phoenix and Goodyear by linking parcel records for housing sales and landscape use to metered household water use (Klaiber et.al. 2014; Smith and Zhao 2015). These data are confidential records and can only be used at local water-provider facilities. We will continue these efforts while exploring new strategies for developing datasets that remove confidential information while keeping the spatiotemporal variation that make these data so valuable.



- *Long-Term Meteorological Database:* The human-induced UHI dwarfs the magnitude of regional climate change as a major driver of long-term social-ecological change in the CAP study area (Georgescu et al. 2012; Ruddell et al. 2012). For this reason, we will assemble a foundational long-term meteorological dataset for the PMA. CAP scientists often request these data and, in the past, each study has had to assemble its own dataset, leading to inefficiencies and inconsistencies across the program. To remedy this, we will synthesize historical data from our urban eddy flux tower, AZMET, the Maricopa County Flood Control District, and the National Weather Service into a standard long-term climate dataset of record for CAP. We will publish these data in easy-to-use formats in the LTER-NIS and summarize with hourly/daily/monthly/ annual aggregations, to match other CAP datasets.

**e. CAP IV Integrated Research Plan**: Nearly two decades of CAP research has made numerous contributions to urban ecology. Thinking of cities as complex social-ecological systems requires a holistic, ecology *of* cities perspective. We are now evolving this thinking to an ecology *for* cities approach that enhances urban sustainability through transdisciplinary partnerships with city practitioners. We have found that climate, vegetation and water use, biodiversity, and social equity are linked, and that environmental perceptions are related to residential landscape decisions, neighborhood-scale ecological characteristics, and property values. We will further articulate these linkages with questions that focus on animal communities (Research Question 1), climate and heat (Research Question 2), urban governance (Research Question 3), residential landscapes and neighborhoods (Research Question 4), and the movement of water and materials into, through, and out of the city (Research Question 5). We have found that urban and desert habitats are both structurally and functionally different, and our focus on urban mountain parks and the Salt River will shed new light on these differences (Research Question 6). Finally, we have found that the functions and services provided by both "design with nature" and built infrastructure are not always as intended. We will address this with transdisciplinary questions focused on urban design, governance, and future scenarios (Research Questions 7 & 8). Questions 1 – 3 are largely about ecology *in* cities while the broadly holistic lens of Questions 4 – 6 is clearly an ecology *of* cities focus and the future-oriented Questions 7 and 8 are about ecology *for* cities. Notably, the research questions we detail below progress from largely ecological or social in nature to more broadly social-ecological. For each research question, we use the icons shown above to identify the IRTs—and thus the researchers—that will bring expertise to that question, and as the questions progress they become steadily more inclusive. Each question has two leads (see Program Management Plan for more on the CAP IV leadership structure) and a lead IRT (the first icon). We identify the long-term data that justify each question and the long-term data and/or model(s) that we will use to answer that question. Finally we also map each question to our central conceptual framework and to the seven LTER Core Areas (Table 2.1).

***Research Question 1.a:*** In a rapidly changing urban ecosystem, how do non-human animals "operate" in space and time to avoid disturbances or to capitalize on resources? (Leads: McGraw & Warren)



***Rationale:*** Classic evolutionary theory predicts that under rapid environmental change, organismic responses will be constrained by intrinsic life history traits such as generation time, dispersal ability, and lifespan (Lande 1988; Davis et al. 2005). Cities present unique environmental challenges and opportunities to which organisms must acclimate and adapt. Some anthropogenic modifications to biotic and abiotic environments are viewed as disruptive (e.g., chemical, noise, and light pollution; Kight and Swaddle 2011), while others are beneficial (e.g., enriched food/water provisions; Oro et al. 2013; Bateman et al. 2015), but surprisingly little work in urban ecology has considered the breadth and depth of these effects across a range of organisms within an urban ecosystem or of fitness-determining life-history traits within particular taxa. These responses need not all be adaptive; they may be relatively rapid and non-genetic changes that allow organisms to cope with or exploit novel urban conditions (Sol et al. 2013). A recent meta-analysis argued that such acclimation is the dominant response by organisms to anthropogenic change, but data gaps remain (Hendry et al. 2008).

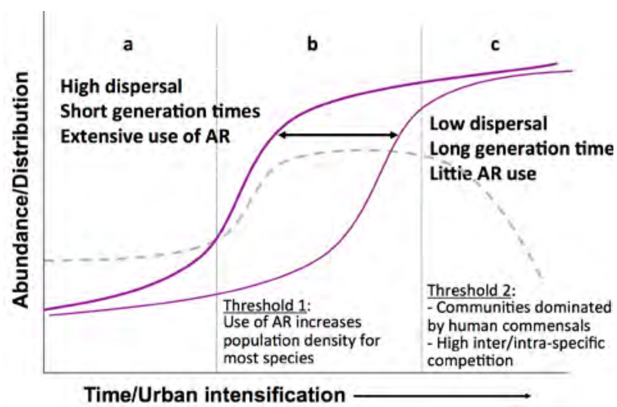
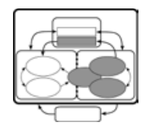



**Figure 2.6**: Hypothesized community-level effects of variation in speed at which different species adapt to city life (modified from Shochat et al. 2010). Long-term datasets allow exploration of temporal delays in responses to altered resources by native generalist species or invading non-natives (solid lines), as a function of intrinsic factors such as vagility, generation time, and exploitation of anthropogenic resources (AR).

Data on urban animal ecology tend to be from relatively brief studies (two to three years) and restricted mostly to long-lived organisms, all of which bias the likelihood of uncovering plastic responses as opposed to putative adaptive ones (Sol et al. 2013). Our long-term observations of birds, arthropods, and herpetofauna provide taxonomically broad, spatially explicit datasets that we are using to answer questions about the balance of positive vs. negative impacts of particular environmental modifications and the speed and intensity with which they impact organisms with different life histories. We expect that urban pressures have clade-specific effects due to a) organismal variation in intrinsic factors, including degree of vagility (e.g. dispersal distances), generation time, and exploitation of anthropogenic resources (Fig. 2.6), and b) the pace of urban development. We expect organisms inhabiting areas of rapid LULCC to respond more strongly, either positively or negatively, than those in more stable portions of the PMA. Notably, we have found decadal declines in avian abundance and diversity across the PMA, with the strongest declines in species that do not typically exploit anthropogenic resources (Banville et al. in review).

IRT Participation

***Approach:*** We will use our long-term data for birds, arthropods, herpetofauna, and LULCC to address large-scale spatial and temporal change in species abundance and distribution. We will bolster these analyses with measures of press and pulse disturbances (per Fig. 2.2), resource availability and distribution (e.g. bird feeders, water, nitrogen deposition; Lerman and Warren 2011), and factors that mediate the effects of anthropogenic activities (e.g. temperature, plant phenology; Neil et al. 2010; Buyantuyev and Wu 2012). We will also collect new data on the effects of nighttime light intensity on species persistence (Hutton and McGraw in review) and the acoustic ecology of the urban ecosystem (Paine et al. 2015). We will classify taxa according to their intrinsic characteristics per published literature and our ongoing species-specific studies. We will use these categories to develop Bayesian models of species abundance and diversity, using time as a covariate (Banville et al. in review) and use the results for species-specific studies on particular faunal communities (e.g. arthropods, birds, herpetofauna) to address individual-level responses.

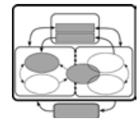


***Research Question 1.b***: How do human provisions of food and water subsidies affect species abundances and distributions, and how does animal presence feed back to human well-being and attachment to place? (Leads: McGraw & Warren)

***Rationale:*** Modern trophic theory recognizes that ecological communities are regulated by a complex interplay of top-down and bottom-up forces, modulated by factors including stress (Menge and Sutherland 1987), productivity (Oksanen et al. 1981), or species composition (Leibold 1996). Yet, consensus on the relative importance of these factors continues to elude ecologists, particularly with respect to the indirect effects of elevated basal resources (Faeth et al. 2005). Humans provide critical resources to urban animals, such as food (e.g. bird feeders), water (e.g. lakes, pools, mesic landscaping), and supplemental habitat (e.g. ornamental plants, buildings for nesting), throughout the urban environment (Goddard et al. 2013; Oro et al. 2013; Bateman et al. 2015). Many non-urban field experiments have shown that supplemental resource provisioning increases wildlife fitness (Robb et al. 2008), but not all effects of such subsidies are positive (Plummer et al. 2013). For example, bird feeders may be a focal point for disease transfer (Becker et al. 2015). Scant attention has been paid in urban ecology to: 1) the array of benefits reaped by species from food or water subsidies; 2) the speed/extent to which particular species benefit or are harmed through their ecologies or life histories; or 3) how resource subsidies interact with other urban changes to yield complex direct and indirect effects on organisms. We expect that species that exploit food and water subsidies will benefit locally and will increase in abundance and distribution in direct association with recent changes in these resources. We also expect that anthropogenically driven variation in resources will decouple many natural-fitness-related processes (e.g. reproduction and sexual signals, predation risk and predator densities, and population dynamics; Plummer et al. 2013).

IRT Participation

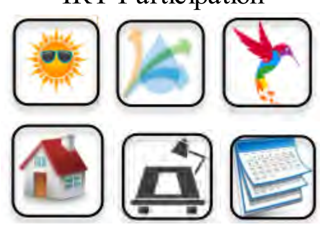
***Approach:*** We propose to capitalize on CAP's long-term faunal observations, residential landscapes research, and Re-PASS surveys (e.g. bird feeder presence; Lepczyk et al. 2012) to detect signals of anthropogenic resources against fluctuating environmental variables (e.g. rainfall) and to map the response of organismal communities to the presence and density of urban water and food subsidies. Specifically, we will use our long-term bird, arthropod, and herpetofaunal data and our LULCC dataset to address large-scale spatiotemporal changes in the distribution of urban food (including agricultural fields) and water bodies and of species abundance and distribution, complemented by ongoing mechanistic, single-species studies of behavioral and physiological effects of elevated resources (Johnson et al. 2012; Giraudeau et al. 2014; Davies et al. 2015). Our intensified ESCA sampling of residential yards in the Re-PASS neighborhoods will provide more detailed data on resource provision and the decision-making processes that lead to provisioning. Humans provide resource subsidies both intentionally, to attract wildlife (e.g. bird feeding), and unintentionally (e.g. swimming pools), and resource provisioning likely contributes to feedbacks from wildlife viewing that enhances human quality of life and attachment to place (Dallimer et al. 2012).



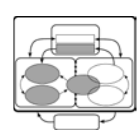
***Research Question 2.a:*** What are the physical dynamics of and controls on heat and climate in the urban ecosystem, including outdoor water use, at scales relevant to plants, people, and [other] animals? (Leads: Hondula & Ruddell)
***Rationale:*** The past three decades of research have established a solid empirical basis for the UHI and the mesoscale climate effects of urbanization in the desert Southwest (Balling and Brazel 1987; Brazel et al. 2007; Georgescu et al. 2011; Chow et al. 2012; Georgescu et al. 2012; Grossman-Clarke et al. 2014). The UHI is a product of altered surface materials that absorb, store, and release more thermal energy than the surrounding desert landscape. Anthropogenic heat emissions also contribute modestly to the effect (Salamanca et al. 2014). Only a few global cities have as strong a UHI as documented for the PMA, with nighttime temperatures often 10° C higher than in the surrounding desert. The UHI provides us with a natural experiment on the social-ecological dynamics of heat, wherein the urban core is substantially hotter, and sometimes wetter, than the desert (Chow et al. 2014). However, city dwellers, the built environment, and the plants and animals that populate the urban ecosystem experience and perceive climate and heat dynamics at a "human scale" of only several meters. At this scale, dramatic gradients create large differences in temperature, solar radiation, and moisture—differences that often far exceed the urban-rural differentials that typically define the UHI. This is the scale at which people, plants, and animals live their lives and experience ecosystem stresses and services related to heat and climate, and it is the scale at which the built environment is managed through policy and engineering.

Many urban ecology questions depend on a quantitative understanding of the physical dynamics of heat and climate, at a multitude of scales. But we lack sufficiently diverse and representative observations of urban ecosystem heat and climate at the human scale because long-term monitoring by weather services typically collects data in isolation from human activities. We propose to expand empirical observations of physical micrometeorology around the city at the "human scale," along with residential water use. CAP II and III pioneered these types of observations in our NDV experimental neighborhood, in the Power Ranch neighborhood in southeastern PMA, with our urban eddy flux tower, and our urban homogenization neighborhood research (Chow et al. 2014; Middel et al. 2014; Volo et al. 2014; Häb et al. 2015b; Hall et al. 2016). In CAP IV, we will expand these observations to include controlled landscape modification experiments, mobile multi-scale observational campaigns and tree-canopy studies, backyard landscape composition and heat campaigns, and our urban flux tower.

IRT Participation



***Approach:*** We will expand backyard micrometeorology (Hall et al. 2016) and mobile transect campaigns (Häb et al. 2015a) to include a stratified sample of Re-PASS neighborhoods, urban core sites, and riparian sites (e.g., Salt River, Indian Bend Wash). This rich spatiotemporal dataset will represent a variety of urban landscapes, creating a comprehensive human-scale microclimate dataset. We will co-locate these observations with other core long-term CAP observations to explore socioeconomic and biological relationships and will include seasonal and diurnal transects of *in situ* measurements of temperature, humidity, wind, canopy structure, radiation, and soil moisture. We will use these data to establish a physical basis for human-scale climate and heat dynamics in arid cities and develop models that provide microscale and regional climate predictions (e.g., Weather Research and Forecasting models (WRF) and urban canopy extension models; Chow et al. 2014; Shaffer et al. 2015; Vanos et al. 2016). These models will allow us to explain and extrapolate urban climate dynamics into the past and future as part of our scenarios and futures work.



***Research Question 2.b:*** What are the human stresses associated with climate and heat, what urban services are affected, how have these stresses and services changed over time, and what role does urban infrastructure play? (Leads: Hondula & Ruddell)

***Rationale:*** Many environmental factors shape the stress experienced by people and organisms in urban ecosystems. CAP work has established heat as a health stressor for cohorts of people, neighborhoods, and specific locations, with demographic and geographic factors determining the severity of stress (Harlan et al. 2012, Petitti et al. 2013, 2016). Using a decade of census-scale observations of temperature, urban form, and demographics, we can now explain the dozens of deaths and hundreds of hospitalizations and emergency room visits each summer in the PMA (Fig. 2.7, Petitti et al. 2016). We will continue to document climate-related stresses and services and how these have changed over time.

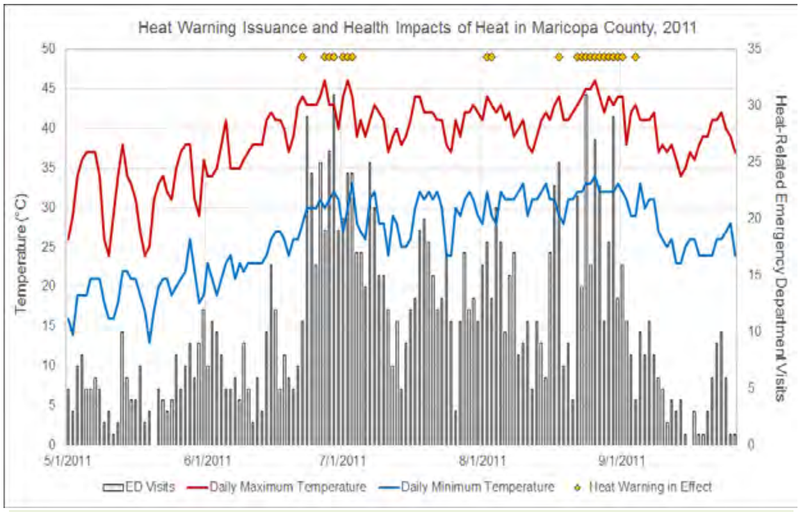


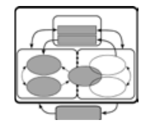

**Figure 2.7**: Comparison of daily temperatures (red and blue lines), heat-related mortality (gray bars), and issuance of heat warning products (red bars) by the Phoenix forecast office of the National Weather Service in summer 2011. Records of issuance of heat advisory products are a long-term data set available for CAP IV as a potential determinant of behavioral changes related to climate and heat (adapted from Pettiti et al. 2015).

The frontier of this science is to link individual outcomes with individually experienced stresses and services at fine "human" spatial scales based on individual exposure (Jenerette et al. in press; Vanos et al., 2016; Kuras et al. 2015). We will emphasize heat stress effects on the health of urban residents, as mediated by a suite of social and cultural determinants that we are only beginning to assess in the context of environmental exposure. Human health is an important dimension of urban ecology. In CAP IV we will focus on growing the evidence base that enables effective identification and deployment of adaptation strategies to mitigate adverse climate-related health outcomes. In the PMA, irrigated landscaping and vegetation mitigate urban heat. We will continue to collaborate with Decision Center for a Desert City (DCDC) researchers to explore relationships between summer heat and water use at both household and neighborhood scales. We have demonstrated how Homeowner Association (HOA) rules for landscaping affect water use and how redesigned rules may be more effective. Interestingly, non-HOA neighborhoods tend to use more water than HOA-governed neighborhoods. Through this research, both CAP and DCDC are working with practitioners from the Phoenix and Maricopa County planning departments on reducing outdoor water use through changes in residential landscaping choices.

IRT Participation

***Approach:*** We propose to collect stratified observations of outdoor human activities co-located with microclimate and backyard transects and in Re-PASS neighborhoods. As an illustrative case, we will examine how neighborhood microclimate and demographics determine the real exposure of its residents to climate stresses and services during the course of daily activity. Infrastructure designs, individual behavior and preferences, and access to resources determine individually experienced microclimates. We expect that health outcomes will be more closely related to individually experienced microclimates than to average regional climatic conditions (Kuras et al. 2015; Bernhard et al. 2015).

This research will assess human-centric microclimate while also accounting for time and activity patterns. We will relate these indicators to health outcomes and to the design of the built environment using our long-term LULCC data and Re-PASS surveys. We will use existing data and new observations to develop "Individually Experienced Temperature" human-scale models of thermal comfort and surface temperature (Vanos et al. 2016) that will run at individual, neighborhood, and citywide scales. We will use these models in conjunction with our urban design experiments to explore how various configurations of urban infrastructure affect the thermal comfort—and ultimately the health—of urban residents. Our results will inform better designs for urban infrastructure. Importantly, because the primary drivers of physical microclimate dynamics are spatial rather than temporal, we will employ a space-for-time substitution to extrapolate microscale measurements to the entire CAP domain and entire history of CAP datasets by matching microclimate observations with LULCC data. The result will be a seamless map of heat and climate services across the PMA and their historical changes at fine spatial scales.

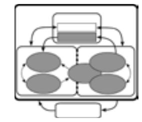


***Research Question 3:*** How do socioeconomic and institutional dynamics affect and control urban infrastructure and associated urban services, and do infrastructure failures and/or concerns for services induce societal actions regarding infrastructure and its governance? (Leads: White & York)
***Rationale:*** We define institutions 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 designing and managing urban infrastructure, 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, yet uncertainty may mediate the impact of the disturbance on adaptations and change (Larsen 2015). While incremental change often dominates the policy-making arena (Arentsen et al. 2000), dramatic institutional change may occur as a result of extreme events (external disturbances in Fig. 2.2; Baumgartner et al. 2014) or shifting coalitions (internal perturbations in Fig. 2.2; Ellison 1998). Infrastructure failures may necessitate allocation of more resources or investment to new technologies (Tompkins and Eakin 2012), including a shift from "fail-safe" gray infrastructures to "design with nature" green, blue, and turquoise infrastructures (Pincetl 2010). Infrastructure itself mediates the opportunities for policy change constraining the decision space (Johnston 2010). Although society often focuses policy-making attention at state and federal levels, local-level governance of land use and infrastructure often determines urban ecosystem structure and function. In short, formal government actors are responsible for only a fraction of decisions about urban infrastructure design and management (Wiek and Larson 2012; K. 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. 2.2), and changes to urban infrastructure, such as improved green spaces, may actually drive demographic changes, such as gentrification (Eckerd 2011).

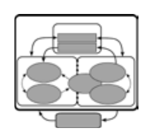
IRT Participation

***Approach:*** Cadenasso and Pickett (2008) demonstrated how increased use of "design with nature" green infrastructure to manage urban stormwater has resulted from environmental change informing federal regulation and legislation. Building upon this foundation, we will analyze long-term datasets to document infrastructure design and management decisions by both government and nongovernmental actors using analytical, qualitative, and quantitative methods for policy change analysis (Sabatier and Weible 2014). We will also use PASS and Re-PASS survey results to evaluate public opinions on various environmental policies and link these perceptions to changes in water, heat, and land cover at an individual level (York and Munroe 2013). We will develop 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 4.a:*** What are the spatiotemporal patterns of change in residential LULCC, design, and management at multiple scales, and how do they affect tradeoffs in local-to-regional urban services? (Leads: Hall & Larson)
***Rationale:*** Residential landscapes compose the dominant fraction of green infrastructure in cities and provide urban services to residents (Cook et al. 2012). Our research has explored theory, patterns, and social-ecological drivers of residential biodiversity (Kinzig et al. 2005; Walker et al. 2009; Ripplinger et al. in review), microclimate (Chow et al. 2012; Middel et al. 2014; Hall et al. 2016), and soil properties (Kaye et al. 2008; Heavenrich and Hall in review). We have also explored the multifaceted factors that drive homeowner landscape preferences (e.g. Larsen and Harlan 2006; Larson et al. 2009a) and how fine-scale LULCC affects "human-scale" climate and UHI effects (Li et al. 2016). However, few studies have considered long-term patterns and outcomes of residential landscape change using a tightly integrated social-ecological approach (Larson et al. 2010; Cook et al. 2012; Larson et al. 2015b). In this research, we will test theory related to ecosystem service tradeoffs (Raudsepp-Hearne et al. 2010) and the social-ecosystem conceptual model of Cook et al. 2012 (Fig. 1.3) by co-developing and integrating our Re-PASS surveys, ESCA sampling, and LULCC datasets. By working across known social-ecological gradients, we aim to better understand how and why people make decisions about their yards and neighborhoods and how the outcomes of these decisions affect critical urban services or disamenities.
***Approach:*** We will assess patterns of residential landscape change using our long-term LULCC datasets and parcel-scale assessments of green infrastructure from the ESCA sampling. Additionally, we will use the Re-PASS dataset to assess the decisions and outcomes of residential landscape design and management, including homeowner attitudes, perceived urban services, and neighborhood norms. We will also assess homeowner perceptions about urban services and risks, including environmental conditions and extreme events such as flooding. To increase social-ecological integration among these long-term datasets, we will co-locate new ESCA plots in the parcels of Re-PASS survey respondents, and both surveys will take place in the same year (2021). Additionally, we will gather data on a recurring basis from the yards of participating homeowners on local microclimate and biodiversity, as we are able to access properties. Our sampling of the patterns and outcomes of residential landscape management will complement our research questions on the institutional drivers of LULCC. For example, we will continue to analyze policy documents to understand the influence of land-use plans, zoning, local ordinances, and other formal intuitions on residential LULCC decisions. Finally, every other year we will conduct semi-structured interviews with urban planners, plant nurseries, and landscape professionals/companies to identify the informal institutions (i.e., norms, customs) governing residential land use/cover change and management.

IRT Participation

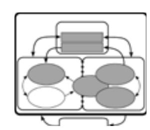


***Research Question 4.b:*** How do institutions, satisfaction with the neighborhood environment, neighborhood setting, and risk perception affect household decision-making, and how does environmental change spur adaptation? (Leads: Larson & York)
***Rationale:*** In cities, individual parcel-level decisions regarding land management and adaptation to social-ecological change are significant, perhaps even the most dominant decisions affecting the landscape (Irwin and Geoghegan 2001). Theoretically, landowner decisions are constrained and encouraged by institutions including, but not limited to, government institutions such as zoning and planning (Kane et al. 2014; York et al. 2014), agricultural subsidy and insurance programs (Eakin et al. 2016), water policies (Harlan et al. 2006; Gober et al. 2013), and private institutions, such as HOA rules (Turner and Ibes 2011; Lerman et al. 2012). Cultural and gender identity (Larson et al. 2011b), as well as neighborhood norms (Larson and Brumand 2014) often mediate these decisions. Changing environmental conditions also spur management and adaption decisions (Morss et al. 2011), but environmental change is not monolithic. Climate change, for instance, impacts neighborhoods differently based upon socio-

demographics and urban services provided by the existing infrastructure (Harlan et al. 2006; Jenerette et al. 2011). Perceptions of risk (Lindell and Hwang 2008; Lo 2013) affect individual decision-making, needs, and well-being (Luck et al. 2011; Matsuoka and Kaplan 2008), as well as satisfaction with the local neighborhood environment (Hur et al. 2010; Ellis et al. 2006). It is thus critical to understand individual perceptions of the environment, the feedbacks between the individual residents and the environment, and how institutions and infrastructure mediate these relationships. We also seek to understand how bottom-up, parcel-scale decisions aggregate to the neighborhood and city scales, and how these decisions affect the functions and services of urban infrastructure.

IRT Participation

***Approach:*** To better understand the decisions of individual residents, we will focus on how homeowners manage their yards, their perceived environmental amenities and risks, and how they cope with presses and pulses (e.g., drought, heat, flooding). This study will follow four major constructs: 1) land management (land cover/vegetation choices, irrigation technologies and practices, fertilizer/chemical applications, and pruning decisions); 2) risk perceptions (of heat stress, water scarcity, flooding); 3) urban adaptation (behaviors to mitigation or cope with heat, drought); and 4) environmental dis/satisfaction (e.g., with birds, trees, water resources). All of these have been incorporated into re-PASS surveys for longitudinal analyses. Residential land use dominates the PMA urban landscape (Kane et al. 2014), and this provides us with an opportunity to examine, using "natural experiments", many unique decision-makers within differing local conditions—i.e. neighborhoods. This will allow us to examine how environmental satisfaction and risk perception lead to management and adaptation decisions. We will couple parcel-scale management decision data with parcel-level analysis using secondary zoning data and our high-resolution LULCC data. This will enable us to address how institutions and individual perceptions of environmental risk or satisfaction drive decision-making at the parcel level, and in turn how these individual parcel-level decisions aggregate to the neighborhood and city scales.



***Research Question 5.a:*** How does existing urban infrastructure affect urban services and human well-being and how is it changing over time? In particular, how does the distribution of infrastructure—legacies of infrastructure design—create "hotspots" for transporting, transforming, and removing materials, and how may these effects be capitalized upon, or corrected? (Leads: Grimm & Hartnett)

***Rationale:*** This research will use a watershed approach to address linkages between infrastructure and urban services by assessing how infrastructure design affects the fate and transport of materials in urban ecosystems. "Design with nature" infrastructure is a key development in urban design that promotes services and benefits (e.g., IBW in Scottsdale; E. Larson et al. 2013). Cities are major sinks for many materials, such as phosphorus and $H_2O$ (Metson et al. 2012), and urban infrastructure regulates biogeochemical function (Larson and Grimm 2012; Hale et al. 2015). For example, Hale et al. (2015) reported that green stormwater infrastructure in IBW increased nutrient retention and decreased runoff, while providing recreation and aesthetic services, relative to gray infrastructure (i.e., pipes) or native desert drainages. Yet, the Hale et al. (2015) study encompassed only two years of relatively mild storm events. As our long-term stormwater database grows, we will continue to link events of different magnitudes to both ecohydrological and social responses.

IRT Participation

***Approach:*** To answer this question, we propose to expand our long-term stormwater sampling in IBW by adding a stormwater collection site up-watershed of the existing outflow location and establishing a sensor network for flow, turbidity, and nutrients over a variety of infrastructure types. The design for these additions will take advantage of existing gradients in "grayness" of infrastructure. We will install sensor sets and automated water samplers at locations along IBW that integrate inputs from subwatersheds with different types of infrastructure. We will couple the data from sensors, discharge gauges, and stormwater chemistry samples with LULCC data and micrometeorological data as inputs to a distributed hydrologic model (modified after Vivoni et al. 2007). We will use the model to determine which infrastructure types are effective at retaining versus conveying water and materials and to test how these services have changed over time. We will link this work with the 2021 Re-PASS survey to ascertain perceptions of the benefits (or harms) residents receive from stormwater infrastructure in their neighborhoods.

We will also explore other types of ecosystems receiving stormwater from IBW to assess how well we can generalize the Hale et al. (2015) conceptual model (Fig. 2.4) to other types of blue and turquoise infrastructure (Fig. 2.8). For example, automated samplers in the "accidental wetlands" of the Salt River will allow us to examine the impact of different land covers on material export and datasondes that we will install in TTL will allow us to detect responses to stormwater inputs and other disturbances. We will supplement this long-term sampling with process-rate studies of nutrient removal and retention in different infrastructure types. Finally, our urban design researchers will analyze city planning and design documents related to "design with nature" infrastructure and, together with our hydrologists and biogeochemists, will hold design charrettes with stormwater managers, planners, and designers to explore impacts of future urban-design processes.

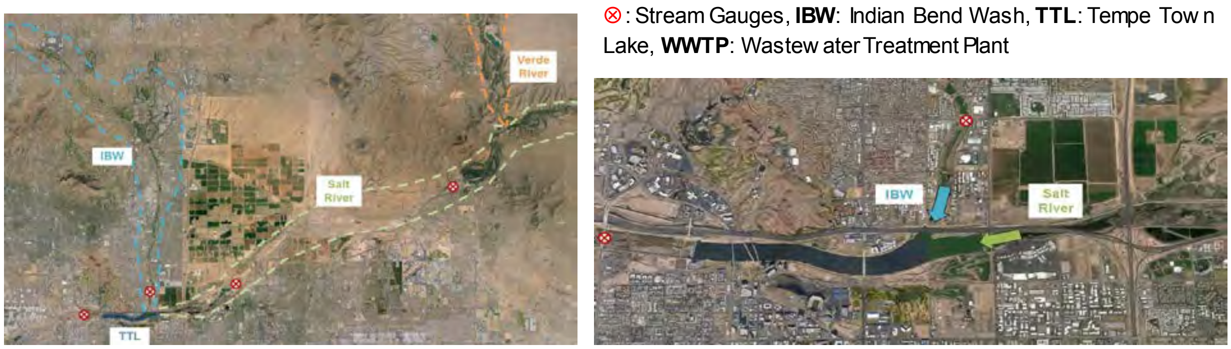
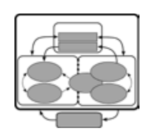



**Figure 2.8**: Left: Regional view of the NE portion of the CAP study area, including the Salt and Verde Rivers, IBW, and TTL. Right: Close-up showing the lower IBW, TTL, and ASU's Tempe campus; two of the "accidental" wetlands are circled in yellow.

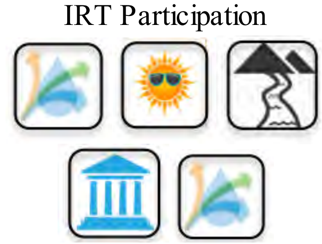
***Research Question 5.b:*** How do presses (climate change, land-use change), pulses (extreme events), and management influence water availability and water quality, organic matter accumulation, and the movement of materials in the urban ecosystem? How do these factors affect people and to what extent do these presses and pulses disrupt or enhance urban services? (Leads: Grimm & Hartnett)



***Rationale:*** This question, based in disturbance theory, concerns the ways that internal and external perturbations, per Figure 2.2, affect the fluxes of water and materials within the urban ecosystem and thereby alter the purveyance of urban services. For example, changes in the variability, seasonality, and extremes in precipitation may or may not be detectable against the urban signal in these data, which may mute perceptions of and responses to these changes. This question relies upon the interpretation and continued collection of long-term biogeochemical data from green (IBW, ESCA, DesFert), blue (RWQ, TTL), and turquoise (Tres Rios) infrastructure. We have documented water-quality variation, on both short and long time scales, in our RWQ and TTL datasets (Figs. 1.8 & 2.5). We have also found that desert plant responses to fertilization vary among years depending upon precipitation (Hall et al. 2011). We now want to determine how these systems respond to change at various time scales. A question further linking the biophysical and social templates in our conceptual framework then becomes whether people's enjoyment of urban lakes and wetlands, or desert wildflowers, or their perceptions of the taste of their drinking water, vary on similar or different time scales than these sorts of climatic events.

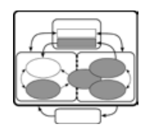
***Approach:*** To answer this question, we will combine a time-series analysis with continued long-term sampling of biogeochemical variables

IRT Participation



in water, air, and soils at sites associated with "design with nature" infrastructure. To examine how increasingly extreme events (pulses) and the press of increasing aridity will affect biogeochemical processes, we will continue high-frequency water quality sampling in TTL, IBW, Tres Rios, and our reservoirs and water-supply canals (RWQ) using *in situ* datasondes, discrete sampling, discharge gauging, and meteorological data. For TTL, we will use these high-resolution data to parameterize a dynamic predictive model that links climate (temperature, precipitation) with biogeochemical processes. We will compare model output with observed patterns to assess system behavior. To better constrain rates that inform parameterization of this model, we will conduct process-rate measurements during summer monsoon and winter frontal passage conditions. We also propose to continue our ARIMA time-series modeling of long-term water quality data from the continued RWQ sampling of CAP's primary surface-water sources (Fig. 2.8) and to relate these trends to long-term patterns in climate variability.

We will determine the effects of LULCC, land management, and atmospheric deposition on slow-cycling soil chemistry variables by analyzing soil characteristics data from our 20-year ESCA dataset. We will continue biogeochemical sampling (atmospheric deposition, soil chemistry, and plant tissue chemistry) at our DesFert sites and assemble climate and weather data from the regional parks. Time-series analyses will enable us to evaluate how nutrient deposition, nutrient storage in soils, soil carbon, tissue chemistry, and plant growth respond to year-to-year changes and longer term climate variation. We will also continue long-term DesFert experimental nutrient additions to test our expectation that N is limiting only to annual plants and only during wet years. We will add rainfall manipulation experiments at select DesFert sites, through collaborations with DroughtNet, to test the impact of reductions and additions of seasonal rainfall on plant growth and soil carbon and nutrients. Finally, we will analyze data on human use of urban mountain parks and preserves (entry numbers, permit applications, estimates of participation) to assess peoples' use of the parks and how this use changes over time. We will couple this information with Re-PASS questions related to perceptions about "design with nature" infrastructure and associated aesthetic and recreational values.



***Research Question 6.a***: How do land-cover mosaics (e.g., riparian areas, wetlands, lakes, and residential areas) along the Salt River vary in their provisioning of urban services, and what role do governance and infrastructure play in shaping these patterns? (Leads: Bateman & Wutich)

***Rationale:*** Phoenix is a river city and the centrally located Salt River is its river (Figs. 2.3 & 2.8). Although it has not been a perennially flowing river since 1938, several reaches of the river throughout the PMA feature riparian, lacustrine, even riverine characteristics. For example, TTL was constructed in the Salt River and the Tres Rios constructed treatment wetlands discharge water into the river. In other areas of the Salt, regular flows from stormwater outfalls support "accidental" wetlands in the riverbed, with potentially important impacts on urban service provisioning (Palta et al. in review).

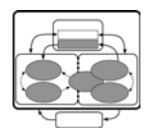
In CAP IV, the Salt River will be a focal point to build our understanding of ecosystem processes, decision-making, and urban planning and design so that we can better manage our urban streams and floodplains for humans and biodiversity. A major challenge facing aridland riparian systems will be managing both climate change and the water demands of human population growth. The Salt River provides cultural urban services as a corridor of green spaces and waterways by enhancing satisfaction of urban residents—particularly of those living near the river (Tyrväinen 1997; Jim and Chen 2006). As urban areas expand worldwide, there is an increasing need to identify sustainable ways to rehabilitate urban rivers and the urban services they provide (Bernhardt and Palmer 2007; Everard and Moggridge 2012). Our place-based research along the Salt River will expand on our previous long-term work quantifying birds, herpetofauna, and arthropods to examine how future growth and LULCC will affect the social-ecological structure and function of the Salt River and the human communities that interact with it.

IRT Participation

***Approach:*** We propose to explore urban service provisioning by the Salt River by evaluating its faunal metacommunities, habitat connectivity, and human use. We will use our long-term vertebrates, invertebrates, and

LULCC data to address large-scale spatial and temporal changes in species abundance and distribution. We will compare service provisioning across LULCC types and different hydrologic regimes (perennial versus intermittent flows). We will also continue to quantify bird, herpetofauna, and ground-dwelling arthropod community structure and abundance. Groundwater, stormwater inputs, and local precipitation support vegetation in urban riparian ecosystems. We will explore how these water sources and ecosystems vary in provisioning plants and animals in terms of supporting different functional groups, guilds, or metacommunities (Banville et al. in review). We will develop Bayesian models to explore food web dynamics as a function of hydrologic condition and determine the importance of aquatic versus terrestrial energy sources to riparian consumers using $^{13}C$ and $^{2}H$ isotopes (Doucett et al. 2007; Bartels et al. 2012). Perennial sites typically support more diverse and abundant aquatic macroinvertebrate communities and thus consumers (invertebrate predators and vertebrates such as lizards and birds) should incorporate a greater proportion of aquatic-derived energy sources in their diet.

As Phoenix becomes more water-efficient (due to increased demand for water, less supply, or both), we will evaluate how water quantity influences the Salt River and its urban services. Using long-term trends in LULCC with past decades of water quality and streamflow data, we will explore how the surrounding watershed has influenced water quantity and quality in close coordination with the work being done to answer Research Question 5a. Different reaches along the Salt River represent a gradient of management intensity, from highly managed and planned (e.g., TTL) to areas supported by passive water inputs forming “accidental” wetlands (Bateman et al. 2015). We will evaluate how social-ecological processes vary among these managed and unmanaged areas (per Palta et al. in review). To determine controls on faunal communities, we will rank multiple regression models using a multi-model inference approach (Burnham and Anderson 2004). We will also continue our sociological evaluation of how humans use and perceive these areas (e.g., recreation, sense of place, perceptions of water scarcity) using Re-PASS survey questions and with more directed place-based sampling of key sites in the river itself (Palta et al. in review).

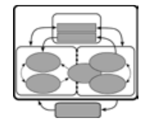


***Research Question 6.b:*** How do ecological properties and processes (e.g., primary productivity, nutrient dynamics, ecological communities) in urban mountain parks and protected areas respond to presses, pulses, and management practices, and how do these responses alter human use, perceptions, and the urban services derived from those areas? (Leads: Grimm & Hall)

***Rationale:*** Urban parks and preserves are thought to provide important services to people, but the demand for and quantification of those services are less well understood (Bagstad et al. 2014). Among the frequently cited benefits, urban parks increase psychological health and quality of life by mitigating floods and climate extremes, by purifying air and water, by enhancing biodiversity and nutrient cycling, and by providing places for physical activity and recreation (Chiesura 2004; Kinzig et al. 2005; Hall et al. 2011; Ibes 2015). Furthermore, local and regional parks contribute $140 billion to local economies in the US and support 1 million jobs. In Arizona alone, parks created $2.1 billion in economic activity in 2013 (NPRA 2015). We propose to coordinate our ongoing long-term monitoring in local and regional parks to identify the 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 will explore the recursive relationship between human actions and park urban services. Our long-term datasets will be key to this effort. Additionally, we will use questions in the 2021 Re-PASS to identify the urban services or dis-amenities of open space areas across a range of socioeconomic communities.

IRT Participation

***Approach:*** We will continue monitoring primary production, nutrient cycling, animal communities, and vegetation structure, composition, and distribution in the long-term experimental sites associated with our bird surveys, ESCA, the Salt River riparian surveys, and the DesFert experiment. We will explore new methods for monitoring ecological variables, including camera traps and audio monitoring equipment, and we will incorporate our findings into current modeling frameworks developed for our system (e.g., the Zhang et al. 2013 ecosystem model). We will use 2021 Re-PASS survey questions to identify residential attitudes, beliefs, and preferences about urban park services. And we will expand our collaboration with the McDowell Sonoran Field Institute to monitor invasive plant species in native open space parks and identify potential sources of invasive species (e.g., from residential landscapes).



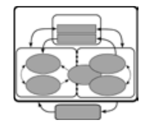
***Research Question 7***: How can governance and institutions support the design of sustainable and resilient "design with nature" infrastructure? (Leads: Chester & Coseo)
***Rationale***: This question addresses knowledge gaps regarding the design process and outcomes of "design with nature" infrastructure. We will test and refine the Childers et al. (2015) Urban Design-Ecology Nexus model through a series of Urban Design Experiment Projects (UDEP). The UDEP will examine how integrating ecology, design, and social science into the design decision-making process of new "design with nature" infrastructure impacts biophysical and social outcomes. Unlike traditional linear design approaches, the UDEP will integrate evidence-based feedback loops into decision-making processes from design, construction, and management stages. Our premise is that research must move from only examining current ecological conditions to also participating in the creation and management of sustainable and resilient constructed ecologies (Lawton and Jones 1995; Felson et al. 2013; Steiner et al. 2013; Grose 2014; Tanner et al. 2015; Childers et al. 2015). Therefore, we will use the Urban Design-Ecology Nexus model of Childers et al. (2015) to co-produce "design with nature" infrastructure. Traditional urban design processes often do not produce "design with nature" infrastructure that enhances ecosystem integrity and human well-being while building adaptive capacity to withstand myriad urban perturbations and uncertainty.

"Design with nature" infrastructure is an ecological approach to design that anticipates failure while adding resilient capacity to the long-term sustainability of urban services (Ahern, 2011, 2013; Grimm et al. 2016). Such "safe-to-fail" infrastructure will enhance the long-term flexibility, adaptability, and resilience of urban systems, thus limiting the loss of critical urban services. In this model, urban services are sustained during non-extreme events, while response during extreme events is more about resilience and less about performance. "Safe-to-fail" infrastructure provides multiple urban services, while "fail-safe" infrastructures, such as levees or concrete river channels, typically provide only one service. Using the "design with nature" approach with "safe to fail" design also avoids hard, rigid, locked-in infrastructure, and associated systemic inertias, making it easier to redesign infrastructure when environmental conditions or societal expectations change. Our stormwater research in IBW is an example of how we are studying the efficacy of "safe-to-fail" infrastructure. As traditional fail-safe gray infrastructure becomes more expensive to build and maintain, and fails too often, municipalities are becoming more interested in using "safe-to-fail design with nature" infrastructure, particularly when facing an uncertain future.

IRT Participation

***Approach:*** To test the Urban Design-Ecology Nexus model, we will build on the Felson and Pickett (2005) concept of *design experiments* or "…urban design projects as ecological experiments" using the design experimental approach of Childers et al. (2015). We will use a Before-After–Control-Reference-Impact (BACRI) experimental design similar to Walsh et al. (2015), which is 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. We will use three criteria to select our UDEP sites: 1) Projects where developers are willing to work with us to include design experiments; 2) projects focused on "design with nature" infrastructure; and 3) projects that allow us to leverage CAP's place-based research for our control and/or reference sites. We will select control locations from existing Re-PASS, ESCA, DesFert, or faunal sampling sites. Finally, to integrate the new sites into existing CAP efforts, we will also incorporate long-term LULCC data to inform the design process with spatial context. Examples of potential UDEP sites include a Low Impact Development streetscape project in downtown Tempe, near

ASU's main campus, and the redevelopment of ASU's campus golf course into a sustainable mixed-use compact development. Notably, both are near TTL, IBW, and the Salt River—all foci of CAP IV place-based research efforts. We will collect data on the case, control, and reference locations, before and after construction, targeting both the design process and outcomes. Data on the design process will be coordinated with efforts in Research Question 5.a to compare past urban design processes with the Urban Design-Ecology Nexus model (Childers et al. 2015). We will collect site data to compare case, control, and reference locations and will apply these evidence-based results to our scenario development (see Research Question 8, below).



***Research Question 8***: What do scenarios of sustainable and resilient futures for the Phoenix urban region look like and what are the tradeoffs and uncertainties among different decisions? (Leads: Iwaniec & Redman)
***Rationale***: In CAP III, we developed participatory modeling approaches to explore desirable and plausible future scenarios for the PMA (Iwaniec et al. 2014). These scenarios provided researchers and city planners with help developing strategies to transition from the current state to a desirable future state (Iwaniec and Wiek 2014; Iwaniec et al. 2014). In CAP IV, we will emphasize the 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 sustainability and resilience. Our objective will be to co-develop scenarios that guide development of urban futures toward sustainable and resilient pathways.

Exploring diverse sustainability and resilience pathways is key to guiding visions and planning in cities. However, sustainability and resilience pathways are different and may even be incompatible (Redman 2014). Our scenario development will explore potential responses, tradeoffs, and uncertainties associated with various presses and pulses, both internal and external (per Fig. 2.2). The resilient pathways will develop strategies to build capacity for the PMA to adapt to "new normal," extreme events, unpredictable changes, and uncertain futures.

IRT Participation

***Approach:*** We will co-develop these scenarios, encouraging city, county, state, federal, and tribal decision-makers, and research partners to participate as full partners and explore the robustness of diverse futures (Lang et al. 2012; Weaver et al. 2014; Kishita et al. 2016). Predictive models are critical for our scenarios and futures work; we will continue 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 model (Middel et al. 2014), and DCDC's WaterSim model (Sampson et al. 2016). We will use our long-term datasets and predictive modeling output to simulate press-and-pulse disturbances in order to evaluate a range of scenarios under different regimes of uncertainty and variability. By building on our social-cultural-economic and biophysical datasets and models, we will explore scenarios that provide a balance of services to enhance human well-being and ecological integrity while avoiding undesirable developments. We will integrate this effort with other projects at ASU and in Phoenix, including the recently funded UREx SRN (see Section II.g), with local and regional stakeholders, and with LTER network-wide scenario activities.

**f. Research Integration and Core Area Connections:** Our conceptual framework (Fig. 2.2) is our most important tool for programmatic integration; we mapped all Research Questions to this framework. The questions begin with those that are more biophysical or social, largely addressing ecology *in* the city (Research Questions 1–3). Our last two questions are broadly transdisciplinary and future-focused, with the sustainability-centered goal of making the PMA a better place to live—they are true ecology *for* the city (7 & 8). The remaining Research Questions are interdisciplinary and holistic, and thus address an ecology *of* the city. Our long-term datasets and experiments also map to the framework in support of these questions. As we note above, we have organized our researchers into eight IRTs and mapped all Research Questions to these. Every question depends on the interdisciplinary expertise of at least three IRTs, and many questions will involve the participation of five or more IRT. This demonstrates the broad extent to which we bring diverse and interdisciplinary groups together to answer all of our research questions. Finally, we have also mapped each Research Question and our long-term datasets and experiments to the seven LTER Core Areas to clarify these integrative connections and to demonstrate our coverage of the Core Areas (Table 2.1).

**Table 2.1.** Mapping of how each CAP IV research question and the CAP IV foundational long-term datasets and experiments map to, and cover, the seven LTER Core Areas.

| | Primary Production | Organic Matter Dyn. | Populations & Communities | Biogeochem. Cycles | Disturbance | LU/LCC Dynamics | Social-Ecological Systems |
|---|---|---|---|---|---|---|---|
| **Question 1.a** | | | X | | X | X | X |
| **Question 1.b** | | | X | | X | X | X |
| **Question 2.a** | | | | | X | X | X |
| **Question 2.b** | X | | X | | X | X | X |
| **Question 3** | | | | | X | X | X |
| **Question 4.a** | X | X | X | X | | X | X |
| **Question 4.b** | | | X | | X | X | X |
| **Question 5.a** | | X | | X | X | X | X |
| **Question 5.b** | | X | | X | X | X | X |
| **Question 6.a** | X | X | X | X | X | X | X |
| **Question 6.b** | | | | | X | X | X |
| **Question 7** | | | | | X | X | X |
| **Question 8** | | | | | | X | X |
| **LU/LC/LA change** | X | | | | | X | |
| **Re-PASS** | X | | X | X | X | X | X |
| **ECSA** | X | X | X | X | | X | |
| **DesFert Experiment** | X | X | X | X | X | X | |
| **Other Faunal Sampling** | | | X | | X | X | |
| **Tempe Town Lake** | X | X | | X | X | X | X |
| **Tres Rios CT wetlands** | X | X | | X | | | X |
| **Regional Water Quality** | | X | | X | X | | X |
| **Economic & Census** | | | | | | X | X |
| **Long-term Meteorology** | X | X | X | X | X | X | X |

**g. Related Research:** CAP has always had a close and collaborative relationship with the DCDC—a NSF-funded Decision-Making Under Uncertainty center that recently began its third round of funding. Three members of the CAP IV Leadership Team are on the DCDC Executive Committee, so we anticipate that this cross-program integration and synthesis will grow during CAP IV. Several CAP scientists are working on an "urban homogenization" NSF-funded Macrosystems research project (Lead PI: P. Groffman) that is supporting urban systems research at CAP and BES, as well as at the FCE, PIE, and CDR LTER sites. Our new focus on residential urban systems and our Residential Landscapes &

Neighborhoods IRT are both products of this collaborative effort. Several ongoing urban systems research networks have leveraged CAP, including the Urban Sustainability RCN (Lead PI: Childers), the new UREx SRN (Lead PI: C. Redman), and the Urbanization & Global Environmental Change Network (see Program Management Plan and Facilities statement for more details).

**h. Cross-Site Research:** We share a long history of collaboration and collegiality with our sister urban LTER program in Baltimore (BES). Much of our work with has been organic and informal, though, and we propose to strengthen and formalize this valuable connection. We will send at least one CAP scientist and student to the BES Annual Meeting and host a BES student and scientist at our annual All Scientist Meeting. Each year, our Executive Committee will work with the equivalent at BES to choose a cross-site theme and use that theme to decide which "ambassadors" to send to each other's meetings to spark collaboration. As a result, every year we will work with BES scientists and students on a new cross-site comparative research project, with the products being synthetic analyses and publications, new multi-city experiments, or proposals for larger initiatives.

## III. Broader Impacts

**a. K-12 Schoolyard Program**: Ecology Explorers, our K-12 Schoolyard program, has connected teachers and students with CAP scientists through schoolyard-friendly urban ecology protocols and learning modules. We host three-to-five day summer professional-development programs to share our research with teachers and help implement these programs throughout the school year. These teacher programs are the most cost-effective way to share our research and impact classrooms (Bestelmeyer et al. 2015). We will continue to offer this program, as well as share urban ecological knowledge directly with students through summer camps. We will tailor lessons to CAP IV research by incorporating urban services and infrastructure into lessons and curriculum modules. Notably, these ideas link well with the Next Generation Science Standards and 21$^{st}$ Century Skills. Additionally, we will create more teaching material that uses CAP data, working with CAP researchers and students to create student-friendly datasets to use in "Data Jam" events (Bestelmeyer et al. 2015).

Through Ecology Explorers, undergraduate students will continue to work directly with low socioeconomic status students in classrooms and in after-school settings. Under the direction of our education coordinator, these students will present a series of active learning lessons around themes such as the urban heat island, urban biodiversity, and residential landscapes. We will complete work on our CAP children's book, focused on our herpetological research. We will craft teaching modules associated with this story, and our student interns will share the book and these resources in classrooms and after-school programs. Finally, we will continue to engage the K-12 community by including our scientists and graduate students in our summer teacher workshops, classroom visits, and family-oriented events. We will highlight CAP research in the "Meet the Scientist" section of our Ecology Explorers website. Ecology Explorers will continue its online presence through this website and through an online Urban Ecology course offered through ASU's Teacher's College Professional Learning Library.

**b. Citizen Science**: Through CAP III, we have engaged in citizen-science projects across the PMA. We will continue these projects while seeking more opportunities with community partners. Our most active project links us with the McDowell Sonoran Conservancy's (MSC) research center, the Field Institute. Citizen scientists collect data that help guide land management in Scottsdale's McDowell Sonoran Mountain Preserve. The Institute manages seven arthropod pitfall trapping transects, and we will test pilot a DesFert experimental site there. We will also continue collaborating with the Central Arizona Conservation Alliance (CAZCA), administered by our long-time community partner, the Desert Botanical Garden (DBG), on a citizen-science wildflower survey. The CAZCA is a partnership among an array of public, nonprofit, and academic entities, including [among others] the City of Phoenix Parks and Recreation Department, Audubon Arizona, and Maricopa County Parks and Recreation Department. The DBG has trained citizen botanists to document plant diversity in regional parks, and these volunteer botanists will continue to participate in the spring wildflower survey at the DesFert sites. In the future, the MSC Field Institute is interested in working with CAP and our CAZCA partners to develop citizen science trainings/workshops for other regional parks. Finally, the Climate & Heat IRT will continue collecting personal temperature data from urban dwellers using “i-buttons.” We will investigate expanding this “i-button” work to schools whose teachers use our Ecology Explorers UHI education module.

**c. Community Partnerships & Engagement:** We will continue to work with organizations in the PMA to share and co-produce urban ecological knowledge that will provide a richer basis for local and regional decision-making. We collaborate with the Sustainable Cities Network to reach our 26 area municipalities and have long-term relationships with many of their decision-makers and planners through our Scenarios & Futures IRT work. Our LULCC team will continue to work with DCDC researchers and Maricopa County water managers to track changes in residential turf landscaping, and they will work with the City of Goodyear to discern how yard architecture 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 we note above, we have strong partnerships with the MSC Field Institute and the CAZCA (see Letters of Commitment). We will continue to work closely with the Valley Permaculture Alliance on their shade tree program. 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 that serves previously homeless families and those at risk of homelessness.

**d. REU and other Student Support Programs:** We will extend our successful REU Program into CAP IV with stipend and research-supply support for two to three students per summer plus travel and subsistence support for out-of-town participants. In our experience, many of our REU students have been local, allowing us to support three students each year. We will continue to benefit from ASU’s ESA SEEDS chapter, based in the School of Life Sciences (CAP Co-PI Grimm is their faculty sponsor), and the ESA’s SPUR Fellowship Program as a recruitment vehicle for our REU Program. We will endeavor to provide REU support to as many underrepresented students as possible. Undergraduate research experiences of all kinds are an excellent pipeline into CAP-related graduate programs, and we will actively recruit minority students using this pipeline.

CAP IV will support graduate research experiences and education in various ways. We will continue our successful Grad Grants program, which annually provides up to $4000 each to as many as 10 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 the previous year’s Grad Grant awardees. In addition to Grad Grant support, CAP will continue to provide travel funds for students to present their research at conferences. Our students benefit from CAP’s infrastructure, including vehicles, lab analysis, technical support, and publication costs. Academic units at ASU that house CAP scientists have agreed to support graduate students (e.g., summer stipends) in their urban research.

**LITERATURE CITED**

**Bold** font denotes the 10 most significant papers from CAP III
blue font denotes papers that acknowledged CAP support
* denotes papers co-authored with CAP III REU students
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