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Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA

G. Darrel Jenerette,[1,5] Sharon L. Harlan,[2] William L. Stefanov,[3] and Chris A. Martin[4]

[1]*Department of Botany and Plant Sciences, University of California Riverside, Riverside, California 92512 USA*
[2]*School of Evolution and Human Change, Arizona State University, Tempe, Arizona 85287 USA*
[3]*Image Science and Analysis Laboratory, Lyndon B. Johnson Space Center, Houston, Texas 77058 USA*
[4]*Department of Applied Sciences and Mathematics, Arizona State University, Glendale, Arizona 85306 USA*

Abstract. Urban ecosystems are subjected to high temperatures—extreme heat events, chronically hot weather, or both—through interactions between local and global climate processes. Urban vegetation may provide a cooling ecosystem service, although many knowledge gaps exist in the biophysical and social dynamics of using this service to reduce climate extremes. To better understand patterns of urban vegetated cooling, the potential water requirements to supply these services, and differential access to these services between residential neighborhoods, we evaluated three decades (1970–2000) of land surface characteristics and residential segregation by income in the Phoenix, Arizona, USA metropolitan region. We developed an ecosystem service trade-offs approach to assess the urban heat riskscape, defined as the spatial variation in risk exposure and potential human vulnerability to extreme heat. In this region, vegetation provided nearly a 25°C surface cooling compared to bare soil on low-humidity summer days; the magnitude of this service was strongly coupled to air temperature and vapor pressure deficits. To estimate the water loss associated with land-surface cooling, we applied a surface energy balance model. Our initial estimates suggest 2.7 mm/d of water may be used in supplying cooling ecosystem services in the Phoenix region on a summer day. The availability and corresponding resource use requirements of these ecosystem services had a strongly positive relationship with neighborhood income in the year 2000. However, economic stratification in access to services is a recent development: no vegetation–income relationship was observed in 1970, and a clear trend of increasing correlation was evident through 2000. To alleviate neighborhood inequality in risks from extreme heat through increased vegetation and evaporative cooling, large increases in regional water use would be required. Together, these results suggest the need for a systems evaluation of the benefits, costs, spatial structure, and temporal trajectory for the use of ecosystem services to moderate climate extremes. Increasing vegetation is one strategy for moderating regional climate changes in urban areas and simultaneously providing multiple ecosystem services. However, vegetation has economic, water, and social equity implications that vary dramatically across neighborhoods and need to be managed through informed environmental policies.

Key words: climate change; economic stratification; ecosystem services; extreme heat events; urban heat riskscape; vegetated cooling.

Introduction

Rising temperatures in urbanized areas have already exceeded predicted mean global temperature increases in many cities and will likely increase further through interactions between local and global climate processes (Oke 1973, Wilby 2008, IPCC 2007). Regionally enhanced urban temperatures, commonly referred to as urban heat islands (UHI), create many socioecological challenges for cities, which affect the majority of the world's population who now live in urban centers (United Nations 2004, IPCC 2007). Future increases in both UHI effects and urban populations are projected globally (IPCC 2007). Although the UHI has been frequently described as a nighttime phenomenon related to increased heat storage, there is mounting evidence of substantial daytime UHI effects related to high surface temperatures (Weng et al. 2004, Jenerette et al. 2007, Imhoff et al. 2010).

High temperatures in cities are associated with negative consequences for human health and well-being (Baker et al. 2002, Patz et al. 2005, Grimmond 2007), including elevated rates of illnesses and deaths directly due to temperature (Curriero et al. 2002, Michelozzi et al. 2009) and indirectly through interactions with air pollution (Filleul et al. 2006, Knowlton et al. 2008). A wide range of other social and environmental problems are also aggravated by high temperature, including

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[5] E-mail: darrel.jenerette@ucr.edu

increased violent crime (Anderson 1987) and energy usage from air conditioning with associated impacts on anthropogenic greenhouse gas emissions (Akbari et al. 2001, Baker et al. 2002). High temperatures affect most biological processes through direct metabolic temperature sensitivity and enzyme regulation, and indirectly through alterations in water availability caused by increased soil drying and increased vapor pressure deficits (Katul et al. 2003, Brown et al. 2004, Jenerette et al. 2009). Biological responses to warming range from altered physiological functioning and trade-offs to mortality and community assembly. Land-cover-dependent urban warming is likely to have even greater future impacts on urban socioecological systems through interactions with global climate changes (Patz et al. 2005, IPCC 2007).

Increasing trees and vegetation in urban areas is one strategy for mitigating UHI effects (Stone and Rodgers 2001, Kalnay and Cai 2003, Jenerette et al. 2007) and cooling is one of many reasons why urban forest expansion programs are becoming popular. A few examples of the many cities with tree-planting initiatives are Los Angeles and San Francisco, California; Phoenix, Arizona; Chicago, Illinois; and Berlin, Germany (initiative descriptions *available online*).[6,7,8,9,10] The urban cooling effect of vegetation can be extensive (Jenerette et al. 2007, Imhoff et al. 2010) and the magnitude depends on variations in local meteorology, availability of water resources, the extent of vegetated coverage, and composition of the vegetation. Planting vegetation for the purpose of regulating urban temperature is an intentional ecosystem modification to provide ecosystem services. Ecosystem services associated with urban cooling may have global benefits through reduced greenhouse gas emissions (Akbari 2002, Baker et al. 2002), regional benefits through reduced electricity demands, and local benefits through direct microclimate modification. Vegetation provides both a potential first-order human safety service during extreme events and during chronic warm conditions. Other local ecosystem services provided by urban vegetation include improved soil drainage, reduction in air pollution, food provisioning from edible plants, and cultural benefits, such as beautification (Loram et al. 2007, McPherson et al. 2011).

Spatial variability in vegetated cooling contributes to a complex mosaic of temperatures within an urbanized area, where the consequences of human exposure to environmental conditions can vary on a continuum between comfortable to lethal. We use the phrase "urban heat riskscape" to describe the heterogeneous spatial and temporal distribution of variables that create conditions for different levels of environmental exposure and adaptive capacity in response to heat hazards. Temperature and vegetation patterns obtained from remotely sensed data, overlaid with the spatial variability of urban population characteristics such as socioeconomic status, race/ethnicity, and age, describe an urban heat riskscape in the Phoenix region (Harlan et al. 2006, Ruddell et al. 2010). Riskscapes are implicit environmental justice concerns that reflect inequalities in exposure to the potential hazard of the environment and the coping (adaptive) capacity of residents. Residents in places with high exposure risk and low coping capacity are more vulnerable to extreme heat and other hazards (Ebi 2009, Wilhelmi and Hayden 2010).

The use of ecosystem services to mitigate the high end of the heat riskscape is an important component of reducing human vulnerability to acute and chronic extreme temperatures. However, the costs of providing temperature regulating ecosystem services, measured either in monetary terms or resource requirements, are often unappreciated (Lyytimaki et al. 2008, Colyvan et al. 2010). Expanding urban vegetation has direct economic costs for its purchase, planting, and on-going maintenance. Potentially more critical, on-going landscape irrigation requires large water resources to sustain transpiration and evaporative cooling from vegetation (Pataki et al. 2011*a*). This water resource requirement is in short supply for many cities (Jenerette and Larsen 2006), imposes further economic costs, and can reduce water available for other uses including agriculture and native ecosystems (Jackson et al. 2001, Baron et al. 2002). The trade-off between ecosystem services related to climate regulation and water demands (Jackson et al. 2008) may place a constraint on the potential long-term sustainability of using vegetation to mitigate high urban temperatures. Little is known about assessing ecosystem service trade-offs: the research emphasis on ecosystem services has focused far more on their quantification, availability, and dynamics (Millennium Ecosystem Assessment Board 2003, Beier et al. 2008). Decision-making about ecosystem services should also include an explicit treatment of associated costs and resource use trade-offs (Farber et al. 2006), as well as social equity considerations in the distribution of services.

The Phoenix, Arizona metropolitan region (hereafter referred to as Phoenix) is located at the northeastern fringe of the lower Colorado River Valley subdivision of the Sonoran Desert in the southwestern United States. In this study, we used Phoenix as a model ecosystem to explore how urbanized regions in arid biomes might use ecosystem services to moderate excessive temperatures and to estimate the amount of water required to supply these services. We estimated the variable temperature distribution and the irrigation requirements for vegetation to mitigate excessive temperatures and examined temporal variation in these relationships at seasonal and decadal scales. We examined the spatial and temporal

[6] ⟨http://egov.cityofchicago.org/chicagotrees/⟩
[7] ⟨http://www.milliontreesla.org/⟩
[8] ⟨http://www.fuf.net/⟩
[9] ⟨http://phoenix.gov/FORESTRY/trees.pdf⟩
[10] ⟨http://www.stadtentwicklung.berlin.de/umwelt/stadtgruen/stadtbaeume/index_en.shtml⟩

relationships between variation in temperature-regulating ecosystem services and neighborhood economic status to describe how the heat riskscape is associated with patterns by neighborhood income levels. Household income is widely known as an indicator of social class that is highly correlated with education, occupation, and race/ethnicity (Scott 1996) and neighborhoods in American cities are segregated by differences in household income (Mayer 1996).

We asked four questions: (1) How variable, both spatially and temporally, is the cooling effect of vegetation in Phoenix? (2) What is the total water use for sustaining vegetation that provides cooling ecosystem services for Phoenix? (3) How could potential rates of water use vary as a result of decisions to sustain different levels of vegetated land cover? (4) Throughout 1970–2000, do the availability and associated costs of cooling ecosystem services depend on neighborhood economic status? We explored two hypotheses in answering these questions. First, characteristic responses of plants to meteorological conditions strongly constrain the cooling potential of vegetation. We propose that a simplified ecophysiological and energy balance model can describe the effects of vegetation on surface temperatures and quantify the water demands associated with vegetated cooling (Blonquist et al. 2009). Second, household income of neighborhood residents is strongly related to the availability of vegetation, ecosystem services, risks, and costs associated with mitigating risks (Harlan et al. 2006, Jenerette et al. 2007). While economic status hypotheses do not describe many potentially important components of socio-biophysical interactions, economic capital is often a principal gradient directly related to and indirectly correlated with other aspects of social stratification and environmental conditions in cities (Hope et al. 2003, Warren et al. 2010).

Our research will show how ecosystem service production can vary through time, how trade-offs in both the benefits and costs of ecosystem services might be evaluated, and how services are differentially available along a key societal gradient. The results will provide a framework for understanding how cities can quantitatively assess potential trade-offs in mitigating the impacts of regional climate change through vegetation management strategies designed to enhance and balance the production of ecosystem services. Finally, the results of our study may be directly applicable to decision-making in Phoenix.

Methods

Study site

The Phoenix metropolitan region is Arizona's largest urban agglomeration, where four million people, or 66% of the state's population, reside in 25 municipalities and three Indian communities. Phoenix was founded by European Americans in 1868 as a farming community and was incorporated as a city in 1881. Ethnic and racial divisions in the community were an integral part of historical development and restrictions were imposed on residential locations for Hispanics and African Americans well into the 20th century (Bolin et al. 2005). Approximately 40% of the population is ethnic minorities (predominantly Hispanics) and the residential segregation between minority and white neighborhoods remains pronounced through the most recent census measurements (Logan and Stults 2011).

The region is hot and dry with mean annual daily temperatures of 30°C, and annual rainfall of 193 mm. Daytime summer air temperature exceeded 43°C on average 23 days per year in the last decade (D. M. Ruddell, D. Hoffman, O. Ahmad, and A. J. Brazel, *unpublished manuscript*). Native vegetation is comprised of Sonoran Desert species with extensive creosote (*Larrea tridentata*) dominated scrub that also includes two dispersed megaflora, the blue palo verde (*Parkinsonia florida*), and desert ironwood (*Olneya tesota*). Residential vegetation includes trees and shrubs from a global species pool intermixed with a diverse assemblage of turf cultivars and management practices. The Central Arizona–Phoenix project, an NSF-funded LTER site since 1998, has extensive documentation of diverse biophysical and social patterns in this region (project description *available online*).[11]

Phoenix has a prominent UHI that has expanded throughout the region and is characterized primarily by elevated nighttime temperatures (Brazel et al. 2000, 2007) and also by increased daytime surface temperatures (Jenerette et al. 2007). Historically, the Phoenix UHI has been modulated by large tracts of irrigated agriculture (Georgescu et al. 2009), but its recent intensification may be due in part to the rapid conversion of land uses from agricultural to urban. The effect of vegetation on reducing surface temperatures in this region has been documented and median neighborhood annual household income has been correlated with vegetation and temperature (Jenerette et al. 2007, Buyantuyev and Wu 2010). The concentration of low-income neighborhoods with high proportions of minorities and low vegetation is in the central core of Phoenix (Bolin et al. 2005) where the UHI is most intense.

Remotely sensed data: land surface temperature and vegetation indices

As primary biophysical data sources, we used remotely sensed imagery collected as part of the Landsat program and local weather station records. We obtained data at decadal intervals of 1970, 1980, 1990, and 2000, corresponding with census survey years. Orthorectified Landsat data (UTM Zone 12, NAD83 datum) were obtained from the EROS Data Center in Sioux Falls, South Dakota and preprocessed using commercial image processing software. The atmospheric component of reflected and emitted energy in each scene

[11] ⟨http://caplter.asu.edu⟩

was modeled and removed using the MODTRAN 4 radiative transfer code implemented by the commercial software package ATCOR 3.0 for Imagine 9.3 (Berk et al. 1998, GEOSYSTEMS 2002) and United States Geological Survey National Elevation Dataset digital elevation models for the Phoenix study area. Following atmospheric correction to obtain apparent surface reflectance and surface temperature, the metropolitan Phoenix study area was subset from each scene and compared to verify geolocation accuracy between subsets using the ENVI 4.7 software (ITT Visual Information Solutions, White Plains, New York, USA). Surface reflectance differences in the near infrared and red bands were used to calculate the normalized difference vegetation index (NDVI). NDVI is a widely used proxy for vegetation patterns readily calculated from several satellite sensor systems (Pettorelli et al. 2005, van Leeuwen et al. 2006). Remotely sensed vegetation indices, such as NDVI, are best associated with the fraction of absorbed photosynthetically active radiation (FAPAR), although frequently remote sensing derived vegetation indices are used as a metric for leaf area (Friedl et al. 1995, Turner et al. 1999). Other indices, including the soil-adjusted vegetation index (SAVI), are also used in many dryland ecosystems (Huete 1988); we chose to use NDVI because of the widespread presence of irrigated vegetation in the Phoenix metropolitan region and a general agreement between these two indices in our study region observed in preliminary analyses.

The earliest imagery was available in 1972 from the Landsat 1 Multispectral Scanner System (MSS). No mid-infrared band was available on Landsat 1 and the spatial resolution of the orthorectified data was 60 m/pixel. Of the two cloud-free scenes available, we used a single cloud-free scene from the summer of 1972 that captured the majority of the Phoenix urban area. Throughout the rest of the analysis, we describe these data as 1970 for comparison with census data. The 1980 imagery was from the Landsat 3 MSS, similar to Landsat 1 in terms of band passes and spatial resolution. Of the two cloud-free scenes available, we used a single cloud-free scene from the 1980 summer season. The 1990 imagery was obtained by the Thematic Mapper (TM) on board Landsat 5, which includes six bands spanning the visible to shortwave infrared wavelengths at 30 m/pixel and a single mid-infrared (10.4–12.5 microns) band at 120 m/pixel. We used all six of the cloud-free scenes distributed throughout the spring, summer, and fall seasons of 1990. The 2000 imagery was obtained by the Enhanced Thematic Mapper Plus (ETM+) instrument on Landsat 7. The ETM+ is similar to the TM sensor in terms of band coverage and spatial resolution, but it has a 60 m/pixel mid-infrared broadband with both high and low gain channels. We used eleven cloud-free scenes that provided full seasonal coverage of the Phoenix metropolitan area for 2000.

All NDVI (1970, 1980, 1990, 2000) and surface temperature (1990, 2000) data were resampled to a common spatial resolution of 30 m/pixel as necessary using a nearest neighbor algorithm to minimize alteration of data values and our interpretations are primarily made at the much larger neighborhood scale. Our application of urban remote sensing follows several recent implementations for improved understanding of UHI spatial patterns (Voogt and Oke 2003, Stefanov et al. 2004, Weng et al. 2004, Imhoff et al. 2010) and extends these applications through analyses of seasonal and decadal changes.

Census data: socioeconomic patterns

As primary social data we used the median annual household income variable from the decadal US Census tracts for the Phoenix region from 1970–2000 to describe neighborhood economic status. Income data were inflation adjusted to the year 2000 for comparison between decades. Census tracts were designed to be relatively homogenous units with respect to population characteristics, economic status, and living conditions at the time they were established. A single tract generally contains between 1000 and 8000 people, with a target size of 4000 people. Census tracts have been used by social scientists as one unit appropriate for neighborhood characterizations (Sampson et al. 1997). As Phoenix has gained population over time, especially around the urban fringes, many tract boundaries have changed between surveys. Because we wanted a consistent tract boundary across decades we used the GeoLytics census data product (Geolytics, East Brunswick, New Jersey, USA), which includes a normalization of census boundaries from 1970 to 2000 developed through a weighting of population characteristics. For each decade, only those tracts predominantly urban or suburban were included; tracts with mostly agriculture or desert were excluded from the analysis. The final number of tracts included from 1970, 1980, 1990, and 2000 increased from 351, 427, 510, to 599, respectively.

Weather station data: daily meteorological conditions

Weather station data were derived from the long-term NOAA weather station at Sky Harbor Airport. We used the hourly reported estimates of air temperature and relative humidity from 11:00–12:00 local time as reference for the date of each satellite image. This time corresponds to typical local image acquisition times for the Landsat sensors over the Phoenix metropolitan area. To extrapolate an estimate of vegetation induced cooling and the water costs associated with cooling, we obtained daily maximum temperature and minimum relative humidity for every day from 1970 to 2005. Prior to 1984 relative humidity (RH) data, an essential variable partly describing vapor pressure deficit, was not recorded for the Sky Harbor weather station; we therefore estimated this variable using a regression relationship developed between 1984–2005 ($RH = 89.92 + 0.16[Tmax - Tmin]^2 - 6.69[Tmax] + 6.36[Tmin]$; $r^2 = 0.57$), where Tmax is the maximum temperature and Tmin is the minimum temperature.

Surface temperature, energy balance, and evaporation analysis

We analyzed intra- and inter-year variation in relationships between the remotely sensed surface temperature, NDVI, and Sky Harbor meteorology to better understand the cooling effect provided by vegetation. To quantify relationships between the variables and avoid potential influences of spatial dependence, a subsampling and bootstrapping approach was used for all subsequent analyses. For each analysis, 5000 pixels were selected from the landscape and relationships were assessed using the statistics as described for the subset of data. This process was then iterated 1000 times and the mean of resulting variables were used when reporting results of statistical models. The precision of the approach was high as the mean standard deviation among all bootstraps for most parameter estimates was less than 1% of the estimate.

We evaluated the correlation coefficient between NDVI and surface temperature for the eleven 2000 scenes and the six 1990 scenes to establish a potential seasonal trend in the cooling derived from vegetation. For each scene a regression analysis was conducted between NDVI and surface temperature. The parameters of this regression, the intercept and slope, respectively describe the bare surface temperature (°C) and the temperature reduction associated with a fully vegetated landscape where NDVI was equal to 1.0 (°C/NDVI). We evaluated the suitability of weather station meteorological patterns at the selected 11:00–12:00 time interval to predict bare surface temperature and the cooling effect of vegetation. We used the resulting model to estimate the historical variation in maximum daily surface temperatures for bare and fully vegetated surfaces from 1970 to 2005 based on records from Sky Harbor.

To estimate the water loss associated with land-surface cooling we applied a simplified surface energy balance model individually for each pixel to describe the total evaporation required for vegetation to reduce the surface temperature below that expected of bare surfaces. We started with the basic surface energy balance equation commonly used for vegetated canopies (Campbell and Norman 1998, Blonquist et al. 2009):

$$R_n = H + \lambda E + S \tag{1}$$

where R_n was the net radiant energy in the canopy, H was the sensible heat flux, λE was the latent heat associated with evaporation, and S was the storage of heat by the canopy (W/m^2). Often several additional terms are included in specific applications including heat generation through anthropogenic processes or energy used in photosynthesis. In this simple first estimate of evaporation we considered only the 24 July 2000 day where the surface temperature and complete Sky Harbor meteorology information were available. We began by estimating the sensible heat flux of the canopy based on the temperature differential between the canopy and air (Campbell and Norman 1998, Blonquist et al. 2009):

$$H = g_h C_p (T_c - T_a) \tag{2}$$

where g_h was the boundary layer heat conductance, C_p was the heat capacity of air, T_c was the temperature of the canopy, and T_a was the temperature of the air. For our implementation of this sensible heat estimate, we considered T_a (°C) as the air temperature recorded at Sky Harbor and T_c (°C) as the remotely sensed estimate of land-surface temperature. While C_p can be reasonably approximated from literature values, g_h varies depending on the canopy structural characteristics. As an initial approximation we assumed g_h was 1.0. We first used this model to estimate the sensible heat at bare surface locations with a T_c described by the intercept between the surface temperature–vegetation relationship. For bare surfaces, we assumed there were no latent heat transfers, and the surface and air temperatures were in steady state so there was no net storage. With these assumptions we estimated R_n as bare surface modeled H. To arrive at an estimate of E, or the water requirements associated with cooling, we subtracted the estimated sensible heat (Eq. 2) for each pixel from estimated R_n:

$$E = (R_n - H)/\lambda. \tag{3}$$

As a coarse evaluation we compared E against three contrasting estimates of land-surface evaporation from this region. We first evaluated the rates in comparison to southern Arizona riparian ET estimates measured from whole ecosystem eddy-covariance instrumentation (Scott et al. 2004). These forest and grassland sites supplied by near-surface groundwater should be similar to irrigated landscaping found in Phoenix. We also compared the estimated E rates with maximum peak water delivered by the Phoenix water authority (Raftelis Financial Consulting PA 2002). Finally, we compared estimated E rates to modeled evapotranspiration patterns from a few selected neighborhoods in the Phoenix metropolitan region (Gober et al. 2010).

Neighborhood variability analysis

To describe the relationship between neighborhood economic status, local cooling, and water requirements, we conducted regression analyses between census tract estimated household median income and two dependent variables for 24 July 2000 as a representative period. We quantified the mean temperatures within each neighborhood and the proportion of area that either exceeded a surface temperature risk threshold (55°C) or was below the surface temperature refugia criteria (50°C). These threshold criteria are higher than those developed using air temperature (Harlan et al. 2006); summer midday surface temperatures are commonly much higher than corresponding air temperatures. As direct relationships are lacking between surface and air temperatures, or human health response to surface temperature, these thresholds were chosen as examples to describe a

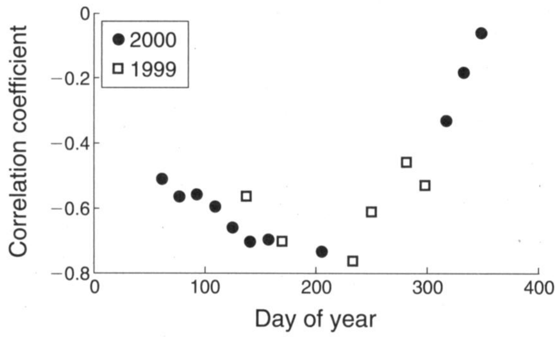

FIG. 1. Correlation between the normalized difference vegetation index (NDVI) and surface temperature for the years 2000 and 1990 for Phoenix, Arizona, USA. Data were derived from Landsat satellite imagery and are the means of 1000 bootstrap samples where, for each, 5000 pixels were randomly selected to avoid potential autocorrelation.

common extreme temperature and a conservative refugia criteria only 5°C cooler. Both criteria should be established based on local conditions and policy decisions about managing the urban heat riskscape and could be evaluated across any temperature scenarios. As an initial assessment to evaluate the consequences of alternate management strategies, we evaluated scenarios for providing additional evaporative cooling to reduce surface temperatures. We quantified how much additional irrigation would be required to reduce surface temperatures to a critical level of 50°C. We examined the spatial patterns in these water requirements for a given scenario and then computed the cost surface for varying critical temperatures and proportions of neighborhoods with temperatures below the specified critical temperature threshold.

To describe the decadal variations in urban vegetation and residential economic status, we evaluated the dynamics of census income data and estimated summer NDVI from 1970 to 2000. We assumed the biophysical relationships between surface temperature and vegetation observed between 1990 and 2000 did not vary in either 1970 or 1980, and therefore earlier data on NDVI could be used as a proxy for vegetation based cooling ecosystem services. For each decade we quantified regional variability in both income and vegetation using the Gini coefficient, which is commonly used in economic studies (Gastwirt 1972). The Gini coefficient identifies the degree of inequality in the distribution of a variable where a value of 0 is perfect equality and a value of 1 is complete inequality.

RESULTS

The seasonal pattern of relationships between NDVI and surface temperature for the years 1990 and 2000 were consistently correlated at the regional scale (Fig. 1). For both years, an inverse correlation between NDVI and surface temperature was strongest during the summer and weakest during winter. The strongest correlation was −0.77, which was observed in early July. Across all dates examined the mean correlation was −0.62. The dynamics of the surface-temperature–vegetation relationship was well described by Sky Harbor meteorology. The intercept of the regression equation between NDVI and surface temperature, a measure of bare surface temperature, was linearly related to air temperature (Fig. 2A). This linear trend was consistent between 15°C and 45°C noon air temperature and corresponding 20°C and 63°C bare surface temperatures. The strength of the vegetated effect on surface temperature cooling, the slope of the NDVI–surface-temperature regression, varied as a saturating relationship with estimated bare surface

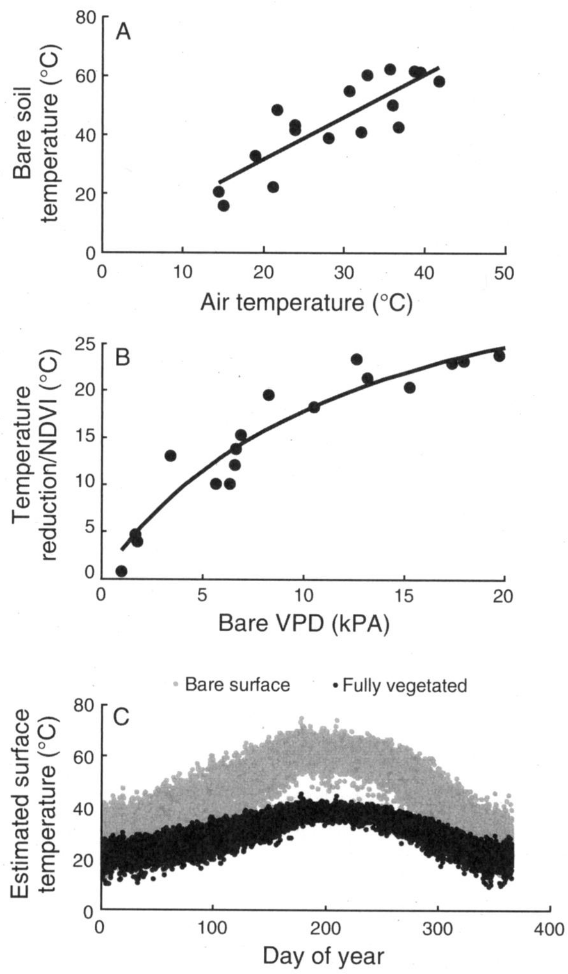

FIG. 2. Relationships between Sky Harbor meteorology and surface temperature patterns. (A) The bare surface temperature is well described by a linear function of air temperature: $y = 2.65 + 1.45x$. The effect of vegetation, the slope of a regression between temperature and NDVI, is well described by a Michaelis-Menton function of estimated bare soil VPD, which is derived from bare surface temperature and relative humidity: $y = 39.69x/(12.21 + x)$. (C) These surface temperature models were used to estimate daily maximum bare surface and fully vegetated temperatures using the Sky Harbor meteorological record from 1970–2005.

vapor pressure deficit (VPD, kPA). This trend, well described by a Michaelis-Menton function, was observed between less than 1 kPA to more than 20 kPA and a corresponding vegetation cooling effect between less than 1°C and nearly 25°C (Fig. 2B). The extremely high VPD estimates correspond to days of less than 20% relative humidity and bare surface temperatures exceeding 60°C. Together these functions allowed estimation of the capacity for vegetated cooling under a range of plausible meteorological conditions. Using the daily meteorological records from Sky Harbor from 1970 to 2005, the annual trajectory and interannual variability in the estimated noon surface temperature was generated for bare surface and fully vegetated states (Fig. 2C). These differences document the large potential reduction in surface temperature means and variability for vegetated surfaces compared to bare surfaces.

The amount of water required to generate the observed surface temperature patterns was estimated over the entire metropolitan region for 24 July 2000 (Fig. 3). We initially estimated the 11:00–12:00 RH period and then upscaled this to whole day estimates for comparisons using hourly meteorology and relationships developed between cooling, vegetation, and Sky Harbor meteorology (Fig. 2A, B). The median estimated whole day water flux across the region was 2.7 mm and the high 95th percentile of fluxes was 7.2 mm.

The estimates of water required for cooling were combined with descriptions of neighborhood economic-status–ecosystem-service relationships (Fig. 4). Higher median neighborhood income was directly associated with greater NDVI, cooler temperatures, and greater estimated water requirements for the production of cooling services. Extending these analyses to better understand urban heat riskscapes, we quantified the proportions of total area in each neighborhood that either exceeded a surface temperature threshold or was available as a cool refugia (Fig. 5). Correlating these proportions with neighborhood economic status, we found higher median household income neighborhoods had less area that exceeded the threshold temperature and more area classified as cool refugia.

Inflation adjusted median household incomes have increased from 1970 to 2000. NDVI has shown a similar increase from 1970 to 1990 but the 2000 NDVI exhibited decadal consistency with 1990 (Fig. 6A). The regional variability in income increased while regional variability in NDVI decreased over this three decade period (Fig. 6B). The relationship between NDVI and income has increased markedly since 1970, when no significant correlation was detected ($P > 0.5$), to a correlation of 0.4 ($P < 0.001$) in 2000 (Fig. 6C). These patterns document a gradual concentration of vegetation into higher income neighborhoods compared with lower income neighborhoods.

To alleviate neighborhood inequality in risks from extreme heat through evaporative cooling, large increases in water were required (Fig. 7A) with proportionately more water required in neighborhoods with lower economic status (Fig. 7B). As an initial analysis of water use for scenarios of management decisions, we estimated the additional water use required for varying threshold critical temperatures and a maximum proportion of area within a neighborhood exposed to this threshold (Fig. 7C). These water use rates were nonlinearly dependent on both management criteria. As the critical temperature threshold decreases, choices on proportional areal exposure became more important in determining additional irrigation needs.

Discussion

Explicitly describing both benefits and costs is essential for developing decision-support tools with which policymakers can evaluate trade-offs for ecosystem services (Turner et al. 2003, Chee 2004, Fisher et al. 2008). This study provides the first intra- and interannual analyses of ecosystem service production and resource requirements with a specific application for vegetation mitigation of the urban heat riskscape. Our regional analysis of water requirements for supplying these ecosystem services provides a metric for computing production efficiency for urban cooling. Efficiency variables that couple benefits and costs can provide information for better management of potentially competing ecosystem services.

In addressing our first question, we documented that vegetation in Phoenix provides a highly variable but well-constrained cooling pattern. The high variability is consistent with patterns of many ecosystem properties that show increases relative to unmanaged ecosystems (Jenerette et al. 2006, Wu et al. 2011). Our results showed that the production of cooling ecosystem services by vegetation in the Phoenix metropolitan region was strongest during the summer and weakest during winter. The availability of this ecosystem service in the summer months substantially mitigated the summer bare surface temperatures in Phoenix, which routinely exceed dangerous levels for humans (Singer and Martin 2008). The high surface temperatures in this region exceeding 60°C negatively influence human health through direct conduction, increasing local air temperature, and radiating substantial longwave radiation back to a human. Modifying the heat riskscape to avoid these high temperature surfaces has the potential to decrease hazardous exposure and detrimental health outcomes for people in cities.

The temporal variations of cooling ecosystem services followed a saturating Michaelis-Menton function of estimated VPD in Phoenix across 1990 and 2000 (Fig. 2B). This saturating pattern between cooling and VPD is consistent with ecophysiological mechanisms relating stomatal control to plant water loss and should broadly be applicable (with varying parameters) for most

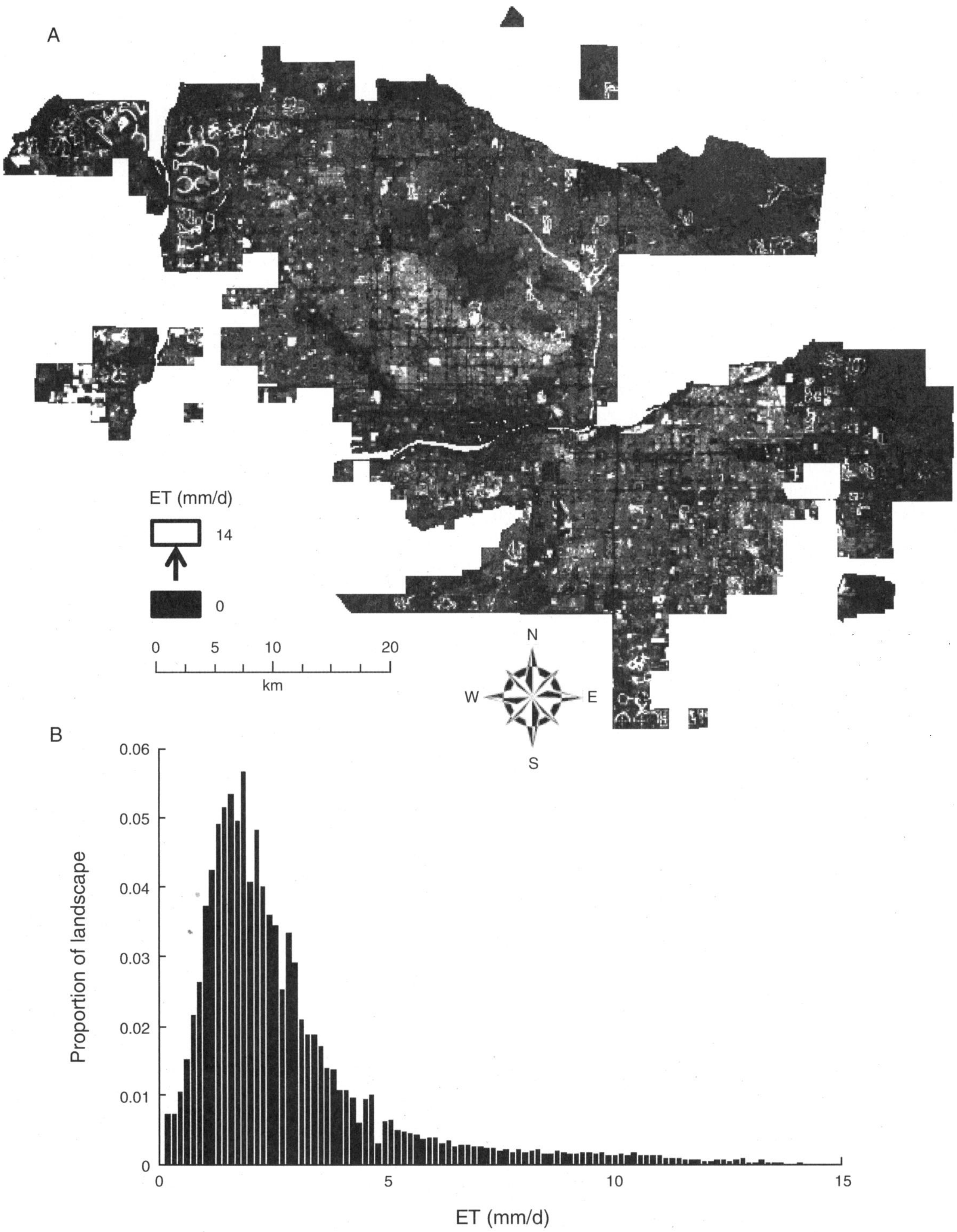

FIG. 3. Estimation of landscape evapotranspiration (ET) associated with vegetation cooling extrapolated over the entire day of 24 July 2000 for Phoenix, Arizona, including (A) mapped patterns and (B) a histogram of fluxes normalized to the proportion of the entire landscape.

vegetation. At low VPD, we expect stomata are maximally open, which results in a nearly linear relationship with evaporation. As water loss across the leaf surface increases, plant and soil hydraulic limitations to move water are potentially reached, which results in plant regulation of stomatal closure and reduced sensitivity to further increases in VPD (Katul et al. 2003, Jenerette et al. 2009).

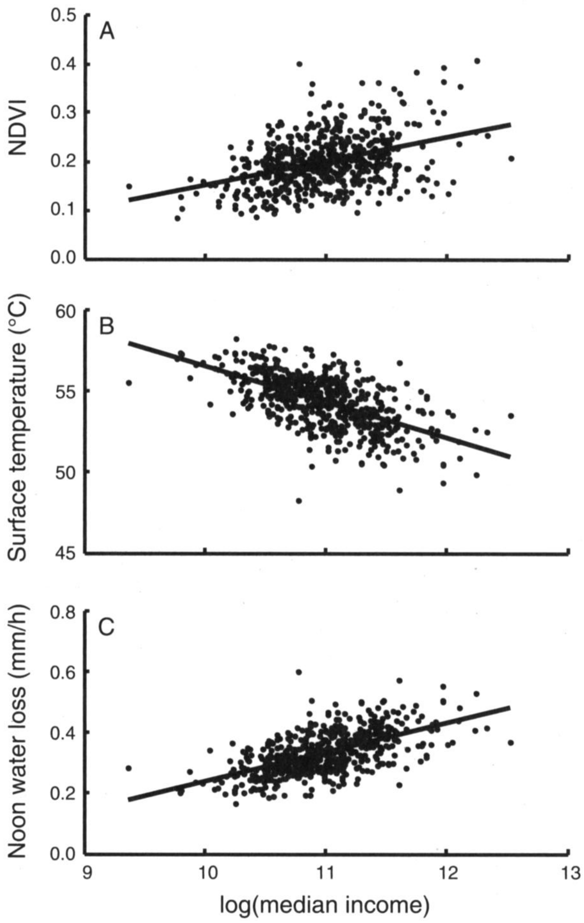

FIG. 4. Relationship between the log of median household income (measured as US$/yr) by census tract with (A) NDVI ($y = -0.32 + 0.048x$), (B) surface temperature ($y = 78.7 - 2.2x$), and (C) estimated noon ET ($y = -0.73 + 0.097x$) for 24 July 2000.

In addressing our second and third questions, we generated an initial estimate of the water requirements associated with the production of cooling ecosystem services. Our estimate of water use provided an initial attempt to describe the water costs associated with vegetative cooling using data sources that are readily available to decision-makers in many cities. We view these estimates and the approach as tentative at this stage and are working to improve the model, parameters, and appropriate validation data to increase prediction skill and properly assess uncertainty. We compared our estimated water fluxes to three sources of information to evaluate general consistency of our estimates. The fluxes we derived for Phoenix are within the range expected for riparian forests and grasslands in southern Arizona and much higher than native Sonoran Desert (Scott et al. 2006, Scott et al. 2009). These estimates were also within an order of magnitude of the reported peak daily water deliveries by the city of Phoenix (Raftelis Financial Consulting PA 2002). Finally, the estimated water fluxes and cooling capacities were similar in magnitudes to those reported for a selection of ten neighborhoods and using a more complex land surface model (Gober et al. 2010). These estimates for Phoenix are somewhat higher than whole tree measured evaporative fluxes in Los Angeles, California (Pataki et al. 2011*b*), where typically temperatures are lower and relative humidities are higher, and within the range observed in summer for different landcovers in Minneapolis-Saint Paul, MN (Peters et al. 2011). A recent meta-analysis of studies using remotely sensed temperature variations to estimate evaporation found a relative error ranging from 15% to 30% (Kalma et al. 2008); we expect our results are within this range as our estimates are consistent with initial comparisons with other energy balance and water use studies in the region.

Our initial assessment suggests important next steps are improving our understanding of the surface heat capacity, boundary layer conductance, albedo, storage, and net radiation terms in the model. All of these terms vary spatially throughout the region and better understanding of this heterogeneity will also be helpful. A future direction for improving the energy balance modeling approach will be to represent the three dimensional land surface characteristics within each pixel and still maintain simplifications where process trade-offs are observed. Such approaches could take advantage of recent land surface model developments (Baldocchi et al. 2002, Ivanov et al. 2008, Jenerette et al. 2009), improved three dimensional land surface data (Asner et al. 2009), and detailed canopy thermal

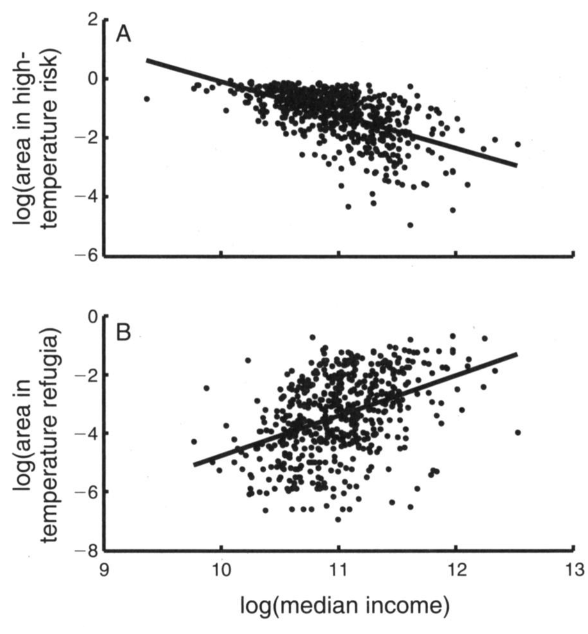

FIG. 5. Relationship between log median household income and the (A) proportion of a neighborhood in high temperature risk (>55°C) (log $y = 11.12 - 1.12x$) and (B) proportion of a neighborhood in a temperature refugium (<50°C) (log $y = -18.5 + 1.38x$).

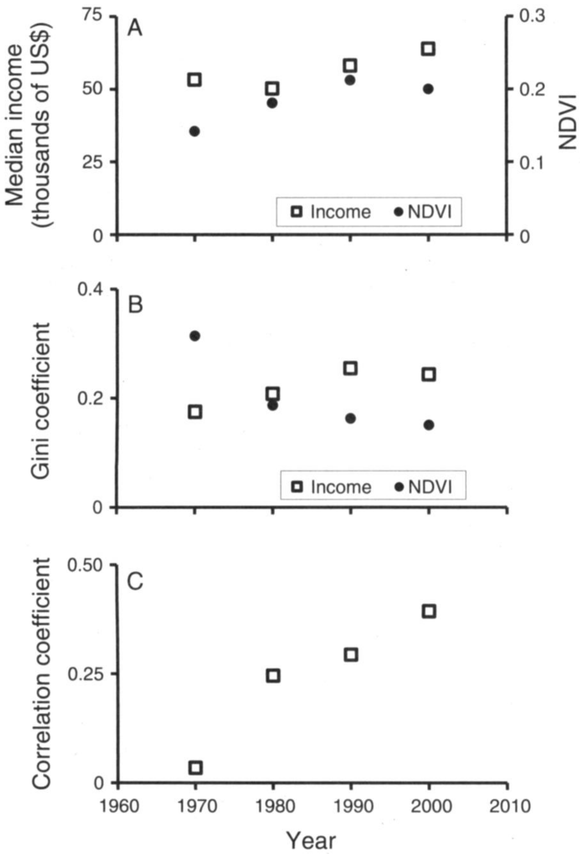

FIG. 6. Thirty-year trajectory of income and vegetation in Phoenix, Arizona, showing (A) average income and NDVI, (B) variability of income and NDVI, and (C) the correlation coefficient of their interaction.

measurements (Blonquist et al. 2009, Leuzinger et al. 2010).

Applications of simplified approaches, such as the one we developed, have benefits as a generic tool that could be incorporated into urban planning and targeted landscape management activities for heat mitigation. As an initial application these analyses can identify places where the lowest increase of irrigated vegetation may have the largest influence on the heat riskscape and provide other ecosystem services with minimal increases in resource costs.

In addressing our fourth question, we documented strong relationships among neighborhood economic status, the availability of cooling-related ecosystem services, and the water uses required for the production of these services (Figs. 4 and 5). These relationships are consistent with recent findings for surface temperature and median household income in Phoenix (Jenerette et al. 2007, Buyantuyev and Wu 2010) and patterns of vegetation and household income in Los Angeles (S. Pincetl, *personal communication*) and more generally for studies of environmental inequalities linked to residential segregation (Pulido 2000, Evans and Kantrowitz 2002, O'Neill et al. 2003). Our findings suggests that vulnerability of the urban poor to heat hazards is influenced by risks associated with living in areas with less vegetation, which expose residents to higher outdoor temperatures. Our heat riskscape for Phoenix is in good agreement with independent indicators of environmental inequality, such as air quality (Grineski et al. 2007) and proximity to contaminated areas (Bolin et al. 2005). High exposure to multiple hazards may contribute to overall public health risks by increasing susceptibility to the effects of extreme heat and other diseases. However, we found the association between vegetation and income is relatively new for Phoenix: as recently as 1970, the coupling of vegetation and associated ecosystem services with economic status was not detected (Fig. 6C). The past 30-year trajectory of increasing income inequality suggests Phoenix residents are on a path of rapidly increasing disparities in living environments. While the causes of the trajectory were not examined in this article, the consequences are leading to dramatically different experiences with urban climate based on neighborhood economic status, which is correlated with ethnicity and educational attainment in this region (Jenerette et al. 2007).

Synthesis: Urban vulnerability to climate change

Addressing questions that span multiple disciplines is necessary for incorporating ecological knowledge into decision-making for sustainability. To couple processes across disciplines, our research used the concept of a heat riskscape to analyze the vulnerability of urban residents to an environmental hazard, in our case extreme heat. Vulnerability is a joint consequence of socio-spatial location in the heat riskscape and the coping mechanisms available to avoid exposure to the riskscape. Mitigating extreme temperature hazards can be accomplished by managing the riskscape to avoid or minimize negative human health consequences.

Increasing vegetation within cities is an effective strategy for reducing the heat riskscape, which is in part why urban tree-planting programs are gaining popularity. However, multiple structural and individual risk factors for heat-related illnesses are associated with urban living (McGeehin and Mirabelli 2001). Landscape management practices must be combined with other policies to improve social support services, housing quality, heat watch/warning systems, and emergency response plans during heat waves. Elderly or otherwise medically impaired individuals who live alone without air-conditioning or family and friends to check on them are most likely to die from heat (Semenza et al. 1996, Kilbourne 2002, Naughton et al. 2002) as exemplified by the 1995 Chicago, Illinois heat wave (Klinenberg 2002) and the 2003 Paris, France heat wave (Poumadère et al. 2005). Ensuring access to indoor climate regulation is an important concern for many people without the means to afford home insulation and pay the electricity bills for air conditioning. Important and well-known public programs for coping with extreme heat are economic

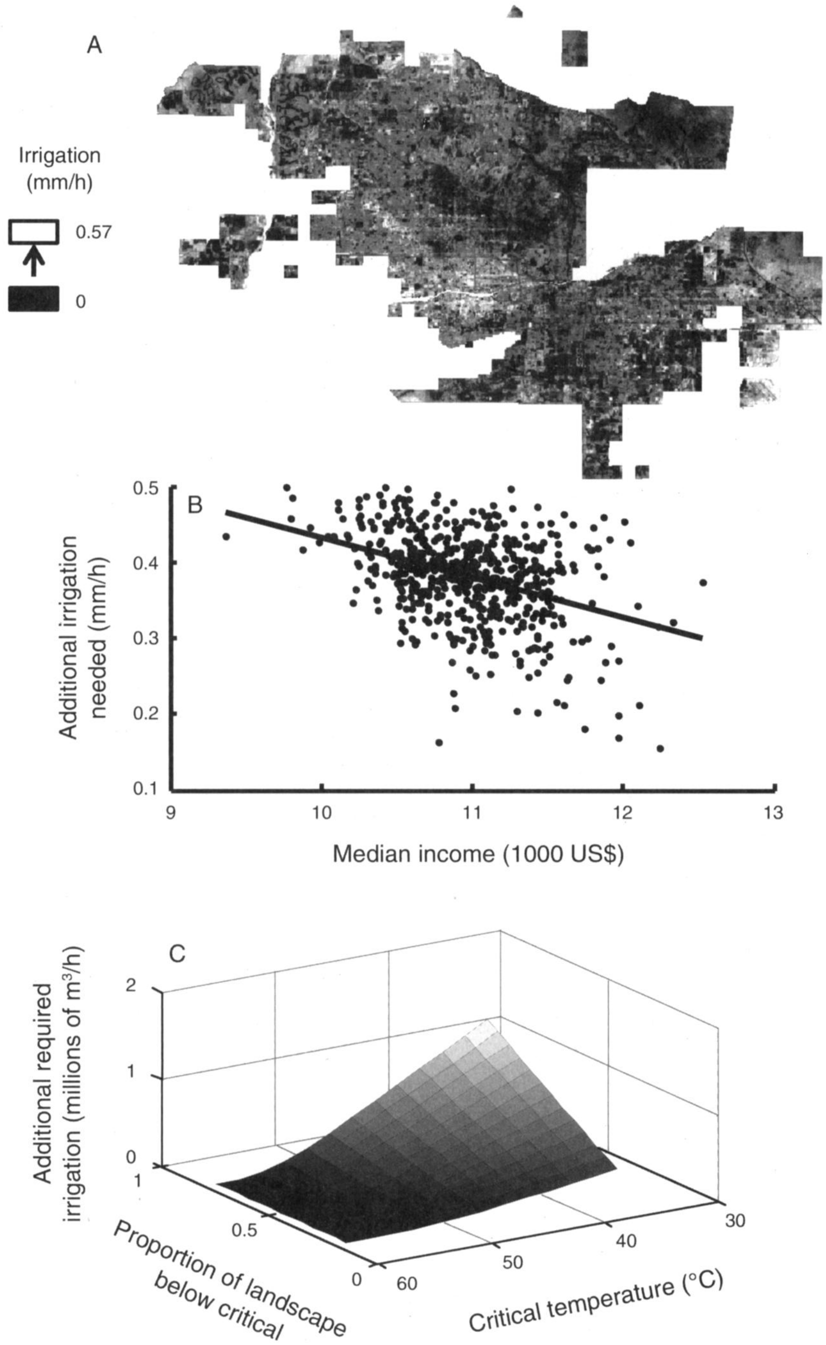

FIG. 7. Water requirements to reduce environmental risk. (A) Mapped patterns of estimated noon water requirements to maintain all surface temperatures below 50°C. (B) Relationship of mean additional cooling water requirements and log median household income for each census tract ($y = 0.96 - 0.052x$). (C) Cost surface of estimated additional water to generate a landscape where some proportion of each neighborhood is below a critical surface temperature.

subsidies for households to purchase climate control, opening air-conditioned buildings to the public, organizing programs to check on the elderly, and social network support to provide temporary relocation assistance. All of these choices have economic and non-economic costs and varying levels of resilience to shocks. Regional landscaping with vegetation, balanced by requirements for irrigation water, may support other heat mitigation programs and provide health co-benefits from additional ecosystem services (Bolund and Hunhammar 1999, Martin 2008, Younger et al. 2008).

The uneven distribution of the heat riskscape is an ongoing challenge to reducing the vulnerability of urban residents to high temperature hazards. The social and environmental justice implications of disenfranchising segments of society based on income, ethnicity, and other factors are widely recognized. Wealthier residents have better access to indoor cooling and can purchase and maintain vegetation to cool the outdoors near individual homes; lower-income households are more dependent on public resources to cope with extreme heat. Equity considerations raise a number of issues for the role of landscape design in mitigating heat riskscapes. Little attention has been directed toward problems caused by the availability of excess ecosystem services to more empowered population groups, which arguably increases the vulnerability of the entire urban system. If key institutional decision makers live and work in areas replete with ecosystem services, then gaps in understanding and differences in lived experiences could lead to public policies and ordinances that exacerbate short- or long-term vulnerabilities arising from extreme temperatures. The trajectory of an increasing correlation between income and vegetation between 1970 and 2000 suggests that inequities will increase in Phoenix in the absence of concerted efforts to intervene with management strategies.

The promotion of cool refugia through urban landscape design can be an efficient use of resources to mitigate heat riskscapes and reduce human vulnerability to heat. These effects and trade-offs will likely vary depending on the amount, type, and arrangement of vegetation as well as surrounding landscape characteristics (Jansson et al. 2007, Shashua-Bar et al. 2009, Chow et al. 2011). Total water requirements to sustain urban vegetation, especially in arid regions, could be lowered substantially by promoting refugia rather than continuous vegetative cover. In addition to reducing direct health risks associated with exposure, parks and other green spaces provide multiple ecosystem services throughout the year.

Ensuring public access to vegetated parks and refugia is essential for fulfilling their role in reducing vulnerability. Access and park quality, however, are highly contested environmental justice issues for low-income neighborhoods in many cities (Wolch et al. 2005, Boone et al. 2009). Within lower-income residential neighborhoods of Phoenix, uneven development has led to neglected parks with less vegetation than higher-income more suburban parks (Guhathakurta and Wichert 1998). Nevertheless, we have observed anecdotally that low-income and minority communities in the inner city of Phoenix use parks extensively for multiple purposes. In historically low-income or minority communities in metro Phoenix, people have long standing links to the parks and attach to them a significant sense of place. Increasing park vegetation in low-income neighborhoods is one strategy for redistributing urban green space and cooler temperatures more equitably. Vegetated walkways and services that facilitate access to parks are also needed to realize the benefits of cool refugia for high-risk populations, such as the elderly and children. The use of cool refugia to mitigate the heat riskscape depends upon the spatial distribution of many landscape elements, from neighboring buildings and impervious surfaces to accessibility of parks.

In evaluating potential mitigation strategies for present and future urban climate changes, a systems analysis that explicitly evaluates the benefits and consequences of various risk reduction and coping strategies is necessary (Gober and Kirkwood 2010). An overriding challenge associated with extreme heat mitigation is untangling the complexities of the water–energy nexus. Urban irrigation water for sustaining vegetation uses a scarce resource and includes energetic requirements for pumping and treatment. However, water use for vegetation may reduce overall and peak electricity demands for air-conditioning during summer days (Kahrl and Roland-Holst 2008, Sovacool and Sovacool 2009). Further, sole dependence on electricity for temperature reduction elevates potential risk to hazardous exposure when electricity delivery systems fail in response to excessive regional demands. Assessing the trade-offs of mitigation strategies, including ecosystem services, for future vulnerability will be challenging, especially if acute events and chronic conditions repeatedly test system resilience. Our analysis is a starting point for quantitative joint assessments of trade-offs in temperature-regulating ecosystem services. A heat riskscape framework can help in understanding the trade-offs of potential consequences of environmental exposure in different places and among different people within cities and it is a useful framework for managing vulnerability to these hazards.

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