Rich Lizards: How Affluence, Land Cover, and the Urban Heat Island Effect Influence Desert Reptiles Persisting in an Urban Landscape

by

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ABSTRACT

A global warming of two degrees Celsius is predicted to drive almost half the world's lizard populations to extinction. Currently, the Phoenix metropolitan region in Arizona, USA, is an average of 3 ^{o}C warmer than the surrounding desert. Using a bare lot as a control, I placed copper lizard models with data loggers in several vegetation and irrigation treatments that represent the dominant backyard landscaping styles in Phoenix (grassy mesic with mist irrigation, drip irrigated xeric, unirrigated native, and a hybrid style known as oasis). Lizard activity time in summer is currently restricted to a few hours in un-irrigated native desert landscaping, while heavily irrigated grass and shade trees allow for continual activity during even the hottest days. Maintaining the existing diversity of landscaping styles (as part of an ongoing mitigation strategy targeted at humans) will be beneficial for lizards. Fourteen native lizard species inhabit the desert surrounding Phoenix, AZ, USA, but only two species persist within heavily developed areas. This pattern is best explained by a combination of socioeconomic status, land cover, and location. Lizard diversity is highest in affluent areas and lizard abundance is greatest near large patches of open desert. The percentage of building cover has a strong negative impact on both diversity and abundance. Despite Phoenix's intense urban heat island effect, which strongly constrains the potential activity and microhabitat use of lizards in summer, thermal patterns have not yet impacted their distribution and relative abundance at larger scales. With the rise of designer habitats and citizen scientists, ecologists and the general public will play a broader role in evaluating and managing urban parks and green spaces in America. This revised decision making process would benefit from the inclusion of concepts from environmental ethics like ecological citizenship, as well as a re-evaluation of traditional conservation priorities. A reduced emphasis on large protected areas, native biodiversity, static park designs, and hard boundaries between nature and the city would allow for a new generation of ethical urban environments, which can provide a wider array of current benefits while remaining adaptable to the needs and values of future generations.

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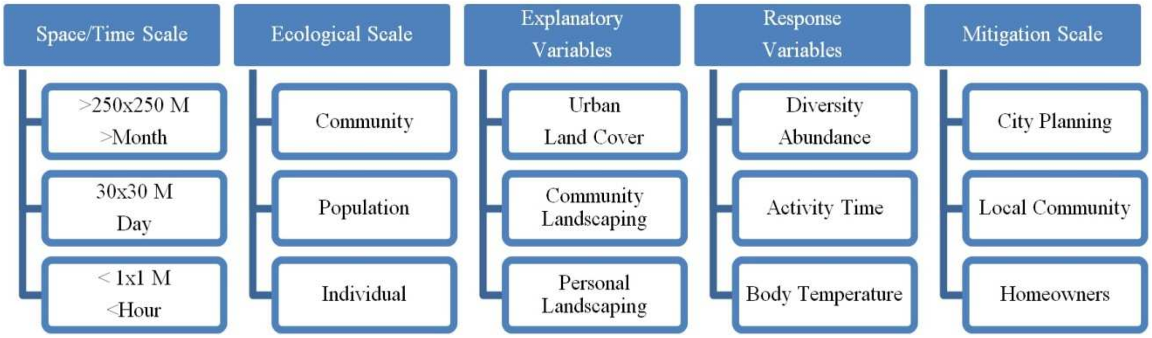
PREFACE

Two questions have driven my work over the past six years, (1) does the urban heat island effect (UHI) influence lizards, and (2) how could the science of urban ecology reshape environmental decision making processes in cities? Chapter one summarizes my major findings and places them in a broader context based on the science and practice of urban ecology over the past decade. As much of this dissertation has been previously published, the articles based on my three main projects were reproduced in an appendix to avoid the appearance of copyright infringement. Their relationships are shown in the following diagram.



Appendix A describes how local landscaping decisions shape the body temperatures and activity patterns of lizards on small and medium spatiotemporal scales. Appendix B describes how large and medium scale changes in urban land cover impact the diversity of lizard communities and population abundances. Appendix C describes the process of how value-based environmental decisions are made at various mitigation scales in cities, and how conflicts arise from mutually exclusive design goals pertaining to urban parks and green space. The epilogue in appendix D explores how my empirical work in appendix A and B is related to the themes of environmental ethics and social justice in appendix C by showing how this knowledge of urban policy processes influences how I design and execute ecological studies in landscapes which are continuously altered by human decisions before, during, and after data collection.

CHAPTER 1

REVIEW AND SYNTHESIS

As environments shaped by natural process are additionally modified by human ecosystem engineering, the basic organismal objectives of survival and reproduction become increasingly hard to meet for many species, often leading to a reduction in biodiversity. In environments like cities, human activities are driving ecological change alongside temperature and rainfall, prompting a scientific shift from study the ecology of organisms *in cities*, to the study *of cities* as dynamic ecosystems with their own ecology (Grimm, Grove et al. 2000). Amazingly, socioeconomic variables like household income now exert a greater influence on plants and reptiles than biophysical variables in some cases (Luck, Smallbone et al. 2009; Ackley, Wu et al. 2015).

Reviews and compilations of vertebrate ecology from an urban ecosystem perspective were first developed for avian species (Marzluff 2001), aided by a large number of preexisting studies of birds in cities. Despite a comparative scarcity of studies on urban reptiles (Müller, Ignatieva et al. 2013), a ~600 page “Urban Herpetology” compilation volume (Mitchell, Jung et al. 2008) offers a comprehensive overview of human activities and their respective impacts, including habitat fragmentation, road effects, pollution, invasive species, and the utility of novel habitats such as golf courses.

The differing physiologies and natural histories of amphibians and reptiles predictably resulted in different study areas, methodologies, results, conservation implications, and future research priorities (also see Barrett and Guyer (2008)). Thus, the first part of this review chapter will be focused on what we have (and have not) learned about urban reptile ecology since the publication of "Urban Herpetology" in 2008. This book made a commendable and prescient effort to include studies of urban wildlife population management, environmental regulations, community education and participatory research, bringing it closer to the most recent trends in urban sustainability, known as ecology *for the city*. This places an emphasis on research that (from the outset) integrates urban planners, engineers, local stakeholders, and scientists to improve urban habitats for all organisms, and lessen the ecological hazards associated with built environments. An emerging research topic with particular relevance to reptiles is the threat posed by the urban heat island effect (UHI). This phenomenon subjects organisms living in cities to higher temperatures than those from rural populations, but only a few studies have investigated UHI effects on ectotherms. Thus, the second half of this review will broaden the ecological context to explore the relationship between our variable urban thermal environments, and how organisms may adapt to, migrate away from, or locally exploit them.

Where Are They (and Where Haven't We Been Looking)?

Most recent studies of urban reptiles continue the trend of being situated in relatively natural parks, streams, forest fragments and other green spaces in or near cities

(Meshaka, Smith et al. 2007; Barrett and Guyer 2008; Vignoli, Mocaer et al. 2009; Garden, McAlpine et al. 2010; Banville and Bateman 2012; Bogosian, Hellgren et al. 2012; Hunt, Guzy et al. 2013; Sullivan, Sullivan et al. 2014). This is partly due to urban reptile densities typically being highest in these areas (sometimes even radically exceeding the biomass of natural habitats) (Ackley and Meylan 2010), but it is also a likely an artifact of urban ecology's relative youth as a field and its basis in applying traditional ecology theories within city limits. Island biogeography is one of the most common themes, where semi-natural areas are treated as islands with varying sizes and degrees of isolation floating amidst a seemingly inhospitable urban sea (Vignoli, Mocaer et al. 2009; Faeth, Bang et al. 2011). However, this very solid urban matrix is fully capable of supporting reptile populations.

Studies in residential areas that often constitute the majority of a city remain rare (Ackley, Angilletta et al. 2015), as are those that include multiple urban land cover and use types (Ackley, Muelleman et al. 2009; Pulev and Sakelarieva 2013), have random study site locations (Germaine and Wakeling 2001; Ackley, Wu et al. 2015) or cover larger regions that include multiple cities (Meshaka 2011). Interestingly, a bell-curved pattern has already emerged from the few available studies where terrestrial reptile diversity increases when moving from natural areas into subtly modified habitats near the urban fringe, before declining in heavily developed areas (Germaine and Wakeling 2001; Ackley, Muelleman et al. 2009; Ackley, Wu et al. 2015), a pattern not simply driven by the presence of exotic species but by biophysical variables and processes like disturbance. These larger scale studies will certainly become more practical with the increasing use of bulk data collection methods such as camera traps (Pagnucco, Paszkowski et al. 2011) and citizen science observation networks (Price and Dorcas 2011; Cunningham, Davis et al. 2012).

What Are They (Not) Doing?

Possible shifts in the behavior, physiology, and community demographics of reptiles living in urban areas have received less attention than in birds, but urban lizards may have lower levels of stress hormones and less symmetrical bodies (French, Fokidis et al. 2008; Lazić, Kaliontzopoulou et al. 2013). Both measures are related to external stressors, however neither have a straightforward cause and effect relationship. Bilateral symmetry should be lower in highly stressed populations, but it is influenced by many other variables. One would think that stress levels would be higher in urban populations regularly exposed to novel disturbances and predators, but the observed reduction in corticosteroids could have resulted from higher resource availability in urban habitats or a down-regulated stress response due to frequent exposure.

Lower and less variable flight initiation distances in urban lizards compared to rural populations support the hypothesis that urban reptiles are down-regulating their responses to stressors (as novel disturbances like walking humans no longer present a high predation risk), allowing for greater resource acquisition time (Grolle, Lopez et al. 2014). Predation is one of the few multi-species processes which have been investigated for urban reptiles. In Florida, explosive population increases of invasive green iguanas occurred when raccoon population control efforts effectively eliminated their sole predator (Meshaka, Smith et al. 2007). Florida’s vast number of introduced reptile species will doubtless make it a test case for the idea that urbanophilic species already thriving in cities should be actively removed and restricted from semi-natural urban areas. Should we make these spaces more attractive to urbanophobic native species, which may soon require alternative conservation initiatives in the face of continual habitat loss (Rosenzweig 2003; Meshaka 2011)?

Urban Heat Islands

The study of rising temperatures as a result of the urban heat island (UHI) effect (and climate change to a lesser extent) has been heavily focused on how organisms (primarily humans and plants) modify their biophysical environment and surrounding thermal landscape. The resulting impacts of higher temperatures on urban organisms have received much less attention (Youngsteadt, Dale et al. 2015). "Urban Herpetology" makes one brief uncited mention of the UHI as a pollutant like noise and light that might reduce habitat quality (Mitchell, Jung et al. 2008). At the time, the UHI was an "unknown unkown" for reptiles: we didn't know if it was a problem and hadn't even thought about solving it. Soon afterwards, we learned that only a 2 ^{o}C increase in global temperatures would not just act as a pollutant and reduce habitat quality, but could effectively result in habitat loss and fragmentation on a massive scale with the potential to drive almost half of all global lizard populations extinct by 2080 (Sinervo, Mendez-de-la-Cruz et al. 2010).

Existing UHIs have already surpassed many pessimistic 100-year global warming predictions, and temperatures in Phoenix, AZ, USA, have currently reduced potential summer lizard surface activity to an hour or two per day in xeric landscapes (Ackley, Angilletta et al. 2015). Phoenix's 3-4 ^{o}C UHI does not yet seem to have resulted in a citywide reduction in lizard diversity and abundance, possibly due to the many patches of mesic landscapes that are 10-15 ^{o}C cooler and still allow for continual activity (Ackley, Wu et al. 2015). This raises the point that global lizard extinctions have already been partially mitigated by the assumptions of previous studies that lizards would not move to cooler habitats, shift their activities to cooler seasons, or undergo physiological or genetic adaptation (Sinervo, Mendez-de-la-Cruz et al. 2010; Urban, Richardson et al. 2014). Thus the UHI is now a "known unknown" for reptiles, we know it's potentially a serious problem, but not what can or should be done to solve it.

Some useful future research directions may be found in the small but growing number of studies on how other organisms react to the UHI. For instance, smaller urban species with shorter generation times are already adapting to higher temperatures. Compared to rural populations, four urban fungi species grow faster at higher temperatures and one urban ant species tolerates heat better, suggesting that the UHI is driving increased performance at higher temperatures (McLean, Angilletta Jr et al. 2005; Angilletta, Wilson et al. 2007). These changes are also having an effect on one of the largest and oldest urban organisms in what is probably the best studied system of its type: that of UHI effects on trees, parasitic scale insects that feed on trees, and second-order "hyperparasites" that feed on scale insects.

Trees are one of the most effective UHI mitigation strategies, and along an urban temperature gradient in Raleigh, NC, USA, trees from warmer areas grow faster but also are more water stressed and in worse condition (Dale and Frank 2014). Tree condition was primarily related to the presence of scale insects, which in turn were strongly influenced by temperature. Warm areas of the city had 13 times more scale insects than cool areas. When raised in a warm greenhouse during a reciprocal transplant experiment, urban scale insects taken from warm areas had higher reproductive rates than those taken from cool areas. The rate of hyperparasitism on the scale insects did not vary with temperature, but hyperparasites were more common in warmer urban areas as a result of increased host abundance (Meineke, Dunn et al. 2013). When comparing Raleigh and the surrounding rural area, scale insect abundance peaked at a certain temperature, but their density was highest in the city (Youngsteadt, Dale et al. 2015).

Increasing urban soil temperatures by ~2.5 ^{o}C resulted in a 10% increase of the leaf area index of trees in Manchester, UK, and a 13% increase in evaporative water loss despite the increased water stress of higher temperatures, presumably resulting in improved environmental cooling from a UHI mitigation standpoint (Rahman, Armson et al. 2014). This factorial experiment simultaneously investigated the influence of urbanization by compacting the soil around certain trees and installing concrete flagstones near the trunk. Pavement can create a soil UHI effect of up to 20 ^{o}C and extend the growing season — this treatment resulted in a 20-30% increase in annual tree growth but it also reduced water loss and associated environmental cooling.

In a parallel with research on global warming, mobile organisms are adaptively responding to the UHI by shifting their behavioral patterns, often to exploit geographic areas and temporal periods that would have otherwise have been too cold. Arrival dates of migratory bird species have traditionally been later in cities than the surrounding rural areas, but the UHI effect seems to now be driving a shift towards earlier arrival times in cities than rural areas (Tryjanowski, Sparks et al. 2013). Elevated temperatures likely contribute to urban plants flowering earlier than their rural counterparts, though differing soil moisture and atmospheric CO_2 levels likely play a role (Neil, Landrum et al. 2010; Buyantuyev and Wu 2012). Of course the UHI is a driver of all three of these variables, and in turn is driven by them. Warmer urban temperatures also increase the potential for sandflies to survive the winter, which may explain isolated populations in Paris, France, and Budapest, Hungary, both of which lie north of the usual range limit for *Phlebotomus* species (Trájer, Mlinárik et al. 2014). As sandflies are the primary vector of leishmaniasis, this may represent another public health concern driven by UHI, which is already linked to heat stroke and respiratory ailments in humans (Harlan, Brazel et al. 2006).

Who Will Win and When?

These varied examples of physiological adaptation, behavioral modification, geographic range shifts and altered seasonal activity patterns all suggest that many organisms have the potential to mitigate their exposure to the UHI effect and climate change. While physically isolated populations close to the equator that have adapted to a narrow range of tolerable temperatures may be at an increased risk of extinction, it is doubtful the assumptions behind Sinervo's prediction of a 40% decline in global lizard populations will hold (Sinervo, Mendez-de-la-Cruz et al. 2010). Species currently limited by cold will likely benefit from the UHI, as long as they can survive increased summer temperatures. The rate of environmental change in cities will doubtless produce sets of winners and losers over the next century, but one thing is certain: there has never been a better time to be an urban herpetologist.

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APPENDIX A

URBAN HEAT ISLAND MITIGATION STRATEGIES AND LIZARD THERMAL ECOLOGY: LANDSCAPING CAN QUADRUPLE POTENTIAL ACTIVITY TIME IN AN ARID CITY

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Urban heat island mitigation strategies and lizard thermal ecology: landscaping can quadruple potential activity time in an arid city

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Abstract A global warming of 2 °C is predicted to drive almost half the world's lizard populations to extinction. Urban heat island (UHI) effects may further exacerbate the impacts of climate change on organisms that are sensitive to small changes in temperature. Currently, the Phoenix metropolitan region in Arizona, USA, is an average of 3 °C warmer than the surrounding desert. With continuing urbanization and climate change, thermal stress will become an increasingly important facet of urban ecology in coming decades. The main objective of our study was to investigate which landscaping styles and microhabitat variables can most effectively reduce the surface temperatures experienced by lizards. Using a bare lot as a control, we placed copper lizard models with data loggers in several vegetation and irrigation treatments that represent the dominant backyard landscaping styles in Phoenix (grassy mesic with mist irrigation, drip irrigated xeric, unirrigated native, and a hybrid style known as oasis). Our lizard models recorded 6915 estimates of potential body temperatures. We show that lizard activity time in summer was restricted to a few hours in un-irrigated native desert landscaping, while heavily irrigated grass and shade trees allowed for continual activity during even the hottest days. Shade, humidity, and sky view factor explained the majority of variation in temperature at a sub-meter scale. We suggest that maintaining the existing diversity of landscaping styles (as part of an ongoing UHI mitigation strategy targeted at humans) will be beneficial for lizards.

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Introduction

The suburbs of Phoenix, Arizona, USA, have been expanding into the Sonoran Desert at a rate of 1 km per year (MIPP 2000). This development process converts a highly reflective natural substrate into impervious urban surfaces with low solar reflectance and high heat storage capacity. The resulting urban heat island (UHI) represents a mean warming of 3 °C over the surrounding desert [with a substantial variance depending on where, how, and when temperatures are recorded (Brazel et al. 2007)]. Urban warming in Phoenix has doubled the yearly "misery hours" for humans (when the temperature-humidity index exceeds 38 °C) and increased heat stress on other organisms (Baker et al. 2002; Brazel et al. 2007; Ruddell et al. 2013). Air-conditioning can maintain indoor temperatures at desirable levels; however, compensating for a UHI has cost as much as US$100 million per year (Akbari et al. 2001).

Strategies that mitigate the UHI effect differ in cost, effectiveness, and the scale at which benefits are realized. White paint and green plants on rooftops can reduce air temperatures within and above buildings (Kumar and Kaushik 2005). Vegetation provides additional benefits of evaporative cooling and shade, especially when irrigated regularly. Certain backyard landscaping strategies can reduce surface temperatures by over 10 °C during the day, creating a heterogeneous thermal landscape that varies more within Phoenix than between the city and the surrounding desert (Brazel et al. 2007). The cooling effect of a large park can extend several hundred meters beyond its border; Phoenix's Tree and Shade Master Plan—a proposal to mitigate Phoenix's UHI—aims to double canopy cover (from 12 to 25 %) by 2030, primarily by planting trees on public lands (Bowler et al. 2010; Chow et al. 2012).

Since private residences constitute the largest type of land use in Phoenix, individuals and local communities can substantially reduce the UHI through landscaping. Most residences are part of private homeowner's associations (MIPP 2000), which control large areas of communal landscaping and dictate the type of vegetation that individuals can have on their own properties. Plant diversity is higher in wealthy areas than poor neighborhoods (Hope et al. 2003), and for every increase of $10,000 in median household income, the mean surface temperature decreases by 0.3 °C (Jenerette et al. 2007).

Mitigation strategies targeted at improving human comfort and energy use often involve planting vegetation, but the consequences for other organisms remain uninvestigated. In particular, reptiles—a cultural icon of desert life—regulate populations of arthropods, mammals, and birds, including species considered as pests. Warming caused by urban development could have dire implications for these ectotherms. Many reptiles prefer body temperatures that enhance physiological performance, which limits their activity in space and time (Adolph 1990; Christian et al. 1983; Grant and Dunham 1988; Hertz et al. 1982). For most species of lizards, the best performance occurs at a body temperature just a few degrees below the lethal limit. Thus, an optimal microhabitat can become lethal with a small increase in temperature (Martin and Huey 2008). In summer, environments often exceed the lethal limit during midday, forcing lizards underground. Being active at a high temperature increases metabolic rate, and thus the need for energy (Angilletta 2009). Many lizards feed on arthropods that also require microhabitats with suitable microclimates. Thus, while urban lizards have the greatest need to feed during summer, they could have the fewest opportunities to do so. Recent models showed that a warming of 2–3 °C can severely restrict activity (Buckley 2008; Kearney and Porter 2004), potentially resulting in the loss of 40 % of all lizard populations by 2080 (Sinervo et al. 2010). Strategies that increase the spatial and temporal frequency of suitable microclimates for lizards will likely promote their persistence.

Most UHI research has focused on broad scale urban climatology; little work has been conducted from an ecological perspective at small scales where organisms (including humans) experience heat (Baker et al. 2002). Thus, we compared microclimates within common types of urban landscaping. We predicted that cooler temperatures in mesic landscapes would increase the potential for summer activity by lizards in Phoenix. We also investigated which physical variables (shade, substrate type, humidity, etc.) had the greatest influence on microhabitat surface temperature. As we did not compare natural and urban sites or lizard populations, this work was not a direct investigation of UHI impacts on organisms. Our goal was to compare the thermal consequences of different residential landscaping patterns and water uses to determine the relative effectiveness of UHI mitigation strategies currently being employed, and their potential relevance for lizards.

Methods

Thermal physiology of lizards

We determined the thermal limits of motor function (a non-lethal proxy for thermal tolerance) and preferred body temperature in two of the three common urban lizard species in Phoenix: *Uta stansburiana* (Side-blotched Lizards, $N=14$) and *Urosaurus ornatus* (Ornate Tree Lizards, $N=7$). The varying sample sizes were due to *Urosaurus ornatus* being present at fewer locations and at lower abundances. Lizards from multiple urban and desert populations were captured using nooses, and housed according to Institutional Animal Care and Use Committee guidelines by veterinary staff. We did not observe a difference in thermal tolerance or preference between urban and rural populations (t-tests, all $P>0.05$). Lizards were given a minimum of two weeks to adjust to captivity and full spectrum lighting on a 12:12 cycle; and at least 48 h elapsed between all physiological tests. Our procedures followed those of Angilletta (2001) and Angilletta et al. (2002), with minor modifications described below.

Thermal tolerance limits were determined by placing lizards in plastic containers and partially submerging them in water baths. The procedure for maximum tolerable temperature was to heat each lizard gradually until it became immobile. Lizards were heated to 35 °C and then placed in a sealed plastic container (~12x12x10 cm) within a water bath set at 55 °C. After 3 min, the lizard was flipped on its back to check its righting response. If the lizard righted itself within two seconds, it was placed back into the container in the bath. This procedure was repeated every minute until the lizard was unable to right itself. At that point, its cloacal temperature was immediately recorded with a type-K thermocouple. The procedure for minimum tolerable temperature was identical, except that lizards were cooled to a body temperature of 20 °C before being placed in a bath set at 4 °C. Each lizard was randomly warmed or cooled first to avoid an artifact caused by the order of measurements.

We measured preferred body temperatures in artificial thermal gradients. Each gradient consisted of an acrylic box with an aluminum floor (250×40 cm). Hot or cold water was continuously circulated through a copper pipe welded under each end, resulting in a gradient of potential body temperatures between 18 °C and 43 °C. These extremes fall within the thermal limits of locomotion, thus preventing animals from becoming incapacitated if they moved to the edges. Natural substrates can be modified by lizards, and were not used to ensure uniform exposure to the thermal gradient and reduce the occurrence of non-thermoregulatory behaviors. Uniform lighting was used for similar reasons, on the same 12:12 cycle used during captivity. On the evening before measurements, each individual lizard was placed in a gradient about three hours before the lights were turned off. On the following morning, lights were turned on at 07:00 h to stimulate activity. Cloacal temperatures were recorded with a type-K thermocouple every two hours, beginning at 09:00 h and ending at 17:00 h. Repeated handling at this frequency has no noticeable effect on the thermoregulatory behaviors of similar lizard species (Schuler et al. 2011). We did not fast animals before measurements because lizards often have food in their guts during activity; however, no food or water was provided in the gradients to discourage foraging behavior. We entered the room only when recording body temperatures. If we found a lizard trying to escape or showing signs of distress (e.g., running against the plastic, standing on hind legs, or panting with an elevated body), we placed it in the center of the gradient without recording its body temperature.

Estimating lizard body temperatures in different landscapes

We studied the thermal environments provided by different landscaping plots in North Desert Village: an experimental housing project owned by Arizona State University (Cook et al. 2004). This site represents the range of residential landscaping in Phoenix, within which a variety of socio-ecological interactions can be studied, such as the behavior and habitat use of desert lizards in an urban environment. In 2005, the barren common areas (~30×30 m) encircled by a ring of six houses were randomly assigned one of the four stereotypical landscaping styles found within Phoenix: 1) mesic, dense shade trees and mist-irrigated grass covering the entire plot; 2) oasis, a small patch of mist-irrigated grass, bare soil, and drip-irrigated bushes and trees; 3) xeric, drip-irrigated desert plants; and 4) native, un-irrigated local desert plants. Another housing cluster received no landscaping or irrigation, reflecting a common landscape found in backyards and undeveloped lots. All plots lie within 250 m of each other, making nutrients and rainfall similar among treatments. These landscapes are maintained by Arizona State University and residents may not modify the area.

To estimate the temperatures that lizards could attain in each plot, we used hollow copper models molded from live animals (Bakken 1992). Such models are used to integrate the parameters that determine an animal's body temperature, such as convection from airflow, radiation from the sun and nearby objects, and conduction between surfaces. The models estimate an index known as the operative environmental temperature, which we will refer to as the estimated body temperature. This index represents the temperature of a static animal in thermal equilibrium with its environment. Our estimates ignore thermal inertia, variations in posture, color change, evaporative cooling and metabolic heating. The latter two physiological processes have a negligible impact on the body temperatures of small lizards (Bakken 1992). Models were painted with Krylon No. 1314 All Purpose Platinum Spray Primer to achieve an absorbance of 82.9 % between 290 and 2600 nm (Peterson et al. 1993); this absorbance value lies within 5 % of most lizard species (Christian et al. 1996). A temperature logger (Maxim iButton® DS1921G, San Jose, CA, USA) was integrated into the design of each model as described in Bakken and Angilletta (2013).

To validate the models, we placed several on the ground next to a restrained lizard shortly after dawn. The lizard's body temperature was measured with a type-k thermocouple wire inserted into the cloaca. As its body temperature increased from ~25 °C to 40 °C, the internal temperatures of the models were recorded simultaneously. Linear regression showed that the copper models captured approximately 96 % of the variation in the body temperature of the lizard and produced a slope of 1.06 and y intercept of −2.5 (perfect models would produce a slope of 1 and a y intercept of 0). Additional comparisons between lizards of both species and models of various sizes and colors on multiple substrates and in multiple conditions (e.g., full sun, dappled sun, and shade) yielded errors typically < 1 °C, which is well within the 2 °C criteria used by Dzialowski (2005).

Using the validated models, we estimated lizard body temperatures in the various yard types at North Desert Village in June and July of 2012 during ~13-h periods when at least some part of the landscape was exposed to direct sunlight. The Phoenix UHI is a year-round phenomenon, but is most pronounced during this period of long days, low wind, and few clouds (Brazel et al. 2007). June and July are also among the hottest months when lizard activity is most restricted. We only collected data on nearly cloudless days with minimal wind, and waited at least three days after the rare rainfall events during this season. Models were placed by walking a random distance in a random direction from the center of the circular plots. Model placement was stratified such that 10 were on the ground and three models were in a random type of vegetation, at a random height, and a random distance from the vegetation's trunk. The 10:3 ratio roughly reflects the portion of bare ground and vegetation in the plots. Vandalism prevented us from collecting data in multiple treatments simultaneously; on any given day, models were moved between the same two treatments every hour, using new sub-locations each time. Each treatment was measured four times over 10 days to achieve one of each possible pairwise combination of treatments. The models recorded temperature at 10-min intervals. Soil temperatures were recorded at depths of 15, 30, 60, and 90 cm using type-T thermocouple wires attached to a control unit (Campbell Scientific 21× Micrologger, Logan, Utah, USA). Copper models were not used as differing size, shape and coloration would not alter underground temperature readings.

To determine how microhabitats influence potential body temperatures at a sub-meter scale, we recorded distances to the nearest shade and vegetation, height above ground, type of substrate, sky view factor (the inverse of canopy coverage, using a handheld densitometer), and relative humidity for each model location. These data were collected separately from plot data, and only between 10:30 and 15:30 h when the thermal variance was relatively constant and rate of change in mean temperature was lowest. Approximately 30 locations were sampled in each landscaping treatment, except for the bare lot where the nearest shade and vegetation were outside the plot ($N = 137$ among all plots).

Statistical analysis

From a lizard's thermal perspective, we tested whether the fixed effect of each plot's landscaping was different from all the other plots (rather than just different from the bare lot). This required fitting a generalized additive mixed model with cubic regression splines to potential lizard body temperatures in each landscape. Our model accounted for several sources of autocorrelation: temperatures recorded at nearly the same time, on the same day, and by the same copper model were similar to one another. Spatial autocorrelation was minimized by continuously moving copper models within and between plots. Changing sun angles and dappled shade patches further reduced the correlation between individual models during the hour in which they were stationary.

Following Zuur et al. (2009), we compared the fits of several models that differed in the structures of their random effects, such as adding unique error variances for each plot and copper model. We also compared a fixed error variance with one that increased exponentially with increasing Julian date and increasing time of day. Including corrections for date and time allowed us to run one test on the entire data set, rather than conducting separate comparison tests for each of the 10 days we compared landscaping types. The latter approach would have resulted in substantial alpha-inflation. Although these model additions did not affect our conclusions qualitatively, they produced a more likely model, as judged by the Akaike Information Criterion (AIC), and reduced the confidence intervals of the parameters, indicating the improved model fit warranted the additional complexity.

To determine which microhabitat characteristics had the most influence on temperature, plot was treated as a random factor, since we were now interested in explanatory variables at a finer scale. As we collected these data on fewer days and during a narrower daily time window, the best error structure was fixed rather than exponential and excluded the random effect of copper model. All microhabitat variables listed above and their likely interactions were treated as fixed factors. The highest order interactions were removed sequentially until we arrived at the model with the lowest AIC. All analyses were conducted using the R software package (CDT 2005).

Results

There was not a significant difference between the tolerance limits or mean preferred temperatures of the two lizard species we tested (t-tests, all $P>0.05$) and their preferred temperature ranges were almost identical (see Table 1). The lower and upper quartiles of body temperatures selected in our thermal gradients were 26 °C and 38 °C. This preferred range lies well within the range of temperatures that permit movement; typically, lizards became immobile when their median body temperatures fell below 10 °C or rose above 45 °C. During calibration, the 176 temperature differences between live lizards and copper models averaged 0.49 °C, and ranged from −0.9 to +3.3 °C.

We recorded a total of 6915 estimates of lizard body temperature at North Desert Village. The potential body temperatures predicted by our statistical model differed among all landscapes ($P<0.01$), but only the oasis and mesic plots were notably cooler than the bare plot on average (Fig. 1). Temperatures commonly exceeded 60 °C in all landscapes around midday, suggesting that thermal constraints on activity have a major impact on the ecology of lizards in Phoenix. In fact, temperatures within the preferred range (<38 °C) were recorded only during the first 2–3 h of daylight in the native, xeric, and bare landscapes. At any given time, the bare

Table 1 Preferred temperature ranges and tolerance limits of lizards

Species (N)	Mean (SD)	Preferred range	Min tolerance (SD)	Max tolerance (SD)
U. ornatus (7)	31.8 (6.4)	25.4–37.4	9.8 (1.1)	44.9 (1.1)
U. stansburiana (14)	32.6 (6.1)	26.8–37.9	10.2 (1.3)	46.4 (1.3)

The mean and standard deviation (SD) of lizard body temperature (°C) in a thermal gradient were not significantly different between species ($P>0.05$). We defined the preferred range as the central 75 % of observed voluntary body temperatures. Mean involuntary tolerance limits were defined as the thermal limits of lizard motor function, again no significant difference was found between species ($P>0.05$)

plot offered only a narrow range of temperatures ($R^2 \approx 0.95$), probably because of its homogeneous topography (Sears et al. 2011). Native landscaping had slightly greater variation in temperature ($R^2 \approx 0.9$). The addition of irrigation (xeric: $R^2 \approx 0.8$), grass (oasis: $R^2 \approx 0.5$–0.6), and trees (mesic: $R^2 \approx 0.4$–0.6) further increased the variance of temperature (Levene's tests, all $P<0.05$). Interestingly, the highest maximum temperatures were always found in the landscaped plots when compared to the bare plot (Fig. 2a).

The heterogeneity of temperature created by landscaping had major consequences for potential lizard body temperatures. Mesic landscaping offered the greatest opportunity for activity, having 65 % more area within the preferred range than the bare habitat (Table 2). Native, xeric, and oasis landscaping resulted in 5–15 % more area of preferred thermal habitat. The mesic landscape also maximized the potential duration of activity. If we assumed that a lizard could be active when at least one of the copper models fell within the preferred range of temperatures, lizards in the mesic landscape could have been active throughout the entire day. By contrast, lizards in the bare, native, and xeric plots could have been active for less than half of the day. Temperatures underground never exceeded the thermal limits of lizards, but did approach values that trigger high metabolic demands in the bare, native, xeric and oasis plots (Fig. 3). In the mesic plot, underground temperatures varied less and were almost 10 °C cooler at a given depth than in other plots.

Three microhabitat characteristics explained more than 50 % of the variation in estimated lizard body temperatures. Not surprisingly, temperatures were cooler in more humid locations and when closer to shade ($P<0.001$ for both). Sky view factor and distance to shade interacted to determine body temperatures ($P<0.001$); increasing sky view increased temperatures at locations in shade but decreased temperature at locations far from shade (Fig. 4). Substrate type, height above ground, and distance to vegetation did not significantly impact estimated body temperatures ($P>0.05$ for all).

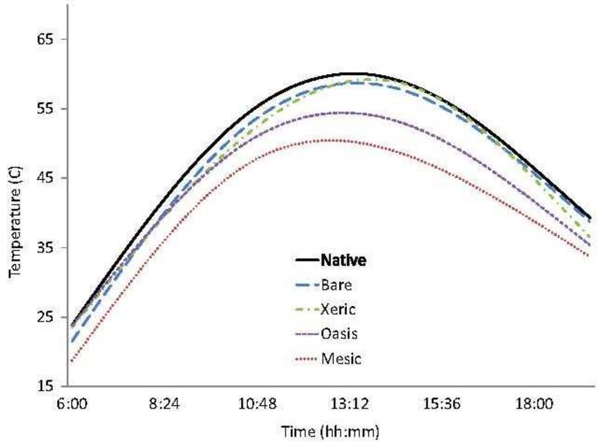

Fig. 1 Each landscaping style enabled lizards to achieve unique patterns of body temperature. The lines show the mean potential body temperatures predicted by our statistical modeling. Using almost 7000 data points, the 95 % confidence intervals are approximately equal to the line widths, thus visually discernible differences are statistically significant. Surprisingly, the native plot was warmer than the bare plot

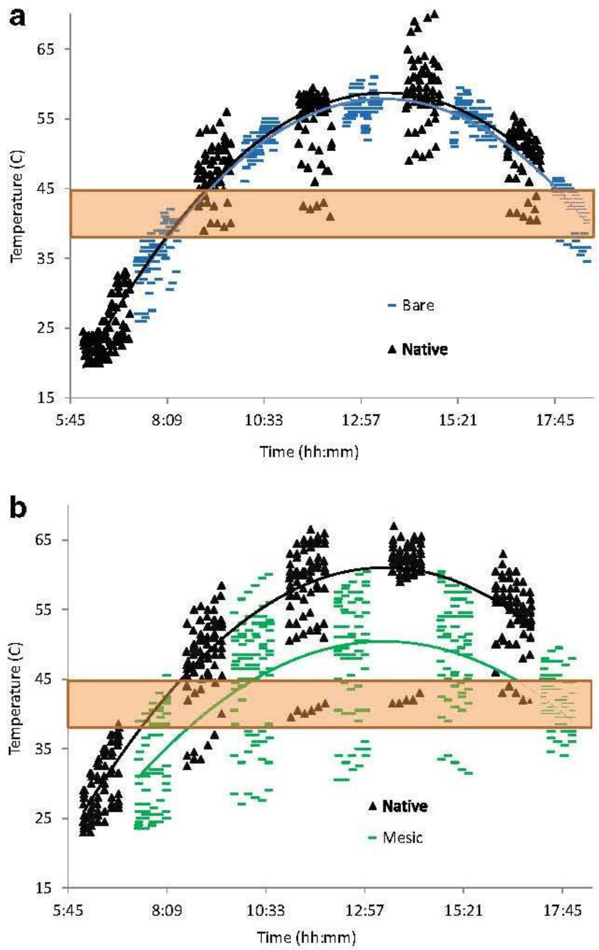

Fig. 2 **a** Un-irrigated native vegetation provided greater variation in potential body temperatures and higher maximum temperatures than bare ground. The orange rectangle indicates the temperatures that exceed a lizard's preferred range (26–38 °C) but fall below the upper limit for movement (45 °C). **b** Mesic vegetation provided even greater thermal variance and lower mean temperatures. Part of the mesic plot remained within the preferred range throughout the day. The mean temperature of the mesic plot remained preferable for approximately an hour longer than did the mean temperature of the native plot. Data depicted in panels **a** and **b** are not directly comparable, as they were recorded on different days

Discussion

Although the mean surface temperature of Phoenix exceeds that of the surrounding desert by 3 °C, microclimates in mesic landscaping are 5–10 °C cooler from a lizard's perspective than in native landscapes. These cooler microclimates come from the humidity and evaporation associated with mist-irrigated grass. The trees, bushes, shade, and drip-irrigation of native and xeric landscapes have minor effects on mean temperatures, when compared to bare ground. Although these conclusions depend on a limited sample of plots at North Desert Village, they

Table 2 The influence of landscaping type on potential lizard activity

	Proportion of area		Proportion of time	
Landscape	Preferred	Tolerable	Preferred	Tolerable
Bare	0.20	0.29	0.23	0.41
Native	0.21	0.32	0.27	0.92
Xeric	0.23	0.41	0.38	1.00
Oasis	0.21	0.48	0.74	1.00
Mesic	0.33	0.54	1.00	1.00

More intensive landscaping caused a higher proportion of the habitat area to fall within a lizard's preferred and tolerable range of temperatures during the summer. Increased landscaping also resulted in an even greater increase of the proportion of time during which any part of the habitat was within the preferred or tolerable limits. The proportion of time within preferred limits is an optimistic estimate of potential lizard activity; if only a small amount of the habitat falls within a lizard's tolerance range, it is doubtful they will know where these areas exists, be able to travel to them, and achieve a net benefit by using them

should be generalizable because shade, humidity, and sky view factor are more important determinants of estimated lizard body temperatures than landscaping type.

Unlike real lizards, our copper models did not move. Thus, temperatures estimated by our models reflect what a lizard's body temperature could be in specific environments without behavioral and physiological thermoregulation. Calculating potential activity time for lizards is challenging, but we can reasonably conclude that lizards would remain inactive when the entire habitat exceeds their preferred range of temperatures. At least some portions of the mesic plot fell within the preferred range throughout the day (Fig. 2b). However, surface temperatures of native and xeric landscapes exceeded the preferred range during the majority of a typical summer day (Fig. 2a). Lizard behavioral ecology will of course influence the subset of microhabitat temperatures they are commonly exposed to. Ornate Tree Lizards (*Urosaurus*

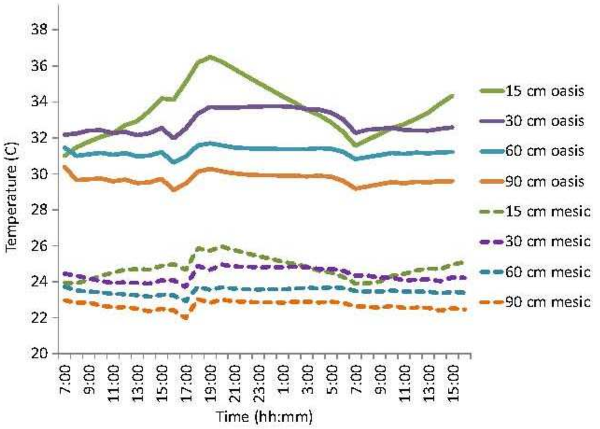

Fig. 3 During a typical summer day, underground temperatures are higher and have more variation at shallow depths. The grassy mesic plot was almost 10 °C cooler on average, sensors in the other plots were buried in bare soil. Underground temperatures in the native, xeric, and bare plots were almost identical to those of the oasis plot, and are not shown. The above ground control unit was often exposed to direct sunlight for a brief period around 7:00 and 17:00 h, which produced a small artificial dip in temperature readings

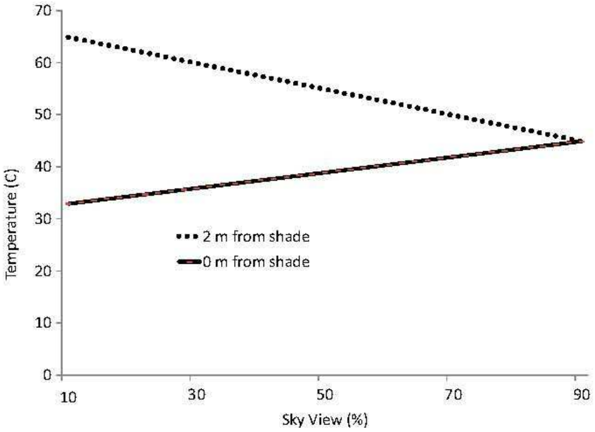

Fig. 4 An interaction was found between distance to shade and sky view. For lizards in full sun, increasing quantities of vegetation (lower sky view and greater canopy coverage) result in higher body temperatures (*dotted line*). Lizards in or near shade were cooled by increasing vegetation (*solid line*), suggesting that the high maximum temperatures found in experimental plots were the result of plants reflecting light and radiating heat onto nearby objects, rather than blocking wind and preventing warm air from moving upwards

ornatus) are primarily arboreal, but can often be found on the ground and will hide in litter and rock piles. Side-blotched Lizards (*Uta stansburiana*) are primarily terrestrial, but can often be found on trees and concrete walls and will utilize existing burrows. The complete lack of preferred surface temperatures during much of the summer could potentially require more extensive use of burrows by all urban lizards in the future.

To use preferred microclimates, lizards must (1) know when and where these microclimates exist, (2) reach them without overheating, and (3) benefit enough from the resulting body temperature to offset the associated energy demands, missed opportunity costs, and predation risks. When these conditions are not met in summer, some lizards will remain underground for days or weeks in a state referred to as aestivation (Pianka 1970). The underground temperatures that we observed in bare, native, xeric, and oasis plots were near the high end of the preferred range of the species we tested, where metabolic demands are greatest. However, the preferred range only applies to animals that are foraging on a daily basis and have adequate water availability; lower body temperatures enable lizards either to aestivate longer or to emerge from aestivation in superior condition. Further warming associated with urban or global change may produce underground temperatures that exceed the upper tolerance limits of some Sonoran Desert reptile species (Cowles and Bogert 1944). Since irrigated grass cools soils by 10 °C, mesic landscaping can extend potential aestivation periods as well as surface activity.

On the sub-meter scale at which most organisms experience heat, vegetation can raise maximal temperatures by reflecting sunlight and radiating heat toward objects already in full sun. This phenomenon would explain our most surprising result: that mean temperatures in native landscaping exceeded those of bare ground. Even mesic landscaping produced higher maximum temperatures than bare ground, despite being much cooler on average. Current plans to increase canopy cover in Phoenix could slightly increase mean surface temperatures if unirrigated native trees are used. However, the associated increase in shade and thermal variation should produce the desired outcome of enabling humans (and lizards) to thermoregulate more effectively. Artificial shade structures could also exacerbate the UHI, depending on the method and scale of measurement. Thermal satellite images are commonly used to estimate surface temperatures (Voogt and Oke 2003), but their bird's-eye view cannot detect shaded areas beneath a canopy. However, the heat stored by the shade structures will be detected, creating an interesting conundrum: mitigation strategies will be effective on small scales at which the UHI is experienced, but may appear counter-productive on larger scales at which the UHI is monitored.

Landscaping projects such as the Tree and Shade Master Plan are more viable components of an UHI mitigation strategy in Phoenix than in other similarly warm and arid climates (Chow and Brazel 2012; Chow et al. 2012). Phoenix has a relatively abundant water supply from groundwater, local rivers, and Colorado River water imported through a canal system (Gober and Kirkwood 2010; Guhathakurta and Gober 2007). Maintaining existing mesic areas could have numerous benefits beyond historical preservation, human comfort, and energy savings, while avoiding the expense and disturbance of converting these established habitats for the purposes of water conservation. We certainly do not advocate increasing overall urban water use or believe that lizards should have a large influence on urban planning, however many local governments may wish to reconsider offering rebates of up to $3000 for property owners who convert grassy areas to xericscapes.

The non-thermal effects of mesic landscaping may be mixed for lizards. The greater abundance of water and arthropods in Phoenix's mesiscapes may be beneficial, but reduced arthropod diversity compared to xericscapes may be detrimental for lizards that specialize on certain prey species (Bang and Faeth 2011). Fortunately, landscapes dappled by various forms of human activity can offer diverse ecological opportunities. The existing variation of backyard landscaping styles are often available within the range of a lizard's daily movements, and could benefit habitat selection on multiple scales: including hourly thermal variation in microhabitats, daily energy requirements, seasonal temperature shifts, and progressive life history stages.

Habitat loss and fragmentation, novel predators and diseases, road mortality, chemical and light pollution, invasive species, and even mountain biking have raised concern among herpetologists (Mitchell et al. 2008). These factors can strongly influence the distribution and relative abundance of species. Nevertheless, temperature dictates when ectotherms can be active, and potentially whether they can survive in an anthropogenic thermal landscape. This widely-overlooked consideration will become increasingly important in an era of climate change and aggressive urban development.

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APPENDIX B

RICH LIZARDS: HOW AFFLUENCE AND LAND COVER INFLUENCE THE DIVERSITY AND ABUNDANCE OF DESERT REPTILES PERSISTING IN AN URBAN LANDSCAPE

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Rich lizards: How affluence and land cover influence the diversity and abundance of desert reptiles persisting in an urban landscape

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ABSTRACT

Fourteen native lizard species inhabit the desert surrounding Phoenix, AZ, USA, but only two occur within heavily developed areas. This pattern is best explained by a combination of socioeconomic status, land-cover, and location. Lizard diversity is highest in affluent areas and lizard abundance is greatest near large patches of open desert. The percentage of building cover had a strong negative impact on both diversity and abundance. Despite Phoenix's intense urban heat island effect, which strongly constrains the potential activity and microhabitat use of lizards in summer, thermal patterns have not yet impacted their distribution and relative abundance at larger scales. As Phoenix emerges from an economic recession, efforts to restrict urban sprawl and encourage higher density development could lower water and energy use while benefiting lizards in undisturbed habitats. However, this would likely exacerbate the urban heat island effect, and pose a threat to native species within the urban landscape.

1. Introduction

Socioeconomic variables such as household income are correlated with ecosystem productivity (Buyantuyev and Wu, 2009) and urban biodiversity patterns of plants (Hope et al., 2003; Walker et al., 2009), birds (Kinzig et al., 2005; Lerman and Warren, 2011), and bats (Li and Wilkins, 2014). In some cases, these "top-down" controls have even more predictive power than the biophysical variables that regulate species distributions and relative abundance from the "bottom-up" (Luck et al., 2009). A ubiquitous "luxury effect" emerged from these studies, in which more affluent areas have higher biodiversity through ecosystem engineering, whereby homeowners introduce exotic plants and supplement natural sources of food and water for animals (Fuller et al., 2008). These changes in the structure and composition of habitats alter the diversity and abundance of arthropods (Bang and Faeth, 2011), which could also influence the habitat selection of highly mobile species such as bats.

Less mobile ground species, such as lizards, risk road mortality when moving in an urban environment and have less choice of which neighborhood they inhabit. However, their persistence in Phoenix, AZ, USA, may still be correlated with affluence because a $10,000 increase in median household income is associated with a 0.3 °C decrease in mean surface temperature (Jenerette et al., 2007). High summer temperatures can reduce the potential activity of lizards in Phoenix to one hour per day (Ackley et al., in press), and cooler temperatures in affluent areas could mitigate a heterogeneous urban heat island effect, which makes the city 3 °C warmer (on average) than the surrounding desert (Brazel et al., 2007). Since management efforts to reduce road mortality and heat stress would differ from efforts to enlarge and connect patches of suitable habitat, determining the relative importance of these variables at different scales will be crucial for managing native species in urban areas. Land-cover maps with a 1 m^2 resolution have recently become available for Phoenix (Li et al., 2014), enabling studies that integrate biophysical and socioeconomic variables with historical changes in the composition and configuration of landscapes. Many of these variables are correlated with each other,

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and may have complex relationships with lizard diversity (e.g., road density could impact dispersal, but may also influence lizards through increased surface temperatures). However, the proliferation of studies that only consider one or two threats to urban reptiles has resulted in uncertainty on how to best concentrate management efforts (Mitchell et al., 2008). Thus, the primary goal of our study is to determine which urban variables have the largest impacts on the diversity and abundance of native lizards.

2. Methods

2.1. Site selection

The Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) project has established over 200 field sites within the city and surrounding desert (Grimm and Redman, 2004). We chose a subset of 28 sites along a gradient of urbanization, stratified by land-use type. Following a protocol similar to Germaine and Wakeling (2001), four sites were located in each of the following categories: desert, urban recreation/open space, agricultural, institutional/commercial, low density residential (>0 and ⩽2 dwelling units per acre), medium density residential (>2 and ⩽5 dwelling units per acre) and high density residential (>5 dwelling units per acre). These land-use categories are roughly equal in relative abundance within Phoenix. Selected plots could not be alongside a ⩾4 lane road, within 0.5 km of an interstate highway, within heavy industrial/commercial areas without open space/landscaping, within 3 km of a previously selected plot, above 600 m elevation, or inaccessible to private citizens by car or foot.

2.2. Response variables

Lizard diversity (number of species per site) and abundance data (lizards per site) were collected by the same person (JWA), using 20 min visual transect surveys at each site. This person scanned the area within 10 m on each side of a 200 m transect for lizards. Time spent identifying species with binoculars was not counted. The orientation and shape of transects were often dictated by roads, in which case it was walked once on each side. As this approach resulted in non-linear transects at many urban sites and some desert sites, the circular buffers mentioned below were drawn as close as possible to the center of the area surveyed. Each site was surveyed twice during fall 2012 (September–October), and four times during spring 2013 (March–May). Surveys were varied to accommodate the range of conditions in which different species were active (25–39 °C air temperature and 08:00–18:00 h on days with low wind and cloud cover). Unidentified lizards were only included in abundance estimates. A site at which only one unidentified lizard was observed was treated as having one species present.

2.3. Explanatory variables

We collected a preliminary data set comprising nearly 50 variables from three functional groups. (1) Site-scale characteristics included measures of habitat area, isolation, land-use history, temperature, traffic, and affluence. (2) Percent abundance of land-cover types within circular buffers of 200-m, 500-m, and 2-km diameter. (3) Landscape-scale metrics of all land-cover types (patch diversity, density, shape, size, spatial configuration, etc.) measured within the same buffers. As expected, Spearman's Rank correlation and a test of variance inflation factors (VIFs) (O'brien, 2007) identified many of these variables as highly correlated; therefore, we began a process of reducing this collinearity to acceptable levels. Data reduction approaches such as principal component analysis (PCA) were not applicable as the preliminary set of explanatory variables was larger than the number of sites we surveyed for lizards.

Extremely high correlations were found between different buffer sizes of the same land-cover types and landscape metrics. Redefining the 500 m and 200 m extents as the difference between their values and the extent they were nested within (500 $\mathrm{m_{new}}$ = 500 m–2 km, 200 $\mathrm{m_{new}}$ = 200 m–500 m) (Zuur et al., 2009) did not reduce their correlations to acceptable levels, so we eliminated the 500-m and 2-km variables because the 200-m extent directly matched the area we surveyed for lizards. The remaining 25 variables were further reduced to 14 by eliminating one of each pair that produced a rank correlation over 0.7. We retained variables according to their management potential, source quality, distinctiveness within our dataset, and if it had been identified as having a significant effect on lizards in previous studies. The final set of 14 variables had variance inflation factors approaching 30, but those in the most likely statistical models had variance inflation factors and rank correlations well below acceptable limits (less than 5 and 0.5, respectively) (Graham, 2003; O'brien, 2007).

We calculated the final set of site variables (see Fig. 2 below) as follows. Straight-line distance to a large desert patch (>5 $\mathrm{km^2}$) was measured in ArcGIS. Median household income was determined from data collected during the 2010 US census (block group data from Maricopa County). Years since a >25% land-cover change was calculated from historical aerial imagery, which are available for Phoenix in ∼15 year intervals from 1937 to 1990, and ∼2 year intervals from 1990 to 2013. The spatial standard deviation of surface temperatures within circular buffers 200 m in diameter was calculated using the Geospatial Modelling Environment and ArcGIS from one of the final images taken by NASA's Landsat 5 Thematic Mapper (Landsat TM) satellite during a day in September 2011 before it was decommissioned. While this was a year before we began collecting lizard data, development (and changes in relative surface temperature differences between sites) had largely stalled following the economic recession. Previous surface temperature images taken in summers of 2010 and 2011 had a correlation of 0.8, despite differences in average temperature between years. We used the standard deviation instead of mean or maximum temperatures for three reasons. First, areas with slightly lower mean temperatures have much greater temperature variance. Second, thermal variation actually impacts potential activity of lizards in Phoenix much more strongly than mean temperatures does (Ackley et al., in press). Third, if future warming in Phoenix imperils the potential for lizards to survive, thermal variation will likely dictate local extinctions rather than maximum temperatures (Ackley et al., in press). Traffic density was calculated within a circular buffer 2 km in diameter, using the Geospatial Modelling Environment and ArcGIS. We used a larger buffer because the data were much coarser in resolution than those for land-cover and temperature. Traffic data were based on a validated model obtained from the Maricopa Association of Government's Transportation Division. Unlike observed traffic counts, modeled traffic data are available for all major road segments within the Phoenix Metropolitan Area. The most recent traffic counts were from 2008. As with temperatures, while average traffic density might have changed since then, relative differences between sites likely remained similar.

We calculated percent abundance of land-cover types using the Geospatial Modelling Environment and ArcGIS from a map with a resolution of 1 $\mathrm{m^2}$ (Li et al., 2014). The classification included trees, grass, shrubs, pavement (roads, sidewalks, and parking lots), buildings, agriculture, and bare soil (including rock). Permanent water was not included in our analysis as it almost never occurred within 200 m of our sites; swimming pools were also removed due to their low relative abundance and a high correlation with grass cover. The accuracy of this ground-truthed map was 92%; it was produced from multi-spectrum aerial photography and cadastral data from summer and fall 2010 (Li et al., 2014). Our site visits and a visual comparison with the most recently available imagery confirmed only minor changes in land-cover (and no major changes in land-use) had occurred within 1 km of our sites.

We calculated landscape metrics for each site from the complete land-cover map (not from individual cover classes) using FRAGSTATS (McGarigal et al., 2002) and ArcGIS. All but one of these metrics were highly correlated with another metric, a specific land-cover type, or a site variable. We only included the most distinctive metric (mean patch size, an indicator of landscape homogeneity), because site and cover data are more widely available and generally easier to calculate, communicate, and manage from an urban planning perspective.

2.4. Statistical analysis

To account for the remaining collinearity between explanatory variables, we constructed a set of possible generalized linear models for lizard abundance, and another set for lizard diversity, following the procedure described in Zuur et al. (2009) using the R software program (R, 2005). Firstly, the explanatory variables were each standardized to have a mean of zero and a standard deviation of one. Then we constructed a set of potential models using an iterative backwards selection procedure that included every possible combination of the explanatory variables this method produces.

We ranked the resulting 90 models (and a null model with no explanatory variables) according to their AIC values, and calculated their AIC weights (the probability that a single model was better than the best model). As no one model stood out as being vastly superior to the others, summing the highest AIC weights until they exceeded 0.95 gave us a reduced set of the most likely models, which we were 95% certain contained the best model (Zuur et al., 2009). We calculated the relative impact of each explanatory variable from this final set by summing the AIC weights of each model it appeared in (its sign [±] was determined by model coefficients). Plotting the normal quantile–quantile or residuals against the expected values derived from the most likely models did not reveal strong violations of the models' assumptions. We found no evidence of spatial auto correlation using spline correlelagrams of Pearson model residuals for all explanatory variables with either diversity or abundance (Zuur et al., 2009).

3. Results

During surveys, we observed more than 300 lizards representing seven native species. Hardly any lizards were seen in the heavily developed area of downtown Phoenix, but similar numbers of lizards were observed in urban parks and sites in open desert. Location did not strongly correlate with diversity; however, a different set of species was present in the city than in the desert (Fig. 1). The most common lizard in developed areas—the ornate tree lizard (*Urosaurus ornatus*)—was never observed in desert areas. The most common lizard in desert areas—the side-blotched lizard (*Uta stansburiana*)—was rarely observed in developed areas. Of the seven species that we encountered, five were rarely observed outside their natural habitats, and only the tiger whiptail (*Aspidoscelis tigris*) was commonly observed across all land uses and cover types.

Our analysis of land-cover types, site variables, and landscape metrics revealed that the proportion of building cover within a 200-m diameter buffer had a relatively large negative impact (<-0.7) on both lizard diversity and abundance (Fig. 2). The proportion of grass, pavement, and agriculture had small (-0.1:-0.3) to moderate (-0.3:-0.7) negative impacts on diversity and abundance. The proportion of bare soil had a moderate negative impact on abundance alone. The proportion of trees and the proportion of shrubs had a negligible ($<|0.1|$) or statistically insignificant ($p > 0.05$) impact on diversity and abundance.

Sites with high median household income had a large increase in lizard diversity, and a small increase in abundance. Sites located more than 5 km^2 from a desert patch had fewer lizards. The number of years since a >25% change in land-cover moderately decreased abundance and slightly decreased diversity. Traffic density and standard deviation of surface temperature within a 200-m diameter did not significantly impact diversity or abundance ($p > 0.05$). Mean patch size of all land-cover types (the only landscape metric included in our analysis) had a moderate positive impact on diversity.

4. Discussion

A weak ($r^2 \approx 0.1$) "luxury effect" of increasing plant richness with increasing average household income has been repeatedly observed in Phoenix, where substantial affluence is required to plant and maintain exotic vegetation in a desert environment (Hope et al., 2003; Walker et al., 2009). We observed a much stronger luxury effect on lizards ($r^2 = 0.26$); in fact, median household income predicted lizard diversity better than any biophysical variable except for building cover. However, all the lizard species we observed were native and homeowners have limited control over them. Since affluence cannot directly enhance lizard diversity, an indirect mechanism must operate. We accounted for correlations between explanatory variables, so the high relative importance of income is not simply a matter of affluent sites having less agricultural cover or being more recently disturbed by land-use change. Income was one of the most distinct variables we considered; all of its other possible regression coefficients with significant diversity variables were very weak or in the direction that would make income less likely to explain diversity.

The positive relationship between affluence and lizard diversity was likely driven by a variable correlated with affluence that we were unable to include in the model, possibly a measure of habitat quality such as the relative abundance of insects or specific plant species. Alternatively, affluence enables one to not only engineer an idealized environment but also to choose where one lives. In Phoenix, high income homeowners prefer more xeric landscaping (Larsen and Harlan, 2006; Larson et al., 2009), and less urban and more natural environments are highly valued regardless of income (Larson et al., 2009). Phoenix residents also prefer (and can correctly estimate) high native bird diversity, but again, low income neighborhoods have fewer species of birds (Lerman and Warren, 2011). If affluent residents are choosing to live in more xeric, less urban, and more biologically diverse areas, they may be indirectly choosing to live in areas with high lizard diversity.

Surface temperatures are substantially lower in affluent areas of Phoenix (Jenerette et al., 2007). This could also explain the luxury effect that we observed, because small differences in temperature may cause global extinctions of lizard populations under climate change (Sinervo et al., 2010). However, our analysis indicated that temperature did not influence the diversity or abundance of lizards during spring or fall surveys. Thermal variation strictly determines the use of microhabitats and the potential duration of activity by lizards in Phoenix during summer (Ackley et al., in press), but this period of potentially lethal heat stress does not yet seem to be having a year-round impact on lizards at larger spatial scales in our study. Future studies will be more likely find an effect, as the loss of foraging opportunities may reduce the population size of future generations, precipitating extinction if individual plasticity and

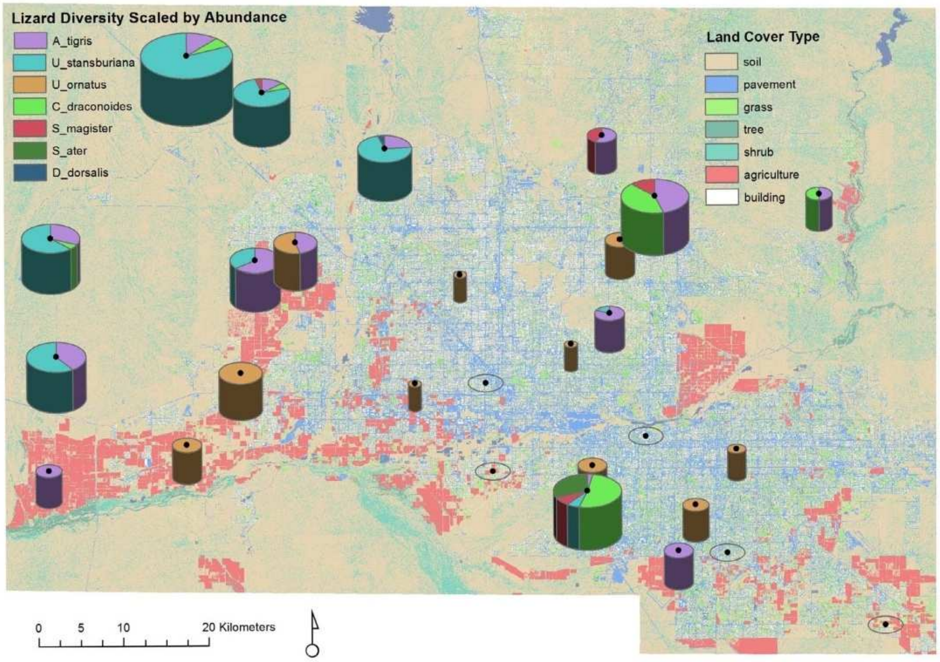

Fig. 1. Lizard abundance declined sharply in Phoenix's urban core. The volume of the cylinders and colored slices indicates relative abundance of different species (the five clear ovals indicate an abundance of zero, the three smallest cylinders indicate a single lizard observation). Sites near the urban fringe and in mostly natural urban parks had similar abundances to desert sites, though a different set of species was present in natural and developed areas. The most species-rich site (bottom center, $N = 5$ species) lies within the largest urban park in the USA. It is the only site with mountainous terrain and had the highest median household income (>200,000 $US per year). The common names of the species listed on the figure are (from top to bottom), tiger whiptail, side-blotched lizard, ornate tree lizard, zebra-tailed lizard, desert spiny lizard, chuckwalla, and desert iguana. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

genetic adaptation cannot track climate changes (Urban et al., 2014).

Instead of using a diversity index that combines the number of species (richness) and their relative abundance (evenness), we decided to consider lizard diversity and abundance separately as they were not strongly correlated and different processes appeared to influence these variables. Diversity and abundance are respectively driven by rare and common species; and management efforts are usually targeted at one or the other. For example, urban habitats could be designed to support rare species and exclude "urban exploiters" that are already thriving (Rosenzweig, 2003). Another issue rarely considered in ecology is the suitability of diversity indices for statistical modeling. Common indices such as the Shannon–Wiener index take on values of either zero, one, or any continuous number greater than one. We are not aware of a probability distribution that works for small numbers of species, because the data cannot include negative values (precluding bell curved distributions) and include discrete counts (precluding the gamma distribution) and continuous numbers (precluding the Poisson and Negative Binomial distributions).

Ecological processes related to habitat size and isolation likely underlie the relationships between land-cover and lizard diversity that we observed. The distance from a large desert patch—a proxy for isolation from a source population—strongly impacted abundance but not diversity. Defining habitat size and fragmentation is challenging in urban environments, because lizards use many built structures and exotic plants. The complete lack of tree lizards at desert sites, and their unparalleled ability to survive in Phoenix's urban core was likely due to their extensive use of concrete walls and introduced shade trees. The desert sites we surveyed were predominantly flat, bare soil, dappled with 10–30% shrub cover (most native tree species have shrub-like morphology, and were usually identified as such by the land-cover classification).

With increasing urbanization, the addition of land-cover types, and fragmentation of large contiguous patches of bare soil patches common to open desert, we observed a reduction in the mean patch area of all land cover types. Although previous studies have used mean patch area as an measure of habitat fragmentation (Fahrig, 2003), this is more appropriate when it is applied to a few types of natural land-cover. When used with highly detailed maps of urban cover such as our map of Phoenix, mean patch area better reflects overall landscape homogeneity. In our case, this variable had a positive impact on lizard diversity.

We found that the years since a land-cover change (>25% conversion) negatively impacted diversity and abundance, suggesting that some changes in land-cover might actually be beneficial on intermediate time scales as undisturbed sites generally had lower diversity. This coincides with previous reports of increased lizard abundance and diversity in lightly developed areas (Ackley et al., 2009; Germaine and Wakeling, 2001). It is important to note that the most recent major land-cover change at any of our sites was 6 years prior to lizard data collection (the oldest available imagery

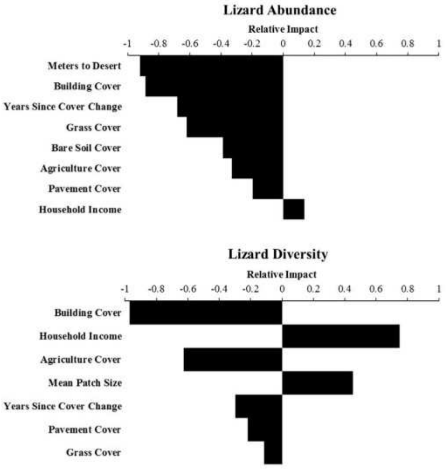

Fig. 2. Lizard diversity was only moderately correlated with abundance ($r^2 = 0.49$), and the relative impact of these response variables was best explained by different factors (relative impact was the variables cumulative AIC weight in the 95% confidence interval of most likely models). Building cover and other consequences of urbanization generally had a negative impact on diversity and abundance, but median household income had a strong positive impact on lizard diversity and a small positive impact on lizard abundance. Variables which were included in our analysis but did not appear to have a significant impact on lizard populations included: traffic density, surface temperatures, and the relative proportional land covers of trees, shrubs, and bare soil (all measured within a 200 m diameter circular buffer).

was taken 76 years ago, this was the value given to undisturbed sites). Thus, we cannot directly attribute this as an example of the bell-curved intermediate disturbance hypothesis where diversity is highest at moderate disturbance frequencies (Grime, 1973). Lizard diversity and abundance might not have declined during or immediately following cover changes, however it seems likely that lizards could get driven out of an area during construction activities, and return as the landscape stabilizes.

Building and agricultural cover had the most consistently negative impacts on lizards in our study. More than half of the land-use changes in Phoenix between 1970 and 2000 involved the urbanization of outlying agricultural fields (Keys et al., 2007), which increased the urban heat island effect while holding overall water use relatively constant during a period of rapid population growth (Chow et al., 2012; Gober and Kirkwood, 2010). More recently, Phoenix's urban fringe had been expanding into the Sonoran Desert at a rate of 1 km per year (MIPP, 2000) prior to the housing-market crash of 2008. An important choice for Phoenix's future ecology is whether to restrict urban sprawl and encourage high density developments that cover smaller areas (Collins et al., 2000), although this would likely have negative consequences for native species currently persisting within the city. As we emerge from the great recession, an opportunity exists to re-imagine what forms of urbanization and economic growth get to count as ecologically sustainable on specific scales—and what elements of nature are desirable to have in a desert city.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2014.11.009.

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APPENDIX C

BRINGING NATURE TO HUMANS: HOW TO EVALUATE THE NEXT GENERATION OF URBAN PARKS AND GREEN SPACES

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Bringing Nature to Humans: How to Evaluate the Next Generation of Urban Parks and Green Spaces

With the rise of designer habitats and citizen scientists, ecologists and the general public will play a broader role in evaluating and managing urban parks and green spaces in America. This revised decision making process would benefit from the inclusion of concepts from environmental ethics like ecological citizenship, as well as a re-evaluation of traditional conservation priorities. A reduced emphasis on large protected areas, native biodiversity, static park designs, and hard boundaries between nature and the city would allow for a new generation of ethical urban environments, which can provide a wider array of current benefits while remaining adaptable to the needs and values of future generations.

Keywords
urban ecology, decision making, science policy, ecological citizenship, urban parks, greenspace

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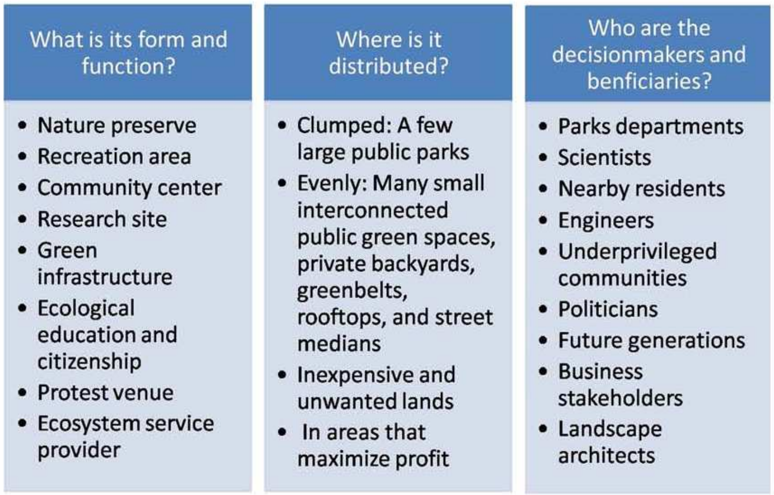
“Either move humans to nature, or bring nature to humans” (Turner et al. 2004).

A PARK BY ANY OTHER NAME

The roles of private urban green spaces and traditional public city parks are being reevaluated as we develop an “Ecology for a Crowded Planet” (Palmer *et al.* 2004). An array of novel design features and goals has emerged, such as biodiversity conservation in an urban context (Fig. 1). Some of the concepts are at odds with historical conservation philosophy and environmental ethics in America, which were based on the preservation of large wilderness areas and emphasized the intrinsic value of nature as a pristine entity. Other traditional conservation priorities—such as eliminating exotic species, maintaining stable historic conditions, and managing for biodiversity as opposed to human utility—will become increasingly untenable in the face of climate change and a growing urban populace. These conflicts need to be reconciled with the modern reality that humans depend on the ecosystem services that nature provides (Sarewitz 2009), and that nature itself is increasingly difficult to define.



What is its form and function?	Where is it distributed?	Who are the decisionmakers and benficiaries?
• Nature preserve • Recreation area • Community center • Research site • Green infrastructure • Ecological education and citizenship • Protest venue • Ecosystem service provider	• Clumped: A few large public parks • Evenly: Many small interconnected public green spaces, private backyards, greenbelts, rooftops, and street medians • Inexpensive and unwanted lands • In areas that maximize profit	• Parks departments • Scientists • Nearby residents • Engineers • Underprivileged communities • Politicians • Future generations • Business stakeholders • Landscape architects

Figure 1. Design elements of urban green space are increasingly diverse, and range from complimentary to mutually exclusive. Many of these novel characteristics stem from a growing cast of stakeholders that have not been traditionally involved in the decision making process of what urban nature should look like, and what ecosystem services it should provide to local communities.

As the forms, functions, users, and stakeholders of urban nature diversify, conflicts can emerge with the historical values embedded in such spaces and the traditional authority of landscape architects and managers (Ackley and Meylan 2010). American parks have been widely viewed as a one-time matter of landscaping and basic engineering, which represented the social trends and aesthetic ideals of its day (Cranz and Boland 2004). As the needs, values, and desires of the day continue to change, the utility of a park's original design is more likely to decline than increase. Modifying such areas and building new ones will necessitate broader roles for ecologists, as well as increased public knowledge of and participation in an ongoing, pluralistic process of design, management, and use of urban parks and green space.

FORM AND FUNCTION

The biophilia hypothesis suggests people have an innate and universal affinity for nature (Wilson 1984); but what species should be imported or encouraged to live in an urban environment which would otherwise not support them? An ongoing and value laden debate in ecology on exotic species further complicates this issue. While fears of invasives that displace native species and drastically change local ecosystems are valid, most exotic species retain a low profile when introduced, and may increase biodiversity and associated ecosystem services (Davis et al. 2011; Hitchmough 2011). An equally relevant question is what species to exclude. Should urban parks to be made unattractive or hostile to "urban exploiter" species that are already thriving in cities (Rosenzweig 2003)? While introduced species can increase biodiversity on a local scale, the presence of similar sets of species in many cities can reduce biodiversity at regional and global scales, known as biotic homogenization (McKinney 2006).

Exposure to nature has been shown to produce tangible benefits in child development, psychological health, and recovery times of hospital patients (Kahn and Kellert 2002; Rohde and Kendle 1994). While exposure to increasing levels of biodiversity correlates with increasing psychological benefits (Fuller et al. 2007), urbanites may continually redefine baseline biodiversity as what they remember from childhood, making it difficult to appreciate cumulative species losses over multiple generations (Miller 2005). Rather than simply "exposing people to nature", an increased emphasis on ecological literacy and public awareness of how species contribute to ecosystem services in urban parks could help instill a conservation ethic in local urban communities, which may have limited opportunities to interact with natural ecosystems (Dearborn and Kark 2010). The increasing prevalence of community gardens could have a complementary effect in urban green spaces. Because local users continually visit gardens to plant, tend, and harvest, this active engagement is one of the most widespread examples of urban ecological citizenship: an environmental ethics concept akin to civic duty that broadens the interactive community bound by rights and obligations to include nature (Light 2001).

A longstanding tradeoff in both public and private urban green space is whether it should be planted and pruned in an orderly fashion using introduced species, or reflect the surrounding natural areas and be allowed to run wild. Some private urban green spaces, such as LandPaths in California, are managed for a degree of unkemptness and have a small number of minimally developed walking paths. They are also invitation only. To gain access, patrons must volunteer their time in upkeep activities, or visit as part of a guided tour. Instead of a passive relaxation experience, park users are encouraged to engage directly with their surroundings as an act of ecological citizenship.

The development of green infrastructure has allowed for natural areas to serve engineering functions, and to beautify built structures that had not been previously designed with aesthetic considerations. Following hurricane Sandy in 2012, there were conventional proposals to construct seawalls to protect lower Manhattan from future storm surges. However, proposals to construct public parks in the form of salt marshes and oyster beds to accomplish the same ends received national attention (Feuer 2012). These dual roles produce challenges for designers who would not normally work together, and can create potential conflicts among newly conjoined user groups, whose needs and values may not overlap.

Of course, predicting who future users will be, as well as their needs and values, represents an additional challenge. For example, the Occupy Wall Street movement physically occupied Zuccotti Park, one of over 500 privately-owned public open spaces in New York City. These areas are often the result of zoning concessions, such as allowing developers to exceed height restrictions, and are commonly offered in exchange for making a portion of developments available for public use. To eliminate the need for fencing and enforcement, a 24-hour access policy was implemented during Zuccotti's development in1968, which later allowed for a worldwide protest movement to develop in 2011. The park ended up serving multiple functions beyond what its original form was designed for.

DISTRIBUTION

The traditional bigger is better conservation philosophy would suggest that one of the best examples of an urban park is South Mountain in Phoenix, AZ. At 17 km long, and 4 km wide, it is the largest city park in the country. Amazingly it lies within 10 km of Phoenix's geographic center, from which the urban fringe extends 20-40 km. However, most urban parks in Phoenix exist not because of their biological value, but because their steep and rocky terrain makes them prohibitively expensive to build on. Thus despite its size, South Mountain does little to protect the most endangered type of land in Phoenix: flat sections of desert scrub favored by real estate developers.

Local history and geography are important factors in a specific city like Phoenix, but more broadly, the locations of city parks and green spaces are heavily influenced by their size and number. In an urban context, tradeoff known as SLOSS (single large or several small) describes how limited resources can be invested to build a network of protected areas. Historically, conservation in North America has emphasized large wildness parks, and moving forward, a smaller number of larger green areas is commonly advocated as a design goal for the next generation of sustainable city parks (Beatley 2010; Forsyth *et al.* 2005). However, the goals associated with urban green space are less about protecting wilderness, and more about improving access to some form of nature. Due to varied urban land covers, uses, and ownership, the decreased feasibility and increased cost of constructing large city parks may outweigh their advantages.

Larger parks support more species per unit area, and are typically advocated as the best practice for protecting large specialist species (which are often endangered and less compatible with urbanization) by maximizing the ratio of stable "interior" areas over disturbed "edge" habitat. Alternatively, several small parks can cover a greater diversity of habitat types, distribute risk of disturbances like fire and disease, allow for multiple adaptive management goals (Gunderson and Holling 2001), and cover a larger region overall. This approach facilitates access, and encourages trips to be made by bicycle and foot instead of car. A network of smaller protected areas is generally going to be less expensive and more physically compatible with fragmented urban landscapes (Miller 2006).

A related tradeoff is whether to construct discrete parks designed that separate and protect nature from day to day human activities, or to integrate urban elements into green spaces that cover roof tops, street medians, and backyards. The latter approach magnifies the risks of living in an urban environment for local species, but an important consideration in cities is that biodiversity outside the boundaries of parks and green space represents a major source of natural exposure for urban residents who lack the means or inclination to travel. Park attendance by local residents has been shown to drop considerably when the travel distance exceeds 100 m (Beatley 2010).

DECISION MAKERS AND BENEFICIARIES

Urban planners and landscape architects have traditionally decided what city parks will be in a top-down fashion. As the era of discrete cities and parks gives way to more integrated designer ecosystems, ecologists will increasingly feature in discussions of what a reconciliation of urban and green could look like (Rosenzweig 2003). Conservation initiatives that emphasize the biological potential of disturbed areas will be a challenge to the traditional approach of attempting to maintain historical conditions and restoring altered habitats to their previous ecological baseline. However, more than 80% percent of the world's ice-free land mass is actively used or inhabited by humans (Ellis and Ramankutty 2008; Sanderson *et al.* 2002), climate change is geographically unrestricted, and ecologists have begun to question whether truly wild areas still exist (Kareiva *et al.* 2007). As a result, static ecological baselines are increasingly becoming constructs of human values, and purely restorative projects can be described as natural "museums" with little regard for present or future ecological conditions and human needs (O'Neil *et al.* 2008). An increased emphasis on ethics and sustainability within urban planning and ecology has the potential to produce socially and biologically beneficial green spaces that protect against natural hazards while remaining adaptable to the needs and values of future generations.

Ironically, novel visions of urban parks are often facilitated by environmental crises. In their absence, an alternative is "muddling through" (Lindblom 1959). This incremental approach emphasizes retaining some of what made the previous system work, will allowing for small decisions to be made on the basis of pragmatic comparisons between different policy options, as opposed to potentially irresolvable disputes over deeply entrenched and widely disparate values. While a primary goal of the Ecological Society of America is to provide useful knowledge to decision makers and the general public (Palmer *et al.* 2004), the ensuing question of sufficiency is: to what degree should local residents and stakeholders participate in visioning, research, and management, and how should their voices be balanced against experts when public opinion is in opposition to scientific consensus? As public scientific literacy grows and ecologists increasingly conduct research in urban areas, both parties will either chose or be forced to exercise their ecological citizenship and become part of the decision making process (Cid and Pouyat 2013). Scientists are often called in the later stages of policy making to assess seemingly contradictory scientific evidence accumulated by opposing parties. Embedding researchers at the outset will minimize uncertainty over the evidence's provenance, and their potential roles as practitioners of basic science, placed-based research designed to answer the question at hand, or advocates for a specific policy (Pouyat *et al.* 2010).

The process of deciding what parks should be amidst a diverse cast of stakeholders is facilitated by integrative concepts like ecosystem services, which allow for a common language, alternative scenario comparisons, and coordination without consensus between multiple parties (Star and Griesemer 1989). However, there is widespread disagreement over which services to count and how to value them. Integrating refined economic valuation tools and public participation could be a way forward (Chiesura 2004). The continual task of re-envisioning desirable forms and functions of individual green spaces and parks could allow for citizens to modify these spaces for future needs, while retaining some historically valued characteristics. A consideration of environmental ethics within urban planning could play an important role in mediating value disputes between competing visions of what urban nature should look like, and what qualifies as sustainable on scales ranging from a green rooftop to a metropolitan area.

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APPENDIX D

EPILOGUE

Pied Beauty — Gerard Manley Hopkins (1877)

Glory be to God for dappled things—
For skies of couple-colour as a brinded cow;
For rose-moles all in stipple upon trout that swim;
Fresh-firecoal chestnut-falls; finches' wings;
Landscape plotted and pieced—fold, fallow, and plough;
And áll trádes, their gear and tackle and trim.

All things counter, original, spare, strange;
Whatever is fickle, freckled (who knows how?)
With swift, slow; sweet, sour; adazzle, dim;
He fathers-forth whose beauty is past change:
Praise him.

A park by any other name

The Eckerd College campus in St. Petersburg, Florida, is a beautiful waterfront "landscape plotted and pieced" with exotic palm trees, native mangroves, manicured grass sports fields, an imported white sand beach, and one vestigial patch of "wild" xeric scrubland. In 1996 and 2004, two stormwater retention ponds were constructed to contain polluted runoff from parking lots. Eckerd's administration viewed them solely as a natural wastewater treatment plant. While not an urban park in name or design, this green infrastructure project came to resemble one in form and function through natural processes — a novel ecosystem of animals, fish, and plants quickly became established, including endangered shorebirds and one of the densest snake populations ever found anywhere in the world (Ackley and Meylan 2010). Biology students and I began using the ponds for ecological research and saw the area as a nature preserve. Staff members with crab traps began using it for urban aquaculture, and many people used it for recreational fishing. The administration was unaware of these user groups; management of grounds was subcontracted, and management of the ponds was sub-subcontracted. Unfortunately, the predominant vegetation type was invasive species of cattail grass, and the sub-subcontractor herbicided the area to comply with a regulations that prohibit propagating invasive species.

Top-down management of this novel ecosystem for one variable had unexpected consequences. The snake population declined by more than 50%, and the herbicide rendered fish unsafe for human consumption. The sub-subcontractor was not aware that anyone would be impacted by their actions, and did not publicize them. This situation came to widespread attention when students (wielding newfound knowledge and power) suggested that the institution had unknowingly harmed endangered species and risked poisoning pond users. Eckerd promptly collaborated with us, grounds keepers, and the faculty environmental affairs committee to develop a more comprehensive management plan.

Universal elegance or dappled pragmatism?

Research on decision-making, institutions, and social organization will become increasingly useful within the dappled field of urban ecology for reasons beyond resolving this type of site-specific dispute over habitat management goals. As scientific literacy within the general public grows and stakeholders of urban green-space proliferate, scientists who increasingly conduct research in urban areas will find they wield less power and authority than in a traditional laboratory or wilderness setting (Gieryn 2002), particularly in cities without an extensive history of urban studies (Gieryn 2006). Simultaneously, these competing groups will point out the uncertainty in our ostensibly immutable laws of science, which will become less useful as the explanatory power of relatively well understood biophysical variables declines and socioeconomic variables begin to dictate the distribution and abundance of organisms in cities (Luck, Smallbone et al. 2009). But this is actually a good thing for ecology and adaptable ecologists.

Our field has been described as "deeply envious" of physics and other sciences that have produced an extensive library of universal laws based on highly simplified model systems; while we have been more successful at producing general patterns gleaned primarily from very large and very small scale studies (Cartwright 1999; Scheiner and Willig 2008). At the medium-scale of analysis exemplified by community and urban ecology, we have had even less success producing general patterns that hold across ecosystems but we have gotten a great deal of practice dealing with complex problems that can only be solved locally (Lawton 1999). This type of place-based research underpins most urban sustainability initiatives and positions ecologists to make meaningful contributions to the future shape of cities. Unfortunately, the relevant institutional training in applied transdisciplinarity for scientists is limited at many schools, and when present, is often available only for a chosen few in exclusive programs like the National Science Foundation's sadly defunct IGERT program (Integrative Graduate Education and Research Traineeship).

"Whatever is fickle, freckled (who knows how?)"

Programs such as this produce dissertations such as mine: a collection of projects tied together less by similar results and subject matter, but more by patterns of variability and uncertainty where consistently optimal decisions are impossible. This type of research produces a broader skill set, which not only allows for complimentary findings between projects—it sometimes allows for the findings in the first place. When inter-departmental budget disputes resulted in the imminent closure of one of my study sites at North Desert Village, I was reminded of my study of retention ponds at Eckerd College. This time however, I was already working with the decision-makers in question, and knew what they were planning in advance. As a result, I was able to use some of the process-knowledge from my study of urban parks to convince the powers that be to extend the closure deadline, and since then, the budget dispute has been resolved and this unique study site remains open.

This in turn allowed me to discover that temperature variability had a much greater influence on lizards at North Desert Village than average temperature, and I was able to use this information to solve a vexing problem in my large scale study of lizards across Phoenix, AZ. Average temperature was variable of particular interest for this study, but it was so highly correlated with other important land-cover variables that including it would have called my results into question. Temperature variability across Phoenix was a much more independent variable, and since it was more relevant to lizards anyway, which solved a statistical and biological problem simultaneously.

“áll trádes, their gear and tackle and trim”

With funding for science becoming increasingly competitive, knowing how to find and successfully apply for money from sources outside your own field is an omnipresent challenge of interdisciplinary work; though dedicated funding programs are becoming a reality. Even so, many of these programs are targeted at fostering collaboration and networking, rather than data collection and analysis. Approximately two percent of my $US100,000 IGERT fellowship (Integrative Graduate Education and Research Traineeship) was actually intended to support research activities—and I had no idea where to look for money to do an urban environmental ethics project, which was the original conception of my paper on urban park design. My solution was to acquire enough disciplinary funding from traditional sources such as the EPA, and then use what was left over to support a project in a field that surprisingly doesn’t exist. One of the biggest surprises in my entire dissertation was the realization that environmental ethicists are still refusing to join ecologists in their migration to urban habits, despite sharing a historical basis in wild areas and a veneration of pragmatic environmentalists like Aldo Leopold (Light 2001; Light 2003).

Surprisingly, nonhuman urban organisms also seem to care about money. While the distribution of lizard species across Phoenix does not yet seem to be influenced by temperature, they are strongly linked to a neighborhood's median household income. People with higher median household incomes can choose to live in a wider range of environments, and can modify their surroundings to a greater degree. This type of totalitarian control over a small piece of a larger landscape has great promise for micro-conservation initiatives in urban habitats, and in larger regions where stewardship authority is held by a small number of powerful individuals. The challenges of passing cross-border and nationwide environmental legislation (Duffy 2005), coupled with the novel species assemblages and locally designed habitats of urban ecosystems, means "several small" environmental management projects can be particularly effective in cities, as opposed to the "single large" paradigm of protecting wilderness areas. Sadly, the historical design and management of urban parks has typically not exploited one of the main advantages of the several small model: rapid adaptive capacity. Again and again, parks "whose beauty is past change" have remained the same while their ecological utility declines with continued local and global changes.

Global Southward Bound

Backyard landscaping and its associated ecology (or lack thereof) is typically thought of as being directed by the homeowner. However, in places like Phoenix, AZ, the majority of residences are part of a larger homeowners association, which often restrict the planting of invasive species. Extreme examples of this are research areas like North

Desert Village, and college campuses like Eckerd, which have near complete control over planting and vegetation removal, employ pest control specialists, and often include "natural" areas designed to attract and support rare native species. Interestingly, they also have a degree of control over human population demographics such as immigration and emigration, much like one of the most successful conservation programs of all time: the Galapagos Islands.

While the government of Ecuador is not known for having a thriving economy, a stable political system, or an exemplary record on human rights, they have become one of the only countries to grant legal protections to natural ecosystems in their constitution. Less than three percent of the Galapagos land area can be built or lived upon, and residency is only conferred on those who are born there. While the lack of transparent democratic process may be distasteful, the majority of new cities will be built in developing countries, many of which lack coherent environmental policies and enforcement mechanisms. Their many small decisions will be made locally, and could be influenced by those who simply show up. Urban ecology and global conservation will have some of their greatest challenges and opportunities in these spaces over the next century. Chief among them will be finding funding to do conservation work in these areas (and offset the associated opportunity costs), but as has been proved by Ecuador, profit is possible.

APPENDIX E

ANIMAL USE AND COPYRIGHT INFORMATION

All animal use was approved by the Institutional Animal Care and Use Committee protocol #11-1186R (see document attached below). All copyrighted information herein was reproduced under “fair use” for non-profit and educational use.

Institutional Animal Care and Use Committee (IACUC)
Office of Research Integrity and Assurance
Arizona State University
660 South Mill Avenue, Suite 315
Tempe, Arizona 85287-6111
Phone: (480) 965-4387 *FAX:* (480) 965-7772

Animal Protocol Review

ASU Protocol Number: **11-1186R**
Protocol Title: **Off the Sand and Onto the Asphalt: Does the Urban Heat Island Influence Desert Lizards?**
Principal Investigator: **Michael Angilletta**
Date of Action: **04/27/2011**

The animal protocol review was considered by the Committee and the following decisions were made:

☐ The original protocol was APPROVED as presented.
☒ The revised protocol was APPROVED as presented.
☐ The protocol was APPROVED with RESTRICTIONS or CHANGES as noted below. The project can only be pursued, subject to your acceptance of these restriction or changes. If you are not agreeable, contact the IACUC Chairperson immediately.
☐ The Committee requests CLARIFICATIONS or CHANGES in the protocol as described in the attached memorandum. The protocol will be considered when these issues are clarified and the revised protocol is submitted.
☐ The protocol was approved, subject to the approval of a WAIVER of provisions of NIH policy as noted below. Waivers require written approval from the granting agencies.
☐ The protocol was DISAPPROVED for reasons outlined in the attached memorandum.
☐ The Committee requests you to contact ____________________ to discuss this proposal.
☐ A copy of this correspondence has been sent to the Vice President for Research.
☐ Amendment was approved as presented.

RESTRICTIONS, CHANGES OR WAIVER REQUIREMENTS:
Total # of Animals: **410** **Pain Level:** **C-5, D-405** **Species:** **Lizards**
Approval Period: **04/27/2011 – 04/26/2014**

Signature: C. Miller for D. Murphy Date: 4/29/11
IACUC Chair or Designee

Original: Principal Investigator
Cc: IACUC Office
IACUC Chair

IACUC Use Only	
Date: 3/24/2011	IACUC Protocol No.: 11-1186R

ANIMAL USE PROTOCOL
ARIZONA STATE UNIVERSITY INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE
(revised March 2010)

Please read "Instructions for Completing the Animal Use Protocol" before completing. **Upon approval, this protocol will become a public record so please follow instructions s.**

PROJECT/PROGRAM TITLE: Off the sand and onto the asphalt: Does the urban heat island influence desert lizards?
SPECIES REQUESTED: Urosaurus ornatus

I. PERSONNEL INFORMATION

A. A single member of the university faculty and/or Principal Investigator (PI) is considered the responsible individual.

NAME:	Michael Angilletta	TITLE:	Associate Professor
AFFILIATION:	SOLS	Office Phone #	480-727-6142
Cell Phone #:	812-841-6974	Dept. Phone #:	(480) 965-0803
Fax #	(480) 965-6899	E-Mail:	Michael.Angilletta@asu.edu

B. Additional contact, if any, for IACUC business

NAME:	Jeffrey Ackley	TITLE:	Graduate Student
AFFILIATION:	SOLS	Office Phone #	4809654975
Cell Phone #:	8604606778	Dept. Phone #:	(480) 965-0803
Fax #		E-Mail:	jwackley@asu.edu

C. Protocol Type

☒ Non-funded research
☐ Grant / Contract (Also submit grant proposal with this protocol)
Granting Agency: Deadline:
Proposal Title:
Proposal Number:
Co-Investigator(s):

☐ Teaching
Course Title, Schedule:

D. Protocol Status:
☒ New
☐ Renewal—Previous Protocol #:

☐ Revision—Previous Protocol #:

E. List all persons involved in this protocol. The first person listed should be the PI.

Name	Title	Role in Protocol (What procedures will each person be doing?)	Species with which individual will have direct contact ("all" or list species)*	IACUC USE ONLY Training (mm/yy)
Michael Angilletta	Associate Professor	PI (All)	All	11/10 HSQ
Jeffrey Ackley	Graduate Student	All	All	1/11 HSQ
Brian Sullivan	Professor	All	All	2/08 Basics, Amp/Rep 12/08, HSQ

For each individual, describe the individual's training and years experience with all listed species and procedures:

The PI, Michael Angilletta, has 15 years of experience working with lizards, including *Urosaurus ornatus*. Training on handling, husbandry, and scientific protocols for physiological research began in graduate school and has continued (as needed) to the present.

Jeffrey Ackley has almost a decade of field experience involving reptiles (snakes, turtles and lizards). Experience with radio tagging/tracking, blood draws (turtles of all sizes), PIT-tagging, toe clipping, surgery assistance, necropsy, transect surveys, and chytrid swabbing.

Brian Sullivan has worked with the Ornate Tree Lizard in Arizona since 1979. Although most studies have been behavioral in focus, a number have required toe-clipping as a marking technique (1980-1983, ASU Dept of Zoology funded research prior to IACUC; IACUC approved protocols from 1996-2004 in association with research of Paul S. Hamilton on behavioral ecology of these lizards).

* The answer provided in this column dictates which Level II species-specific IACUC training modules are required for each individual. An individual only needs to complete Level II certification for those species with which he or she will directly work.

Note: ASU requires that all personnel engaged in animal research or teaching be qualified through training or experience in order to conduct the work humanely. The IACUC requires the successful completion and renewal of Level I – The Humane Care and Use of Laboratory Animals as well as Level II species-specific training at least once every 3 years. A link to the individual training modules is available on the IACUC ASU homepage at: http://hazel.forest.net/latanet/client/asu/introduction.htm.

F. Have all personnel on this protocol completed the required IACUC Level I and Species-Specific Level II Training Modules as well as the Occupational Health and Safety Program Health Surveillance Questionnaire? The Training Modules and the Health Surveillance

Questionnaire (HSQ) can be found at http://researchintegrity.asu.edu/iacuc/training/exams.htm

☒ Yes. Proceed to section B.
☐ No. List the individuals who are not in compliance and identify their deficiencies with an "X" in the appropriate columns:

Name	**Training Modules**		**HSQ Clearance**
	Level I	**Level II**	

G. Describe any non-routine measures such as special vaccines or personal protective equipment that is required for animal and/ or human safety:

none

H. Do you plan to use Department of Animal Care & Technologies (DACT) personnel and resources? If yes, for what facilities and procedures? (If this use is new or an expansion of previous use, please contact the DACT well in advance of need). no

II. PROJECT DESCRIPTION AND PROGRAM REQUIREMENTS

The University Animal Care and Use Committee (IACUC) is composed of both active animal users and lay persons. Regardless of background, each member has one vote, and it is therefore particularly important that the language of the application be understood by all. This applies to all sections of the application, but it is especially important that the goals and justifications of the proposed research be spelled out in the clearest possible terms. NOTE: Upon approval, this protocol will become a public record, so please do not disclose proprietary information such as home telephone number and address.

A. Please provide a brief (300 words or less) synopsis in **laymen terms** of proposed research.

A global rise of just 2°C is predicted to drive almost 40% of all lizard populations extinct by 2080 (Sinervo et al. 2010). The ecological impacts of elevated temperatures may already be observable in cities, which are often warmer than their rural surroundings. This urban heat island (UHI) has known consequences for air quality and human health, but it also can be used as a proxy for climate change, enabling us to predict how global warming will impact organisms and ecosystems. In Phoenix, Arizona, lizards have been exposed to significant urban warming for many years, and their diversity has declined with increasing urbanization. If the anthropogenic thermal landscape is partly responsible, effects of the UHI should be evident at the multiple scales in which temperature influences the natural history of ectotherms. These include thermoregulation of individuals, dynamics of populations, and structures of communities. We propose to integrate a mechanistic study of how microhabitat temperature impacts behavior in ornate tree lizard populations, with a comprehensive study of how the urban landscape impacts the diversity in lizard communities. Our research goals are to measure the spatial and temporal structure of the UHI at scales relevant to individual ectotherms, and to determine the relative significance of the UHI, and non-thermal urban variables, for the continued viability of lizard populations in Phoenix.

submerged. After 2 minutes, the two layers will be separated and the animal will be removed. The low rate of respiration of lizards, especially at low body temperature, minimizes the stress caused this procedure, which means we do not need to sacrifice an animal to make the moulds.

Each mould will be used repeatedly to make the final copper models, a new mould will only be needed if a mould is broken. Each copper model is then painted and fitted with a temperature sensor/data logger (similar to but smaller than a thermocron iButton). Model accuracy will be validated against up to 5 different live OTLs during a pilot project in summer of 2011. A model and a recently captured lizard will be kept in an air conditioned car at ~25°C until they both reach thermal equilibrium. The lizard will then be tethered to the ground in the sun, next to the model. The tether will be constructed from thin elastic harness (fitting like a backpack), which will be tied to stake in the ground. During the procedure, we will continuously monitor the lizard's body temperature and behavioral responses. Body temperature will be recorded by a small-gauge, lubricated thermocouple inserted in its cloaca and secured with surgical tape. The temperatures of the lizard and the model will be recorded until the lizard warms to 36°C [note that these lizards routinely reach temperatures as high as this during normal activity, and can tolerate temperatures as high as 40°C (Lowe and Vance 1955)], or if it begins to shows signs of thermal stress (e.g., open mouth panting). On a typical sunny day, the animal would take less than 20 minutes to reach an equilibrium body temperature. After this procedure, the lizard will be released in the shade.

We will also use mark-recapture methods at each site to estimate OTL growth rate, survival, and population structure, using Schumacher's closed population model (Ackley and Meylan 2010). **All lizards will be captured with a noose on a fishing pole**, which is a standard, painless technique used by herpetologists (Dunham et al. 1988). **All lizards captured during any procedure will be marked with a unique toe clip sequence in which up to four digits will be removed with surgical scissors.** Toes will be clipped to ~2 mm distal from the joint with hand/foot to avoid confusion with toes lost naturally. No more than two digits will be removed per foot. Pressure will be applied to any bleeding foot until bleeding stops. Lidocaine jelly will be applied to each toe after clipping. Scissors will be sterilized in ethanol between animals. Animals will be released at their exact point of capture (marked with wire flag upon capture). Animals captured as part of large scale field experiments will be marked with permanent (toe clips) and temporary but more visible (nail polish) marks. Nail polish will be painted dorsally between the hind legs, no more than 3 circles 1-2 mm in diameter for visual identification. Permanent markings are also necessary in this case to ensure proper identification when nail polish wears off or is lost during ecdysis.

All procedures (molding, validation, and euthanasia) will be completed within 6 hour time periods, no animals will be kept overnight. Molding and euthanasia may require transporting the animals to by car ASU from the field. They will be kept in cloth bags, and released within 6 hours of capture.

***Significance*:** This study will integrate ecology, physiology, behavior, and climatology to better understanding the impacts of urbanization and global warming. We will disseminate resulting management implications to relevant policy makers (e.g. Phoenix Tree and Shade Master Plan). To raise local awareness of urban ecology, we will create reptile and UHI learning modules for Ecology Explorers, a component of CAP-LTER that works with science teachers and K-12 students throughout Phoenix. We will also provide all data and results to CAP-LTER; this will be the first instance of reptiles being included within the 200 point survey. Also, indirect broader impacts and scientific outreach will come from doing highly visible field research and working with property owners in disadvantaged neighborhoods, which are inequitably exposed to the UHI.

Ackley, J. W. and P. A. Meylan. 2010. Watersnake eden: Use of stormwater retention ponds by Mangrove Salt Marsh Snakes (Nerodia clarkii compressicauda) in urban Florida. Hepetological Conservation and Biology **5**:17-22.

Dunham, AE., P.J. Morin and H.M. Wilbur. 1988. Methods for the study of reptile populations. Pp. 330-386. *In:*Biology of the Reptilia, Vol. 16, C. Gans and RB. Huey (eds). Alan R Liss, New York, NY.

Grant, B. W. 1990. Trade-Offs in Activity Time and Physiological Performance for Thermoregulating Desert Lizards, Sceloporus Merriami. Ecology **71**:2323-2333.

Grant, B. W. and A. E. Dunham. 1988. Thermally Imposed Time Constraints on the Activity of the Desert Lizard Sceloporus Merriami. Ecology **69**:167-176.

Lowe, C.H. and V.J. vance. 1955. Acclimation of the Critical Thermal Maximum of the Reptile Urosaurus ornatus. Science **122**:73-74.

Sinervo, B., F. Mendez-de-la-Cruz, D. B. Miles, B. Heulin, E. Bastiaans, M. Villagran-Santa Cruz, R. Lara-Resendiz, N. Martinez-Mendez, M. L. Calderon-Espinosa, R. N. Meza-Lazaro, H. Gadsden, L. J. Avila, M. Morando, I. J. De la Riva, P. V. Sepulveda, C. F. D. Rocha, N. Ibarguengoytia, C. A. Puntriano, M. Massot, V. Lepetz, T. A. Oksanen, D. G. Chapple, A. M. Bauer, W. R. Branch, J. Clobert, and J. W. Sites, Jr. 2010. Erosion of Lizard Diversity by Climate Change and Altered Thermal Niches. Science **328**:894-899.

C. RATIONALE FOR INVOLVING ANIMALS AND THE APPROPRIATENESS OF THE **SPECIES AND NUMBER** USED. Keeping in mind the principles of the "3 R's" (Refinement, Reduction, and Replacement answer the following:

1. Why must live vertebrates be used in this study?

Lizards play a central role in food webs, and thus models of their response to climate change will complement similar models made for invertebrates and plants. Mechanistic models of climate-change impacts must be parameterized with data on physiology and behavior to make predictions about, and be compared to, real populations. Dead lizards can be used for both constructing the models and validating them in the field. However, the physical/physiological/thermal characteristics of dead lizards are different, leading to inaccuracies in the copper models, and the field validation process. Using preserved specimens results in unacceptably large inaccuracies, and as we do not have a source of fresh-killed lizards, we would have to kill the lizards specifically for use in these procedures. We expect all the animals to be released without a major injury, and thus using live lizards will prevent us from having to kill lizards.

2. Why are you using the requested species rather than other species?

Urosaurus ornatus is an excellent model for our research for several reasons: 1) it is the only lizard which is abundant across the entire Phoenix metro area, and thus can be readily found in both warmer and cooler parts of the city. 2) Much is already known about its natural history, ecology and phylogeny.

3. What is the rationale supporting the numbers of animals proposed? Typically, a power analysis should be performed to support the proposed sample sizes. A table depicting the number of animals to be used is required.

Making and validating copper models will require a very small number of animals, perhaps as few as one to make the models with dental gel, and one to field-validate the models. No more than five lizards will be used for each procedure, for a potential total of five animals subjected to USDA category C (validation), and five animals subjected to category D (moulds). Mark-recapture models can be biased by small sample sizes, and these models assume that equal effort was used attempting to capture all animals in an area or population. The adequate number of lizard toes clipped thus cannot be determined by power analysis, but will be a product of lizard population densities at each site, the area, and number of sites sampled. Using the 30x30m CAP LTER plots provides a feasible and natural history relevant area, which allows us to integrate the long-term ecological data available for these sites. Based on preliminary surveys, I do not expect to toe-clip more than 50 lizards at each of the eight sites (50x8=400). Therefore, the 400 animals listed in section 6 is a hypothetical maximum. I may capture far fewer lizards.

What refinements, if any, have been made to reduce the number of animals used and the potential detrimental effects on the study animals?
As my unit of replication is the site, 8 is the minimum to determine statistical significance and to capture most of the environmental variation between sites.

4. If the procedures will cause pain or distress to the animals, provide a written narrative of the methods used to determine whether or not alternatives exist to these procedures.

Toe-clipping is the only means of quickly and relatively painlessly marking reptiles and amphibians under field conditions (Declining Amphibian Task Force Report, 1995; SSAR/ASIH guidelines for use of amphibians and reptiles in research, 1987;2001). Lizards marked by toe-clipping resume normal activity (e.g., basking, feeding) immediately upon release, clearly indicating the absence of significant trauma or pain associated with this marking technique. I have also searched the online literature for alternatives to toe clipping. Moreover, the literature suggests that other techniques for individual identification (e.g., PIT tags) may cause more stress than toe clipping which in some lizards appears to cause negligible increases in stress hormones and negligible declines in locomotory performance. Since toe clipping is a potentially painful procedure, we will administer analgesics to reduce pain. Schmidt and. Schwarzkopf (2010) recently compared the impact of toe clipping and visual elastomer tagging on locomotion in skinks. The article is unavailable through ASU, but the abstract states that visual elastomer was "marginally superior". Given the increased cost, complication, and likelihood of mistakes due to adopting this new technique that we have less experience with, we still believe toe-clipping to be the best method for our study. We specifically searched for all permutations of osteomyelitis, toe-clipping, and lizards. This returned no articles in ISI web of science and only one relevant article in Google scholar (Gartrell and Hare 2005) which is not available through ASU. The abstract does not mention toe-clipping, but describes digital osteomyelitis occurring in captive geckos after the humidity was changed in their enclosures. We do not believe this to be a factor in our study.

III. CONTROLLED SUBSTANCES

A. Does this protocol involve the use of DEA-listed control substances (e.g., ketamine, pentobarbital, androgens, diazepam, buprenorphine)?

☒ No. Proceed to section **IV**.

☐ Yes. List all controlled substances:

IV. EMERGENCY CONTACT

A. Who should be contacted in case of an animal emergency? **Note: This information will be redacted if this protocol is requested as a public document.**

Name:	Jeffrey Ackley
Home Phone #	8604606778
Office Phone #	n/a
Cell Phone #:	8604606778

V. DUPLICATION AND ALTERNATIVES

The Animal Welfare Act requires that you document your justifications with data from **two** or more sources. One source **must** be a set of searches of a relevant database: name the database searched, the terms searched, when it was searched and the frequency of searches. The second source can be a set of searches of a second relevant database, or consultation with a laboratory animal science veterinarian, or courses/meetings/consultations with qualified personnel. Sufficient documentation, such as the consultant's name and qualifications and the date and content of the consult, should be provided to the IACUC to demonstrate the expert's knowledge of the availability of alternatives in the specific field of study. Consultation with the university attending veterinarian **must** be performed if the animals are expected to experience pain or distress. Examples include PUBMED, Web of Science. **[**Note: USDA Animal Welfare Information Center provides an in depth listing of database resources on their website at http://awic.nal.usda.gov/nal_display/index.php?info_center=3&tax_level=1&tax_subject=184.**]**

A. Provide the following details for the most recent literature search used to explore for duplicative research. (The literature search documents that the research will not unnecessarily duplicate previous research). **Teaching protocols do not need to conduct this search.**

Date that search was conducted (Must be within 60 days of the IACUC review date): 3/22/11
Database used: ISI Web of Science
Publication years covered by the search: 1900 to present
Keywords used: thermal physiology AND Urosaurus; temperature AND urban ecology AND lizards;
Climate change AND reptiles; Urban Heat Island AND reptiles, temperature AND performance AND Urosaurus; critical thermal maximum AND Urosaurus; preferred AND temperature AND Urosaurus
No articles were found that address even a similar question.

B. Provide the following details for the most recent literature search used to explore for alternatives to animal use and alternatives to painful procedures. Alternatives should be considered for any aspect of the protocol that may cause more than momentary or slight pain or distress to the animal. Alternatives to be considered include those that would: 1) refine the procedure to minimize discomfort that the animal(s) may experience; 2) reduce the number of animals used overall; or 3) replace animals with non-animal alternatives (e.g., computer models or tissue culture). **All protocols (both research and teaching) MUST conduct this search.**

Date that search was conducted (Must be within 60 days of the IACUC review date): 3/22/11
Database used: ISI Web of Science
Publication years covered by the search: 1900 to present
Keywords used: critical thermal maximum, thermal stress; toe clipping AND lizards, toes AND lizard, PIT AND Tag AND lizard, osteomyelitis AND toe clipping AND lizards, osteomyelitis AND toe clipping.

C. Results of search for alternatives: Please comment on the application(s) of any identified alternatives, including how these alternatives may be or may not be incorporated to modify a procedure to either lessen or eliminate potential pain and distress. You must include sufficient information for the IACUC to determine that a reasonable, good faith effort was made to determine the availability of alternatives. If the search identified any alternative methods (ones that could be used to accomplish the goals of the animal use proposal), you must clearly explain and justify why this alternative cannot be used.

A search related to toe-clipping yielded no alternative method of permanent marking that was less invasive yet equally reliable. Several studies have examined the effects of toe-clipping on performance of lizards, and only one of these suggests a decrease in performance. Bloch and Irschick (2005) found that toe clipping reduced clinging performance of arboreal lizards by interfering with the function of toe pads. OTL do not possess toe pads, and thus should not be affected in the same manner. A similar study showed toe clipping caused negligible declines in the running speeds of skinks, which rely on claws for traction as do the species studied by us (Borges-Landaez and Shine 2003). Finally, another study of skinks showed that PIT tags (an alternative to toe clipping as a permanent marker) induced more stress than did toe-clipping (as indicated by plasma levels of corticosterone). Specifically, microchip implantation caused stress for 14 days compared to a more transient stress « 2 hours) caused by tail autonomy and no detectable stress for toe clipping (Langkilde and Shine 2006). Schmidt and. Schwarzkopf (2010) recently compared the impact of toe clipping and visual elastomer tagging on locomotion in skinks. The article is unavailable through ASU, but the abstract states that visual elastomer was "marginally superior". Given the increased cost, complication, and likelihood of mistakes due to adopting this new technique that we have less experience with, we still believe toe-clipping to be the best method for our study.

We searched for all permutations of osteomyelitis, toe-clipping, and lizards. This returned no articles in ISI Web of Science and only one relevant article in Google scholar (Gartrell and Hare 2005) which is not available through ASU. The abstract does not mention toe-clipping, but describes digital osteomyelitis occurring in captive geckos after the humidity was changed in their enclosures. We do not believe this to be a factor in our study.

Dead lizards could be used to construct the models and validating them in the field. However, we do not have a source of fresh-killed lizards. Thus, we would have to kill the lizards specifically for use in these procedures. Tethering of live animals when validating the physical models will be brief (see above), and animals will not be permitted to heat up beyond their range of preferred body temperatures. We expect all the animals to be released without injury, and thus using live lizards will prevent us from having to kill lizards. Computer modeling is not a viable alternative because the too many unknown parameters would exist in the model. In fact, the use of physical models moulded from real animals was adopted because computer models could not be parameterized successfully for complex environments.

References

Bloch, N. and I. O. J. 2005. Toe-clipping dramatically reduces clinging perfonnance in a pad-bearing
lizard *(Anolis carolinensis).* Jounral of Herpetology 39:288-293.
Borges-Landaez, P. A. and R. Shine. 2003. Influence of toe clipping on running speed in *Eulamprus*
quoyii, an Australian scincid lizard. Journal of Herpetology 37:592-595.
Langkilde, T. and R. Shine. 2006. How much stress do researchers inflict on their study animals? A case
study using a scincid lizard, *Eulamprus heatwolei.* Jounrnal of Experimental Biology 209:1035-1043.
(Schmidt and Schwarzkopf 2010)
Schmidt, K. and L. Schwarzkopf (2010). "Visible implant elastomer tagging and toe-clipping: effects of marking on locomotor performance of frogs and skinks." The Herpetological Journal **20**: 99-105.

D. Describe any other procedures (e.g., participation in meetings, review of journals) that are used to explore and evaluate alternatives: I have professional and personal relationships with a number of herpetologists, and attend scientific meetings that would likely expose me to recent developments.

E. Does this research replicate previous work?

☒ No. Proceed to section **VI.**

☐ Yes. Explain why the replication is necessary:

☐ Not applicable. This is a teaching protocol.

VI. CATEGORY OF PAIN OR DISTRESS

The USDA Regulations define a "painful or distressful procedure" as "any procedure that would reasonably be expected to cause more than slight or momentary pain or distress in a human being to which that procedure was applied; that is, pain in excess of that caused by injections or other minor procedures." Using the table below, list all species of live vertebrate animals to be used in the proposed study and indicate the number of animals to be used under the appropriate USDA category. For an animal undergoing multiple procedures, list the animal under the highest level of pain expected for that animal.

Species	Number per USDA Category*				Total number of animals requested
	B	C	D	E	
Urosaurus ornatus		5	405		410

*USDA PAIN CATEGORIES: (see http://researchintegrity.asu.edu/iacuc/apply/USDApaincategories-examples.doc for a more complete description of the below categories)

Classification B: Includes animals that are used solely for breeding (e.g., to produce experimental animals or to maintain experimental lines).

Classification C: Includes the use of animals in procedures involving no pain or distress (e.g., non-invasive parenteral drug delivery, peripheral blood collection, euthanasia, short-term manual or chemical restraint, and tumor propagation or toe-clipping performed according to ASU guidelines).

Classification D: Alleviated pain. Animals used in procedures that could cause pain or distress but appropriate anesthetic, analgesic, or tranquilizing drugs are used (e.g., surgery, periorbital blood collection, perfusion, or administration of irritating chemicals.

Classification E: Unalleviated pain. Includes the use of animals in procedures that involve pain or distress but the use of appropriate anesthetic or analgesic would have an adverse effect (e.g., negative conditioning, unrelieved post-surgical pain, death without euthanasia).

VII. ASSURANCE:

The information contained herein is accurate to the best of my knowledge. I have carefully compared the proposed work with the current state of knowledge in this field by reviewing the literature and it is my professional opinion that the proposed work meets high standards of scientific merit. If the study involves pain and distress to the animal, whether or not it is relieved by anesthetics or analgesics, I have (1) reviewed the literature related to this work and have found no significant studies which could make this protocol unnecessarily duplicative, and (2) considered alternatives to animal use and found none available, as described above. Procedures involving animals will be carried out humanely and all procedures will be performed by or under the direction of trained or experienced persons. Any revisions to animal care and use in this project will be promptly forwarded to the Institutional Animal Care and Use Committee for review. Revised protocols will not be used until Committee clearance is received. The use of alternatives to animal models has been considered and found to be unacceptable at this time.

The principal investigator, by signing below, and the IACUC recognize that other medications may be given to the animals for veterinary care purposes (including humane euthanasia of animals in pain that cannot be controlled, as determined by the University Veterinarian or an euthanasia-certified principal investigator).

Michael J Angilletta Jr

4/1/11

Principal Investigator – Please Print   Date

Principal Investigator Signature   Date

***Department Chair   Date

***College Dean   Date

*****ASU Polytechnic requires these signatures.**

NOTE: Principal investigators are requested to attach a two-page biosketch reflecting their most recent pertinent experience. **Also include a current curriculum vitae for all senior participants.**

DETAILED USE OF ANIMALS
This section must be completed for each species used.

Link to additional Detailed use of Animals form:

Common Name: Ornate Tree Lizard

Scientific Name: Urosaurus ornatus

I. ANIMAL INFORMATION

A. Is this a threatened or endangered species?

☒ No. Proceed to section I. B.

☐ Yes. Describe why this work must be done on this species and why the project will not have a significant negative impact on the species:

B. Maximum # of animals to be used

Per Year:	200	Entire three years of protocol:	410

C. Sex: both Age or Weight Range: all

D. Source (e.g., commercial versus other, donated, captured from wild): captured from wild Animals used in all procedures (molding, validation, and euthanasia) will be captured and released on the same day, and will not be kept overnight.

E. Please LIST all labs and/or rooms **outside of the ASU centralized vivaria** where you intend to keep or use live animals in connection with the animal use covered under this protocol. This list is for IACUC information to assure each location is inspected semi-annually. **Listing rooms here does not assure approval of this space for use.**

Building	Room #	Max Length of Stay	Method of Transport	Purpose
LSE	722	2 hours	Cloth sack in car	Creating Jeltrate Moulds

II. MAJOR CATEGORIES OF USE

A. Will animals be immunized for antibody production?

☒ No. Proceed to section II. B.

☐ Yes. Complete the following table.

Injection:

Volume of injectate	Adjuvant	Route	Min. Frequency	Max. # of injections

I.

Collection: If terminal, check here ☐ Otherwise complete the following.

Route	Max. Volume	Min. Frequency	Max. # of collections

B. Will tissues or blood be harvested (other than for antibody production)?

☒ No. Proceed to section II. C.

☐ Yes. Will tissues be collected post-mortem only?

☐ Yes. Proceed to section II.C.

☐ No. Complete Appendix 1.

C. Will animals be food restricted (calorically or specific constituents)?
☒ No. Proceed to section II. D.
☐ Yes.
What are the restriction parameters? Provide scientific justification

How will you monitor for negative effects of food restriction (include information on how you will account for animal growth)?

D. Will animals be water restricted?
☒ No. Proceed to section II. E.
☐ Yes.
What are the restriction parameters? Provide scientific justification

How will you monitor for negative effects of water restriction (include information on how you will account for animal growth)?

E. Will pharmacologic or toxicologic materials be used apart from surgical use, including but not limited to tranquilizers, sedatives, analgesics, and anesthetics?
☒ No. Proceed to section II. F.
☐ Yes. Complete the following for each material.

Agent	Dose	Route	Purpose

Provide scientific justification:

F. Will irradiation or radioisotopes be used?
☒ No. Proceed to section II. G.
☐ Yes. List here and attach ASU Radioisotope Approval Form.

Agent	Dose	Route	Purpose

Provide scientific justification

G. Will toxic chemicals, carcinogens, recombinant DNA, or infectious agents be used in conjunction with animal use?
☒ No. Proceed to section II. H.
☐ Yes. List the agent, dose, route, and purpose in the table below ______________.

Agent	Dose	Route	Purpose

Provide the Institutional Biosafety Committee (IBC) approval #:

Provide scientific justification for the need to use these agents:

H. Will animals be exposed to trauma, injury, burning, freezing, or electric shock?
☒ No. Proceed to section II. I.
☐ Yes. List and justify each exposure.
Provide scientific justification:

I. Will animals be exposed to environmental stress (e.g., temperature, physical restraint, forced exercise)?
☐ No. Proceed to section II. J.

☒ Yes. List and scientifically justify each exposure.

Five or fewer lizards will be briefly (< 1 hour) exposed to higher temperatures than they might prefer to be in. In order to compare the rate at which the animal and model warm and their respective temperatures, they must be exposed to the same thermal conditions (same substrate, sun exposure, etc.); thus the lizard(s) must tethered near the model (this is also logistically necessary for all potential data collection methods (thermometer, thermocouple, and data logger). As our primary goal is to determine if the model accurately tracks the lizard near it's maximum thermal tolerance, the lizard must be exposed to high temperatures. The animal(s) will be removed before their body temperature reaches their maximum thermal tolerance, resulting in minor/negligible heat stress and what we would describe as temporary inconvenience due to the tether. Previous field measurements of lizard body temperatures have shown they prefer to be almost as hot as their maximum tolerance, so our lizard(s) will not be subjected to temperatures they would not encounter naturally.

J. Will animals undergo surgery?
☒ No. Proceed to section II. K.
☐ Yes. Attach Appendix 2.

K. Will any animals have a device (e.g., thermocouple, cannula, electrode) that extends chronically through the skin?
☒ No. Proceed to section II. L.
☐ Yes. Describe wound management measures to minimize chances of infection around the device where it penetrates the skin:

L. Will animals need any special husbandry considerations?
☒ No. Proceed to section II. M.
☐ Yes. Describe special procedures and provide scientific justification:

M. Will any animals need to be individually identified?
☐ No. Proceed to section III.
☒ Yes. Describe the marking technique to be used, why that technique was chosen, how it will be performed, and on what age range of animals?

All lizards captured during any procedure will be restrained by hand, and marked with a unique toe clip sequence in which up to four digits will be removed with surgical scissors. Toes will be clipped to -2 mm distal from the joint with hand/foot to avoid confusion with toes lost naturally. No more than two digits will be removed per foot. Pressure will be applied to any bleeding foot until bleeding stops. Lidocaine jelly will be applied to each toe after clipping. Scissors will be sterilized in 10% bleach solution between animals. Animals will be released at their exact point of capture (marked with wire flag upon capture). Animals captured as part of large scale field experiments will be marked with permanent (toe clips) and temporary but more visible (nail polish) marks. Nail polish will be painted dorsally between the hind legs, no more than 3 circles 1-2 mm in diameter for visual identification. Permanent markings are also necessary in this case to ensure proper identification when nail polish wears off or is lost during ecdysis.

Toe-clipping is the only means of quickly and relatively painlessly marking reptiles and amphibians under field conditions (Declining Amphibian Task Force Report, 1995; SSAR/ASIH guidelines for use of amphibians and reptiles in research, 1987;2001). Lizards marked by toe-clipping resume normal activity (e.g., basking, feeding) immediately upon release, clearly indicating the absence of significant trauma or pain associated with this marking technique. I have also searched the online literature for alternatives to toe clipping. Moreover, the literature suggests that other techniques for individual identification (e.g., PIT tags) may cause more stress than toe clipping which in some lizards appears to cause negligible increases in stress hormones and negligible declines in locomotory performance. Since toe clipping is a potentially painful procedure, I will administer analgesics to reduce pain.

III. DETRIMENTAL SEQUELAE

A. Will animals possibly experience clinical signs intentionally or as a possible side effect of the study?

☒ No. Proceed to section IV.

☐ Yes. Complete the following.

Possible Clinical Effect	Probability of Occurrence	Treatment

IV. END POINT CRITERIA

A. What clinical signs will be used as a basis for removal of an animal from the study?

If a lizard is injured during capture/handling, in the molding gel, or while tethered and we will evaluate the likelihood of the resulting pain and (potential) physical handicap affecting its long-term survival. If we judge that the lizard is not likely to survive for more than a month, (due to increased risk of predation, decreased mobility, and/or inability to feed) we will euthanize it by returning to ASU, placing the lizard in an airtight plastic bag, squeezing out all the air, quickly filling the bag with pure compressed CO_2, and then leaving it undisturbed for at least an hour. Inhalation of pure CO_2 results in unconsciousness (within seconds), from which the animals do not wake up. Animals will be euthanized the same day, and will not be kept overnight.

V. EUTHANASIA

A. Chemical/Gas Methods, if any:

Agent	Dose	Route
CO_2	3-5 liters (gas)	Inhalation

If using a chemical method for euthanasia, what secondary physical means (e.g., thoracotomy) will be used to assure euthanasia? Decapitation

B. Physical Methods, if any:

☐ Cervical dislocation (mice, immature rats)*

☐ Decapitation*

☐ Exanguination under anesthesia

For methods that are marked with an *, provide a scientific justification here for the need to use this method (provide references if possible):

C. Name(s) and qualifications of person(s) performing euthanasia:

1. Name	2. Qualification
Michael Angilletta	Over the past 15 years, the PI has gained experience in euthanizing reptiles. For the first five years, the PI used decapitation, but in the last ten years has combined lethal injection with decapitation. The PI also has experience with CO_2 euthenasia.
Jeffrey Ackley	Trained in CO_2 euthanasia and decapitation of reptiles and mammals while working at two wildlife rehabilitation centers.