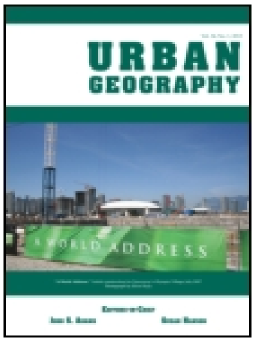

Urban Geography

ISSN: 0272-3638 (Print) 1938-2847 (Online) Journal homepage: https://www.tandfonline.com/loi/rurb20

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To cite this article: Patricia Gober , Ariane Middel , Anthony Brazel , Soe Myint , Heejun Chang , Jiunn-Der Duh & Lily House-Peters (2012) Tradeoffs Between Water Conservation and Temperature Amelioration In Phoenix and Portland: Implications For Urban Sustainability, Urban Geography, 33:7, 1030-1054, DOI: 10.2747/0272-3638.33.7.1030

To link to this article: https://doi.org/10.2747/0272-3638.33.7.1030

TRADEOFFS BETWEEN WATER CONSERVATION AND TEMPERATURE AMELIORATION IN PHOENIX AND PORTLAND: IMPLICATIONS FOR URBAN SUSTAINABILITY[1]

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Abstract: This study addresses a classic sustainability challenge—the tradeoff between water conservation and temperature amelioration in rapidly growing cities, using Phoenix, Arizona and Portland, Oregon as case studies. An urban energy balance model— LUMPS (Local-Scale Urban Meteorological Parameterization Scheme)—is used to represent the tradeoff between outdoor water use and nighttime cooling during hot, dry summer months. Tradeoffs were characterized under three scenarios of land use change and three climate-change assumptions. Decreasing vegetation density reduced outdoor water use but sacrificed nighttime cooling. Increasing vegetated surfaces accelerated nighttime cooling, but increased outdoor water use by ~20%. Replacing impervious surfaces with buildings achieved similar improvements in nighttime cooling with minimal increases in outdoor water use; it was the most water-efficient cooling strategy. The fact that nighttime cooling rates and outdoor water use were more sensitive to land use scenarios than climate-change simulations suggested that cities can adapt to a warmer climate by manipulating land use. [Key words: water conservation, temperature amelioration, climate change, urban heat island, sustainability.]

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[1] This research was supported by the National Oceanic and Atmospheric Administration (Grant NA09OAR4310140) and by the National Science Foundation (Grant SES-0951366, Decision Center for a Desert City II: Urban Climate Adaptation). Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the sponsoring agencies.

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Urban Geography, 2012, **33**, 7, pp. 1030–1054. http://dx.doi.org/10.2747/0272-3638.33.7.1030

SUSTAINABILITY TRADEOFFS

Sustainability science has raised awareness of the interconnectedness of urban land, water, and energy systems, and of the potential significance of feedbacks in these systems in the face of environmental and societal change (Turner et al., 2003; Liu et al., 2007; Hind and Pickering, 2008; Gober, 2010). Urban water demand is part of this complex system, dependent upon multiple-scale, human-environmental interactions (House-Peters and Chang, 2011b). Linkages within and among resource systems are relevant not only for environmental and sustainability scientists who study these systems but also for those who develop and implement policies for them. Single-purpose policies sometimes miss critical tradeoffs and produce unintended consequences. This study focuses on the tradeoff between water conservation and temperature amelioration—both worthy goals, but sometimes at odds, as for example in cities with well-developed urban heat island (UHI) effects that seek to conserve water by reducing outdoor use.

We chose Phoenix and Portland as case studies for these tradeoffs because both cities have been shown to have significant urban heat island (UHI) effects (Brazel et al., 2007; Hart and Sailor, 2009); they use a substantial amount of municipal water outdoors to maintain ornamental lawns and non-native trees and shrubs (~50% in Phoenix and ~40% in Portland); and they are subject to increasing water stress from climate change. The Pacific Northwest is experiencing more frequent winter flooding and summer warming (Mote et al., 2003), and downscaled global climate models predict increasing annual temperatures and higher precipitation variability (with less summer precipitation). The U.S. Southwest is in the throes of a multi-year drought (ADWR, 2010; Balling and Goodrich, 2010), and long-term climate models indicate increasing annual temperatures and higher precipitation variability. Higher winter temperatures would lead to higher-elevation snow lines that, in turn, would affect the timing of snowmelt and summer flows and ultimately the quantity and timing of water supplies in both Portland (Palmer and Hahn, 2002) and Phoenix (National Research Council, 2007).

One obvious strategy for sustaining growth in the face of climate-induced water stress is to reduce discretionary outdoor water use. The risk, however, is that the shift to a less vegetated landscape will intensify UHI effects. In many cities, especially those in arid regions, there is a well-documented relationship between lower temperatures and the presence of irrigated vegetation (Stabler et al., 2005; Coutts et al., 2007; Jenerette et al., 2007; Gober et al., 2010). Evaporation from soil moisture and transpiration from plant leaves lowers surface temperatures through latent heat fluxes (the energy used to evaporate water), and shade from trees reinforces the cooling properties of vegetation. Changes in vegetated surfaces have consequences for both the evaporative and thermal properties of urban neighborhoods, and thus present land planners and water managers with a difficult choice between water conservation and temperature control.

We analyzed that choice by quantifying relationships between vegetation density and outdoor water use, daytime heating rates, nighttime cooling rates, and an index of the cooling efficiency of water in Phoenix and Portland. A neighborhood-level surface energy balance (SEB) model, LUMPS (Local-Scale Urban Meteorological Parameterization Scheme) was used (Grimmond and Oke, 2002; Loridian et al., 2011) to investigate how the different surface properties and regional climates of the two cities affected relationships between vegetation density and heat management and outdoor water use. We also explored the consequences of implementing three land use scenarios (“greening,” “xeriscaping,” and “densification”) as well as three climate-change assumptions in each city. Results provided insight into potential strategies for managing the tradeoff between temperature amelioration and water conservation under current and future climate conditions.

URBAN TEMPERATURES AND WATER USE

The UHI is the most obvious impact of urbanization on local-scale weather and climate (Oke, 1982). It is typically defined as the tendency for cities to be warmer than the surrounding rural countryside (Unger, 2004), and is most prominent at night when excess heat stored in urban surfaces during the daytime is released into the atmosphere. UHI intensity is determined by building density and height-width ratio, road and traffic density, building and surface materials, vegetation type and density, sky-view factor (exposure of urban surfaces to the sky), and local and regional synoptic weather conditions (Brazel et al., 2007; Coutts et al., 2007; Hart and Sailor, 2009). The UHI is an outcome of urbanization, not climate change, but offers valuable clues as to how complex urban systems may function under warmer climate conditions.

Thermal properties vary within the city with the spatial structure of the built environment, surface materials, open space, and prevailing development patterns. These variations point to possible heat mitigation strategies. Excess heating in Tel Aviv, Israel has been associated with high building density, heavy traffic flows, daytime heat sources, and low sea-breeze ventilation (Saaroni et al., 2000). Nighttime temperatures in Phoenix have been related to development zones (e.g., urban core, infill, agricultural fringe, desert fringe, exurban) and the pace of new housing construction (Brazel et al., 2007), vegetation density (Stabler et al., 2005; Jenerette et al., 2007), and the distribution of impervious surfaces (Guhathakurta and Gober, 2010). Tree cover is the most important determinant of afternoon temperatures in Portland, followed by traffic density (Hart and Sailor, 2009). In Atlanta, UHI effects are reduced by tree canopy but heightened by grass cover and imperious surfaces (Stone and Norman, 2006), although in Atlanta, grass cover replaces natural forest whereas in Phoenix it replaces farmland or open desert, and thus would be expected to have different impacts on thermal conditions. Strategies for UHI mitigation often involve alterations to urban design and manipulation of urban vegetation (Sailor and Dietsch, 2007).

Arid and water-stressed cities must pay special attention to the water consequences of heat management. Shashua-Bar et al. (2009) measured the heat reduction properties of six different combinations of trees, lawns, and overhead shade mesh in experimental urban courtyards in the Negev highlands of southern Israel. They found substantial daytime cooling in courtyards treated with trees and grass compared to an untreated courtyard. To measure the tradeoff between water and temperature, they developed an index of efficiency that considers the amount of cooling produced by a given amount of outdoor water use (the ratio of sensible heat removed from the space relative to the latent heat of evaporation). Unshaded grass had relatively little effect on temperature but high water requirements, while shaded grass (with trees or a shade mesh) produced substantial cooling and reduced total water use by 50%. In a follow-up study of the effects of urban design features on thermal stress, Shashua-Bar et al. (2011) used a discomfort scale ranging from “very hot” to “comfortable” to evaluate different heat-mitigation strategies. Shade trees provided the most noticeable cooling, followed by shaded grass treatments (either through trees or mesh), but high water requirements made the latter an inefficient strategy for UHI mitigation in a water-scarce environment.

Mitchell et al. (2008) used an urban SEB model to estimate the effects of water-sensitive urban designs on heating and water exchanges in Canberra, Australia. They found considerable potential for moderating suburban peak afternoon temperatures using water-sensitive urban designs such as green roofs. Adding vegetated roofs without cutting back on outdoor watering reduced the maximum temperatures by 0.5°C compared to a desert city with no vegetation. Adding a wetland and grass swale to this scenario provided little additional reduction in peak temperatures beyond the conventional suburban design because these features accounted for only a small portion of the relevant land area. Reducing garden watering by 50% and 100% onto the vegetated roof scenario raised peak daytime temperatures only marginally, suggesting that garden watering could be reduced without substantially increasing peak daytime temperatures.

Gober et al. (2010) used a local-scale SEB model in Phoenix to evaluate the effects of vegetated landscaping on outdoor water use and nighttime cooling in 10 census tracts in the inner city, where UHI effects are very pronounced and have been linked to human health problems and deteriorating comfort (Harlan et al., 2006; Ruddell et al., 2010). Focus was on the nighttime, when the UHI affects residents' abilities to exercise outside, participate in outdoor community events, and visit pedestrian-oriented commercial spaces. The 10 tracts included industrial zones dominated by impervious surfaces and buildings, residential zones with native desert landscape treatments, and residential zones with lush vegetated cover. Results showed that nighttime cooling rates were strongly related to the presence of vegetated surfaces, and these surfaces required sizeable doses of municipal water in the summertime. A nonlinear relationship between vegetation density and the ratio of cooling relative to outdoor water use (the so-called "efficiency index") suggested that there was a critical threshold beyond which adding more vegetation and outdoor water produced little additional cooling. The efficiency index was highest in arid neighborhoods with little vegetated cover, where the addition of watered landscapes produced significant cooling effects. Findings revealed that a water-saving campaign focused on densely vegetated neighborhoods produced substantial water savings with minimal short-term effects on thermal properties. Results also showed that a more compact city with higher building density and fewer impervious surfaces improved nighttime cooling rates with marginal increases in outdoor water use. This line of inquiry was extended to the Portland area by Middel et al. (2011a), who investigated the sensitivity of LUMPS outputs to varying climate and land-surface conditions (model results are highly sensitive to solar radiation), and House-Peters and Chang (2011a) who considered the effects of climate change on the SEB in Portland suburb of Hillsboro. Findings from the latter study showed that a warming climate raises evapotranspiration (ET), prompting us to speculate that Portland would require sizeable additions of outdoor water to retain current landscapes and manage heat in a warmer climate.

Although previous studies have offered vital insight into the tradeoff between outdoor water use and temperature regulation at their respective study sites, it is difficult to draw definitive conclusions from them because they differed in methodology (empirical versus modeling approaches), scales of analysis (ranging from courtyards to census tracts), and regional climate conditions. The project reported on here was an attempt to replicate an

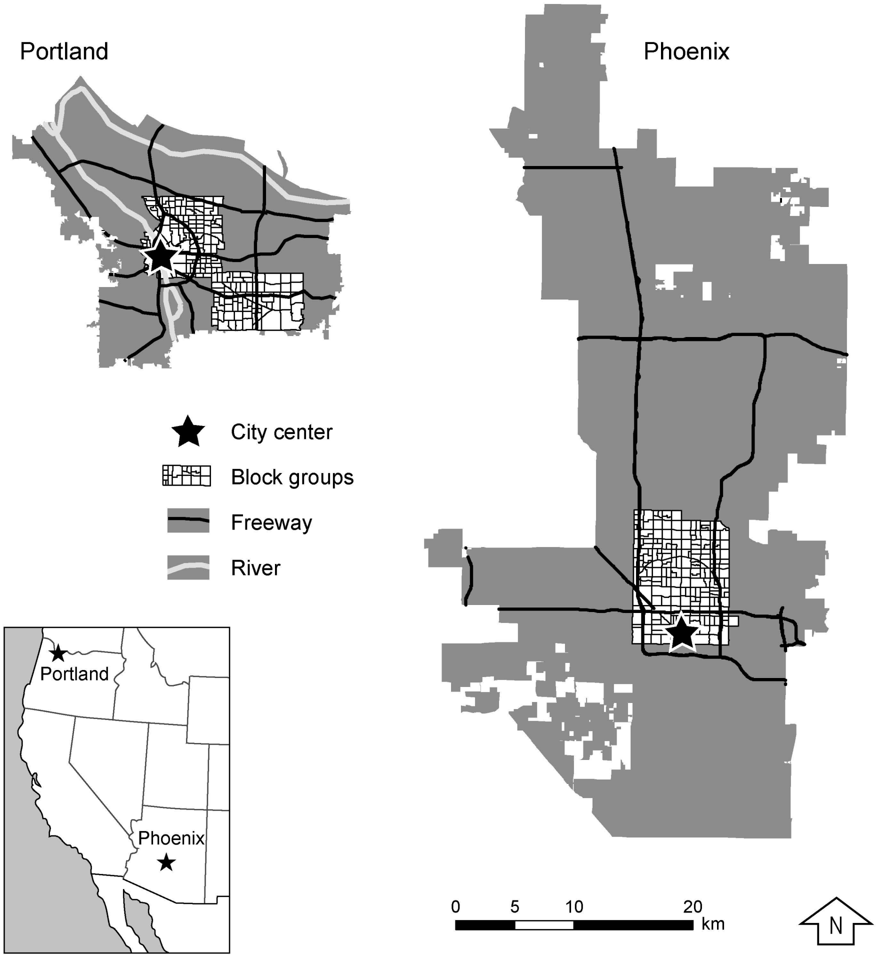

Fig. 1. Study sites in Phoenix and Portland.

identical experiment in two cities, standardizing the unit of analysis, variables of interest, land cover metrics, and modeling approach. The broad objectives were to determine whether the tradeoffs between heat management and water use that pertain to Phoenix can be generalized to other cities; determine how tradeoffs are affected by regional climate and surface morphology; and isolate strategies for managing them in the face of growing water stress, a warmer climate, and continued urban growth.

STUDY AREAS

We used contiguous census block groups (BGs) in Phoenix (n = 173) and Portland (n = 177) for the analysis (Fig. 1). BGs generally contain between 600 and 3,000 people, with

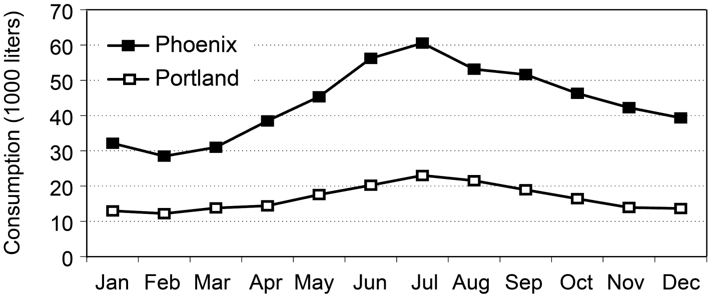

Fig. 2. Average monthly single-family household water consumption in Phoenix and Portland, 2005–2009.

an optimum size of 1,500 people, and are delineated by local participants as part of the U.S. Census Bureau's Participant Statistical Areas Program. BGs in the two study areas were equivalent in average size: 0.39 km^2 in Phoenix and 0.41 km^2 in Portland, and they encompassed a similar land area: 68.3 km^2 in Phoenix and 72.3 km^2 in Portland. BGs were smaller and more homogeneous than the census tracts used in Gober et al. (2010), and therefore conformed more closely to Grimmond and Oke's (2002) delineation of an urban neighborhood. Both Phoenix and Portland study sites included city centers as well as adjacent residential neighborhoods and commercial areas.

We compared thermal and evaporative conditions for June in Phoenix with July in Portland to emphasize months in which water stress is high and control for regional climate effects to the extent possible. Thirty-year (1971–2000) climate records showed that Phoenix received an average of just 2.3 mm of precipitation in June, accounting for 1.1% of annual precipitation. Portland's Mediterranean climate experienced similar conditions in July—just 18.3 mm of precipitation, representing 1.9% of its annual average. We used the Minimum-Month Method to estimate outdoor water use. This method compared consumption in hot summer months, when artificial irrigation is needed to support plant growth and pool evaporation, with cool winter months, when little artificial irrigation is used (Dziegielewki et al., 1993; Vickers, 2001) (Fig. 2). For the 2005–2009 period, the ratio of June to February (the lowest month) consumption in Phoenix was 1.97; the ratio of July to February in Portland was 2.12, indicating that a substantial portion (roughly half) of municipal water use during hot, dry summer months was used to sustain outdoor landscapes and lifestyles. These peak-demand months are especially relevant to urban water management because they are the basis upon which the water infrastructure is built and operational rules are based.

A second reason for choosing June in Phoenix and July in Portland was to control, to the extent possible, for regional climate effects. Had we compared the annual averages of the two cities, regional climate effects (Portland's long wet, cool season and Phoenix's aridity and warm temperatures) would have overwhelmed the local effects of vegetation density and surface morphology. Even then, however, significant and relevant climate conditions differentiated the two cities: (1) the diurnal temperature range is 5°C greater in Phoenix than in Portland; (2) daytime humidity is 30% lower in Phoenix; (3) the number of clear days in respective months favors Phoenix by a 2:1 ratio; and (4) solar radiation peaks at around 200 watts per square meter higher in Phoenix than in Portland. We used the period between 1999 and 2009 as the baseline for climate conditions in the two cities to even out inter-annual variability in temperature and precipitation.

The surface morphology and ecological structure of the two study sites also differ in important respects. Portland is an older, denser city with natural tree cover whereas Phoenix developed more recently, is less densely settled, and less densely vegetated. Still, Phoenix's environmental history has produced a more lush landscape than one might expect in a desert city with less than 200 mm of annual rainfall. Modern settlement dating to the late 19th and early 20th century was based first on irrigated agriculture (Gammage, 2003; Gober, 2006) and later on large-scale urbanization. After World War II, irrigated farmlands and citrus groves gave way to suburban trees and lawns, and today Phoenix looks and feels more like a huge oasis than a desert city. In Portland, dense tree cover occurs naturally from hospitable growing conditions associated with its temperate maritime climate. Although mature trees were replaced by grass and smaller trees when subdivisions were developed, many trees have been planted along streets and streams as well as in parks and natural areas as a result of the collaborative efforts by the city and residential and conservation groups. One of Portland's sustainability goals is to increase the tree canopy to 33% from the current coverage of 26% (City of Portland, 2009). Older neighborhoods with more extensive tree canopies typically use less residential water than newly developed areas with turf grass (Chang et al., 2010).

METHODS AND DATA

LUMPS Model

Following the work of Grimmond and Oke (2002), we used LUMPS version 5.3 (Loridian et al., 2011) to partition the flow of net radiation into three parts: (1) the sensible heat flux (energy that warms the air directly); (2) latent heat flux (energy that evaporates water); and (3) change in stored heat (Equation 1).

$$Q^* = Q_H + Q_E + \Delta Q_S \text{ (Eq. 1)}$$

where Q^* = net radiation, Q_H = sensible heat flux (energy used to heat the air), Q_E = latent heat flux (energy used to evaporate water), and ΔQ_S = change in heat storage.

The model uses simple measurements of surface-cover characteristics (vegetated areas, buildings, impervious surfaces, etc.) and standard weather observations (temperature, humidity, wind speed, incoming solar radiation, and pressure) to estimate energy fluxes on an hourly time step. LUMPS consists of linked equations that calculate heat storage (Q_S), turbulent sensible (Q_H), and latent (Q_E) heat fluxes using known relationships and coefficients derived from field analysis collected over a decade in seven North American cities: Mexico City, Miami, Tucson, Los Angeles, Sacramento, Vancouver, and Chicago. For a detailed description of the model, see Grimmond and Oke (2002).

In an earlier study, Gober et al. (2010) used two empirical procedures to verify LUMPS results in Phoenix. In the first, municipal water meter records, adjusted for outdoor water use and augmented with data from monitored wells and flood irrigation records from the Salt River Project, were correlated with LUMPS ET estimates. Latent heat fluxes were derived and averaged for a month and then compared with monthly water records. The simple linear correlation between observed water use and ET modeled from LUMPS was positive and statistically significant (r^2 = .89). Discrepancies between modeled and observed results occurred in heterogeneous tracts where residential neighborhoods abutted industrial zones. This finding, in fact, led to the switch from census tracts to BGs for this study because they are smaller and more homogeneous units of analysis. In the second verification experiment, the change in LUMPS cooling rate estimates at boundary layer height (30 m) between 8 p.m. and midnight was compared to ASTER Level 2 images taken in June 2007. The distribution of LUMPS average cooling rates corresponded closely (r^2 = .81) with the pattern of ASTER surface temperatures at 8:35 p.m.

We ran LUMPS for each BG in Phoenix and Portland using six land cover classes derived from QuickBird and GeoEye imagery: fractions of buildings, soil, trees and shrubs, grass, impervious surfaces, and water bodies. Hourly weather data were retrieved from weather stations near the study areas. We were restricted to standard weather stations to provide data input because no flux tower data were available. We ran LUMPS with default parameters, assuming that all vegetation was artificially irrigated. LUMPS output included hourly sensible and latent heat fluxes and heat storage.

Heating rates at midday (noon in Phoenix and 1 p.m. in Portland to account for the fact that Portland is on daylight savings time in the summer and Phoenix is not) were derived from the LUMPS sensible heat flux using an expression referenced in Mitchell et al. (2008). Cooling rates during the early evening hours (8–10 p.m. in Phoenix and 9–11p.m. in Portland) were computed from nighttime estimates at the 30-meter boundary layer height—above the roof level. This height was determined empirically by comparing cooling rates calculated from LUMPS fluxes with average nighttime cooling rates from weather files and adjusting the boundary layer height accordingly. We then compared our estimated boundary layer height to Grossman-Clarke et al.'s (2008) estimates in Phoenix and determined that they were comparable. In reality, boundary layer height varies with surface morphology and throughout the night. As House-Peters and Chang (2011a) point out, the choice of 30 meters is a very conservative estimate; a less conservative estimate would amplify the cooling rates in the same direction as our findings (positive cooling rates would become even larger with increasing boundary layer height; negative cooling rates would decrease even more). We chose the more conservative approach because we were primarily concerned with the relative changes in cooling rates, not so much in their absolute values.

LUMPS model code calculates the latent heat flux in energy units of watts per square meter. We converted these units to mass transport per square surface area expressed as kilograms per square meter using the principle of latent heat of vaporization (typically expressed as joules per kilogram, where 1 watt is by definition 1 joule per second). This parameter involves the energy it takes to change the state of water from a liquid to a vapor.

Land Cover Classification

The LUMPS model required detailed characteristics of surface cover as inputs. We used QuickBird multispectral data at 2.5 m spatial resolution acquired on May 29, 2007 for Phoenix and GeoEye satellite data acquired on August 19, 2009, pan-sharpened to 0.5 m from their original 2.5 m spatial resolution, for Portland. Both QuickBird and GeoEye multispectral data have four similar channels ranging from the blue visible to the near infrared portion of the electromagnetic spectrum: blue—B1 (0.45–0.52 μm and 0.45–0.51 μm), green—B2 (0.52–0.60 μm and 0.51–0.58 μm), red—B3 (0.63–0.69 μm and 0.655–

0.69 µm), and near infrared—B4 (0.76–0.90 µm and 0.78–0.92 µm), respectively. A 2007 0.91 m (3 ft) feature-height layer derived from the difference between a LIDAR-generated digital surface model (DSM) and digital elevation model (DEM) was also used in the classification of Portland data. We employed an object-based image analysis approach to identify six land cover categories: buildings, roads and parking lots (impervious surfaces), unmanaged soil, trees and shrubs, grass, and water bodies (Gober et al., 2010).

Traditional image classification techniques are inadequate for high-resolution urban land cover mapping because they do not consider the images' spatial properties (Green et al., 1993; Muller, 1997; Kiema and Bahr, 2001; Myint et al., 2002; Myint, 2003). Hence, we employed an object-based classification approach that used segmented objects at different scalar levels as vital units instead of considering the per-pixel basis at a single scale for image classification (Desclée et al., 2006; Navulur, 2007). There are two options for selecting objects to assign classes. The membership function defines rules and constraints to control the classification procedure based on the user's expert knowledge. The nearest neighbor option is a non-parametric classifier and is therefore independent of the assumption that data values follow a normal distribution. This technique allows unlimited applicability of the classification system to other areas, requiring only the additional selection or modification of new objects (training samples) until a satisfactory result is obtained (Ivits and Koch, 2002; Definiens, 2004). The object-based classifier[3] produced an overall accuracy of 90.40% for the QuickBird image (Phoenix) and 89.99% for the GeoEye image (Portland). These accuracy levels are higher than the minimum mapping accuracy of 85% required for most resource management applications (Anderson et al., 1976; Townshend, 1981).

The remote sensing analysis produced surface properties (Table 1) that conformed to our expectations of Portland as a denser city with more land covered by buildings than in Phoenix (25.4% vs. 20.6%) and slightly more land in impervious surfaces in streets and parking lots (25.6% vs. 25.4%); but the latter difference was not statistically significant. Large differences between the two cities occurred in the amount of vegetated land cover, where Portland had substantially more tree cover (28.8% vs. 12.0%) while Phoenix had more in grass (24.4% vs. 18.3%). We derived a new variable, the "vegetated fraction," (%grass + %trees + %water) to measure the size of the land area that would generate ET and thereby require supplemental watering during the summer. Grimmond and Oke (2002, p. 798) observed that "there are overall relations between surface cover, such as the fraction of green space or area irrigated at each site, and the Q_E fluxes …" at their study sites.

Scenarios and Assumptions

We developed "what-if" scenarios to explore the effects of adding and subtracting vegetation and replacing impervious surfaces with buildings. We also explored the ramifications

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[3] We produced error matrices in order to analyze and evaluate each method. These error matrices show the contingency of the class to which each pixel truly belongs (columns) on the map unit to which it is allocated by the selected analysis (rows). From the error matrix, overall accuracy, producer's accuracy, user's accuracy, and a kappa coefficient were generated. It has been suggested that a minimum of 50 sample points for each land use/land cover category in the error matrix be collected for the accuracy assessment of any image classification (Congalton, 1991). We selected 500 sample points that led to approximately 70 points per class (seven total classes) for the accuracy assessment. A minimum of 50 points per class was set for generating 500 points using a stratified random sampling approach.

TABLE 1. LAND COVER FRACTIONS DERIVED FROM QUICKBIRD (PHOENIX) AND GEOEYE (PORTLAND) IMAGERY

	Phoenix (n = 173)		Portland (n = 177)				
	Mean	σ	Mean	σ	t-statistic	Significance	Mean difference
Buildings	0.206	0.044	0.254	0.569	–8.815	0	–0.050
Impervious	0.254	0.089	0.256	0.081	–0.293	0.77	–0.003
Soil	0.173	0.062	0.018	0.020	31.736	0	0.155
Trees	0.120	0.046	0.288	0.110	–18.796	0	–0.169
Grass	0.243	0.088	0.183	0.068	6.163	0	0.056
Water	0.004	0.005	0.000	0.000	8.426	0	0.004
Veg. fraction	0.367	0.122	0.471	0.116	–8.200	0	–0.105

of changing the temperature inputs based on the results of downscaled climate models. This exploratory exercise was informed by Bankes (1993) distinction between consolidative modeling, which uses known facts to replicate an actual system, and exploratory modeling in which models are used to investigate the consequences of varying assumptions and hypotheses. The former is useful in optimization and prediction, whereas the latter acknowledges that not all relevant and important information is available and not all modeling produces a completely accurate representation of the system at hand. Exploratory modeling is appropriate in situations like ours where there is a high level of system complexity, and nonlinear behaviors and feedbacks can result in unintended consequences. Our primary aim with LUMPS was to investigate the current states of neighborhood thermal and evaporative properties and see how they would change if we manipulated surface morphology and future climate.

Following from Gober et al. (2010) and Middel et al. (2011b), we identified three possible development scenarios for the two study areas. The first was a "greening" scenario, created by increasing trees and grasses by 5% each and reducing impervious surfaces by 10%. In this scenario, sidewalks would be replaced with lawns, and lawns and shade trees would be planted in and adjacent to parking lots and bus stops. In Portland, where almost 50% of the land area is already devoted to vegetated landscapes, we had no choice but to reduce impervious surfaces to achieve greening. In changing the fraction of impervious surfaces, we recognized that there were multiple, interacting processes at work. Both adding vegetated landscaping and subtracting impervious surfaces would enhance nighttime cooling.

The second "xeriscaping" scenario simulated a water conservation campaign focused on reducing outdoor water use. Trees and grasses were reduced by 5% each, and unmanaged soil (bare ground) was increased by 10%. Here we expected to see a reduction in $Q_{E,}$ accelerated daytime heating, and depressed nighttime cooling. Outdoor water would be saved, but heat management would be jeopardized. The extent of this effect and its spatial properties were revealed by the modeling exercise.

Vegetated fractions remained constant in the third "densification" scenario while urban design features were altered to investigate the potential thermal and evaporative properties of a more compact city. Densification was implemented by adding 10% building cover and subtracting the impervious surface fraction by 10%. This scenario simulated effects of establishing growth boundaries to curb urban expansion. It did not add taller buildings, but added land covered in buildings, as for example, when an office building replaces a downtown parking lot or when apartment blocks replace single-family homes in mature suburbs. We expected this scenario to accelerate nighttime cooling due to the reduction in heat-retentive impervious surfaces.

In addition to the land cover scenarios, we altered three assumptions about LUMPS temperature inputs based on statistically downscaled data from three general circulation models (GCMs): UKMO-HadCM3 (Gordon et al., 2000), IPSL-CM (Marti et al., 2005), and PCM (Washington et al., 2000), using the B1 emissions scenario. The B1 emissions scenario is characterized by rapid economic growth and transition toward a service and information economy; world population growth to nine billion by 2050; the introduction of clean and resource-efficient technologies; and global solutions leading to economic, social, and environmental stability (IPCC, 2000). The B1 scenario leads to relatively small increases in carbon concentrations and moderate to low temperature increases. Downscaled GCMs were obtained from the University of Washington Climate Impacts group (Salathé et al., 2007). The statistical downscaling method first bias-corrected the data based on the monthly statistical distribution of temperature and precipitation in the observed 1950–1999 period, and then used a dynamical scaling method to downscale the precipitation data. We used only temperature results for 2040 to alter LUMPS inputs, thereby adding 2.2ºC in Phoenix and 3.0ºC in Portland (for June and July, respectively) in the UKMO-HadCM3 (Assumption 1), 1.8ºC for Phoenix and 1.8ºC for Portland in the IPSL-CM (Assumption 2), and 1.2ºC for Phoenix and 0.8ºC for Portland for PCM (Assumption 3).

Climate and Weather Data

Use of the LUMPS model required standard meteorological observations at an hourly time step. Minimum requirements included air temperature, atmospheric pressure, incoming solar radiation, and precipitation. For Phoenix, we used data from the Encanto Park weather station, a neighborhood site maintained by the Arizona Meteorological Network, rather than the official National Weather Service site at Sky Harbor Airport to achieve better correspondence with baseline data in the climate models. Daily minimum and maximum temperatures at the neighborhood site were more consistent with historical temperatures (1915–2007) in the baseline data for the climate models because they did not exhibit the rise in minimum temperatures associated with the city's UHI effect (Fig. 3). The consistency of these minimums and maximums supported the assumption that climate model results can be uniformly applied across all hours of the day. For Portland, we used climate data from the Portland International Airport weather station, which is located 2 km north of the study area, because a neighborhood site was not available.

RESULTS AND DISCUSSION

Descriptive Statistics

Relevant outputs from LUMPS were the sensible heat flux (Q_H) and latent heat flux (Q_E) in the SEB equation. Latent heat was summed for the month and reported as a daily

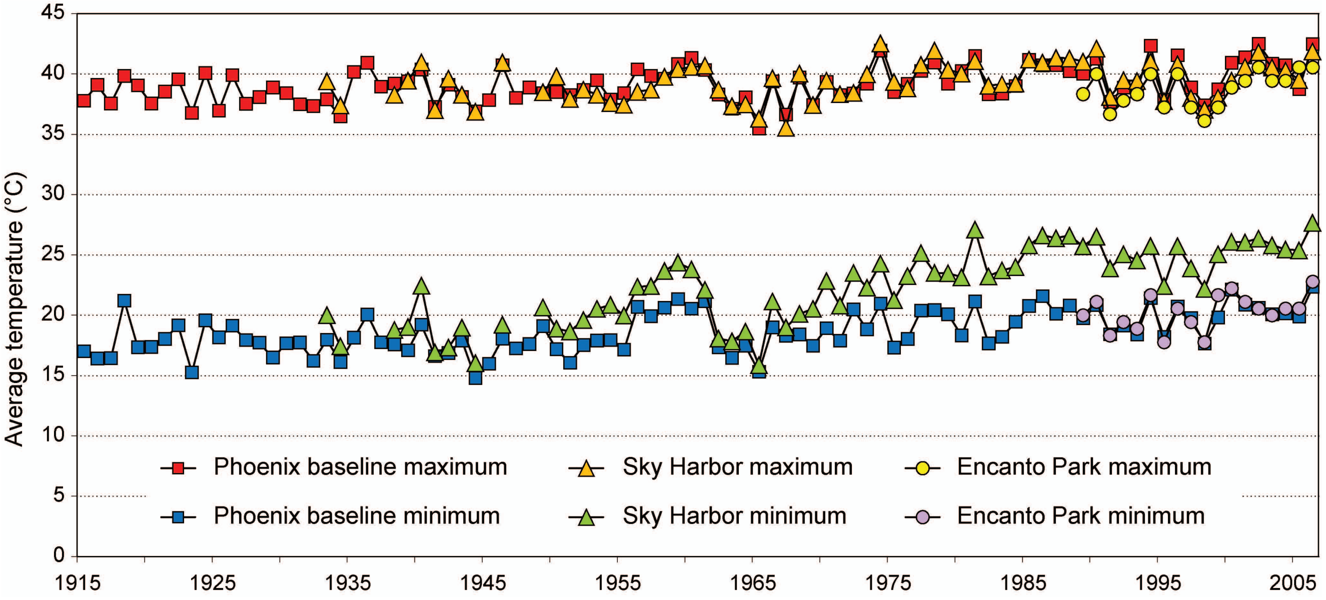

Fig. 3. Historical maximum and minimum temperatures for downscaled Phoenix baseline data, Sky Harbor Airport, and Encanto Park sites.

TABLE 2. RESULTS OF PRELIMINARY RUNS OF LUMPS FOR BASE-CASE OUTPUT

	Phoenix (n = 173) June		Portland (n = 177) July				
	Mean	σ	Mean	σ	*t*-statistic	Significance	Mean difference
Daily ET (kgm^{-2})	1.931	0.409	1.845	0.327	–2.106	0.035	0.004
Heating rate at noon (°C)[a]	0.768	0.051	0.644	0.027	28.331	0	0.124
Cooling rate in evening (°C)[b]	–0.171	0.187	0.236	0.248	–17.335	0	–0.406
Cooling efficiency index	–0.073	0.092	0.156	0.180	–15.007	0	–0.229

[a] 12 p.m. in Phoenix and 1 p.m. in Portland.
[b] 8–10 p.m. in Phoenix and 9–11 p.m. in Portland.

average ET (Table 2). The heating rate is the change in Q_H at midday, calculated at the 30-meter boundary layer height, after Mitchell et al. (2008). Having no a priori knowledge of the boundary level height, we assumed that at night the boundary layer would be at 30 m—just about the height of a tower equivalent over an urban neighborhood. The cooling rate was the average hourly change in sensible heat during early evening hours at this tower level in the two cities. Metrics were computed for each BG in Portland and Phoenix and then averaged citywide. We also reported cooling efficiency, the ratio of nighttime cooling rates and daily ET—how much cooling is achieved with a given amount of ET.

The mean daily ET was higher in Phoenix than in Portland; the actual difference was statistically significant but small in an absolute sense (Table 2). While it was hotter in Phoenix, Portland had more vegetated surfaces from which ET was derived. Average heating rates were higher at midday in Phoenix than in Portland (0.77°C/hour vs. 0.64°C/hour), and it cooled faster and earlier in the evening as the dry desert air facilitated the release of energy to the atmosphere (-0.17°C/hour vs. 0.24°C/hour). The cooling rate was represented as a change in sensible heat (Q_H). In Phoenix, the sign for the cooling rate was in the expected negative direction. In Portland, however, the cooling rate was positive, indicating that most of the city's BGs were still warming at the lower boundary layer during early evening hours. Detailed analysis of hourly cooling rates between 8 p.m. and midnight (9 p.m. and 1 a.m. in Portland) showed consistent cooling in most of the Phoenix BGs throughout this period, but warming in a majority of Portland's until 10 or 11 p.m. when the switchover to cooling occurred. Grimmond and Oke (2002) described similar circumstances at their study sites, particularly in built-up areas, where the layer of air above roof height (where LUMPS temperatures are estimated) can warm for much of the night and, in extreme cases, all night. This does not mean, however, that warming is still occurring at ground level. The release of heat, particularly from impervious surfaces below roof height, results in low-level cooling but warming in the sub-layer immediately above. Portland's average cooling efficiency index also was positive because the cooling rate was the numerator in the cooling efficiency ratio.

Table 3. Regression results with vegetated fraction as the independent variable and SEB metrics as dependent variables

	Phoenix (n = 173)	Portland (n = 177)
Daily ET	b = 3.335; r^2 = .994 t = 168.920; p = .000	b = 2.808; r^2 = .990 t = 132.755; p = .000
Heating rate	b = -.375; r^2 = .816 t = -27.632; p = .000	b = -.169; r^2 = .507 t = -13.481; p = .000
Cooling rate	b = -1.357; r^2 = .785 t = -25.068; p = .000	b = -1.857 ; r^2 = .756 t = -23.344; p = .000
Cooling efficiency index	constant = -.275; r^2 = .714 b_1 = .066 F = 426.129; p = .000	constant = -.264; r^2 = .765 b_1 = .182 F = 640.202; p = .000

Figures 4A–4D display relationships between the vegetated fraction and ET, heating rates, cooling rates, and cooling efficiency for the two cities. Table 3 presents results of regression analyses, with the vegetated fraction as the independent variable and LUMPS output metrics (ET, heating rate, cooling rate, and cooling efficiency) as dependent variables. The graphs and table revealed the high level of consistency in the behavior of the SEB variables because they were derived from the same LUMPS code and because the analysis was undertaken for months when the two cities were most alike climatically. Differences derived mainly from Portland's cooler, more humid climate and from its higher overall vegetated fraction.

Vegetation density regulated both daytime heating and nighttime cooling with more substantial effects on cooling than heating rates. The relationship between cooling efficiency and vegetated fraction is nonlinear in both cities, although the critical turning point occurred at a much higher vegetated fraction in Portland than in Phoenix, ~55% versus 25%. Phoenix's dry, desert climate releases energy to the atmosphere, facilitates nighttime cooling, and achieves comparable levels of efficiency at much lower vegetated fractions.

Regression coefficients in Table 3 quantified sensitivities of the LUMPS metrics to changes in the vegetated fraction. ET was slightly more sensitive to changes in the vegetated fraction in Phoenix because its hot, dry climate is more effective in moving water to the air from the soil and water vapor through the stomata in plant leaves (Fig. 4A). Heating rates also were more sensitive in Phoenix (b = -0.375 versus -0.169 in Portland) (Fig. 4B). The regression coefficient (slope coefficient) for the cooling rate was slightly higher in Portland (-1.86ºC/hour versus -1.36ºC/hour in Phoenix) because of differences in surface morphology (Fig. 4C). In Portland, sparse vegetation accompanies lots of buildings and impervious surfaces—just the types of places where Grimmond and Oke found continued heating in the lower boundary layer after dark, and in some cases, throughout the night. Areas of sparse vegetation in Phoenix also were quite urbanized, but had substantially more coverage in unmanaged soil (bare ground and open desert) which cools faster than impervious surfaces.

Areas with higher vegetated fractions were less efficient in converting ET into additional cooling, with higher sensitivity in Portland than in Phoenix (Fig. 4D and Table 3). In Phoenix, the gains in cooling from additional vegetation petered out at ~25%, while in

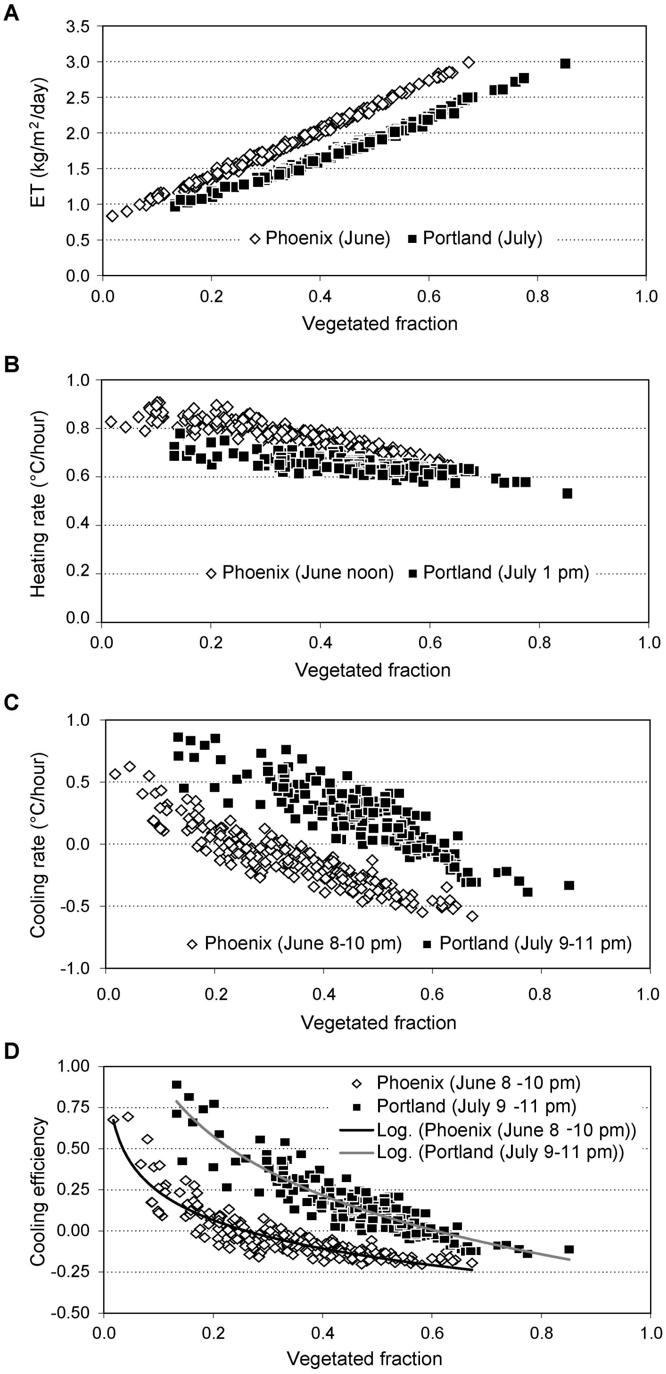

Fig. 4. Effects of vegetated fraction on outdoor water use, heating and cooling rates, and cooling efficiency in Phoenix and Portland.

Portland they extended to ~55%, accounting for Portland's steeper slope. Adding more vegetation after the 30, 40, and even 50% levels produced more cooling and improved the cooling efficiency in Portland, but not in Phoenix. An UHI-mitigation strategy of planting trees and shrubs would achieve the desired outcome—cooling—over a much wider range of Portland's than Phoenix's urban surfaces.

What-If Scenarios

We used LUMPS to simulate various scenarios of UHI mitigation and water conservation. Scenario 1 (greening) emphasized temperature control; Scenario 2 (xeriscaping) stressed water conservation; and Scenario 3 blended the two, attempting to reduce temperatures with minimal water consequences. There are complex, interacting processes at work in all the scenarios because adding one type of cover necessarily requires subtracting another. These were arguably most problematic for interpreting the first scenario, which added to the vegetated fraction by subtracting impervious surfaces. Both changes enhanced cooling, and it was not possible to separate their effects. Interactions also occurred, but were more difficult to interpret, between unmanaged soil and vegetative fraction in Scenario 2 and between buildings and impervious surfaces in Scenario 3. The goal of this study was not to tease out these feedbacks and quantify them, but rather to use LUMPS as a credible system dynamics model with empirically validated parameters for exploratory purposes.

Scenario 1 substantially increased ET, had little effect on daytime heating rates, accelerated nighttime cooling in Phoenix, and reduced the rate of nighttime heating in Portland over the base case (Table 4). Accelerated cooling (~0.2 °C/hour), however, came at a cost of increased outdoor water use by ~20%. Overall cooling efficiency was improved in both cities as the 20% increase in daily outdoor water use produced improvements of 142% in the nighttime cooling rate in Phoenix and 89% in Portland. Gains in cooling efficiency came from the accelerated cooling in very arid, highly built-up areas, pushing them, especially in Phoenix, steeply down the efficiency curve (Fig. 5A). Results suggested that (1) a spatially explicit approach that targets greening in these neighborhoods would minimize the water requirements to achieve cooling, and (2) the coverage, and thus water use, necessary to achieve appreciable cooling gains would be greater in a humid city like Portland than in an arid city like Phoenix.

Scenario 2 simulated the possible impacts of a water conservation program targeted on outside water use. This scenario decreased outdoor water use by 15% in Phoenix and 13% in Portland, but reduced the capacity for heat management in both cities. They warmed faster during the day and cooled more slowly at night. The daytime heating rate increased by 7% in Phoenix and 6% in Portland. The more significant impacts occurred at night when Phoenix's cooling rate increased from -0.17ºC to -0.04ºC. In this scenario, most of Phoenix did not begin to cool until after 10 p.m., a significant shift in terms of human impacts and potential usability of urbanized spaces. Portland's cooling rate increased from 0.24 ºC in the base case to 0.36ºC in Scenario 2. Both cities lost cooling efficiency as the 15% savings in water came with a 122% loss in nighttime cooling capacity in Phoenix, and a 13% savings in water resulted in a 53% loss in cooling in Portland. The most severe impacts of Scenario 2 occurred in industrial and commercial neighborhoods with little vegetation (Fig. 5B).

Table 4. LUMPS output variables in base case and Scenarios 1, 2, and 3

LUMPS Output	Phoenix (*n* = 173)	Portland (*n* = 177)
Base case		
Total ET	10079.853	10194.251
Average daily ET	1.931	1.847
Heating rate	0.768	0.644
Cooling rate	–0.171	0.236
Cooling efficiency index	–0.073	0.156
Scenario 1—"greening"		
Total ET	12068.469	11921.166
Average daily ET	2.312	2.160
Heating rate	0.750	0.631
Cooling rate	–0.414	0.056
Cooling efficiency index	–0.175	0.043
Scenario 2—"xeriscaping"		
Total ET	8562.7341	8905.4814
Average daily ET	1.640	1.614
Heating rate	0.822	0.684
Cooling rate	–0.039	0.361
Cooling efficiency index	0.006	0.269
Scenario 3—"densification"		
Total ET	10483.362	10567.143
Average daily ET	2.008	1.915
Heating rate	0.820	0.683
Cooling rate	–0.405	0.085
Cooling efficiency index	–0.195	0.068

ET increased slightly in Scenario 3, even though the vegetated fraction remained constant because daytime heating rates increased (from 0.77ºC/hour to 0.82ºC/hour in Phoenix and from 0.64ºC/hour to 0.68ºC/hour in Portland). Improvements in nighttime cooling over the base case were comparable to Scenario 1, and cooling efficiencies were better because vegetated surfaces were not changed. The price for these improvements in cooling rates and efficiency were modest increases in daytime heating that were already quite high in arid, industrial, and commercial neighborhoods. The climatic processes that account for the improvements in nighttime cooling are built into the empirically derived coefficients of the LUMPS model. Possible explanations are that heat storage in building rooftops is less than heat storage in impervious surfaces and increased roughness associated with adding buildings leads to better ventilation and accelerated cooling. It is also possible that the one-dimensional-nature LUMPS results do not fully capture the dynamics of three-dimensional urban surfaces, and future research is needed to resolve these modeling issues.

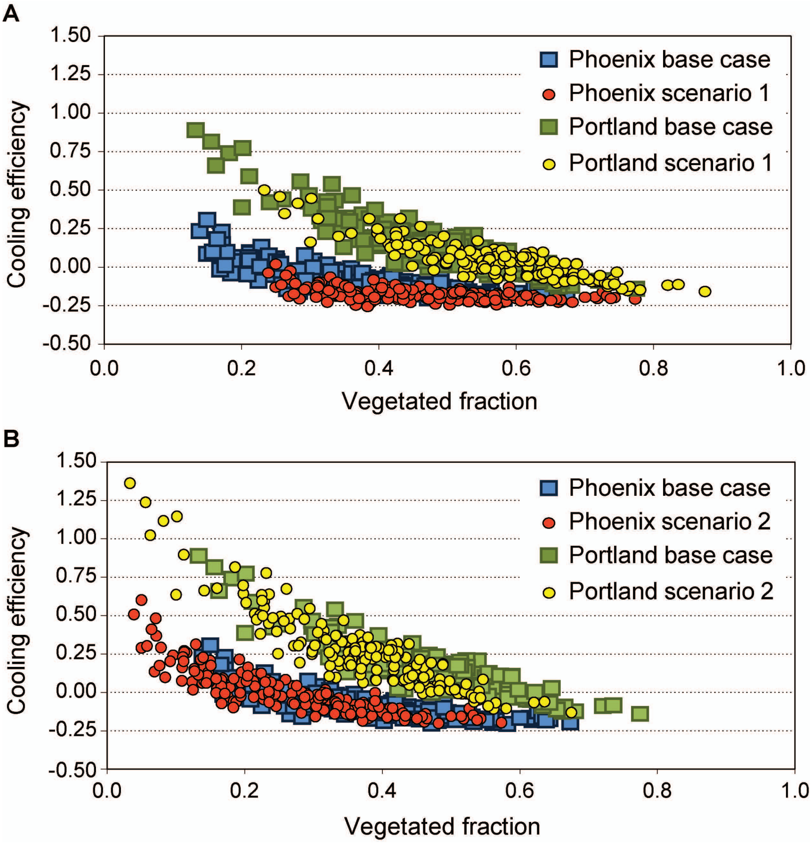

Fig. 5. Changes in BG cooling efficiencies under Scenario 1 (greening) and Scenario 2 (xeriscaping) compared to base case conditions.

These experiments underscored the complexity of decisions about heat management and water conservation in the two cities. Greening facilitated cooling but required more outdoor water; xeriscaping saved water but jeopardized nighttime cooling; and densification accelerated nighttime cooling without substantial increases in outdoor water use, but increased daytime heating. These are by no means the only scenarios that could have been developed; but they illustrated the kinds of experiments that can guide future choices and alert planners and city officials to the multi-faceted consequences of decisions about UHI mitigation and water conservation. Ultimate decisions are not science questions, but value judgments—how much weight will urban decision-makers place on water security versus temperature control, daytime versus nighttime comfort, and comfort in pedestrian-oriented downtown spaces and industrial districts versus more vegetated residential neighborhoods.

Climate Change Assumptions

We altered model inputs for the two cities to account for future climate conditions based on statistically downscaled data from three general circulation models (GCMs)

Table 5. LUMPS output variables for base case and climate-change assumptions

LUMPS output	Phoenix (n = 173)	Portland (n = 177)
Base case		
Total ET	10079.853	10194.251
Average daily ET	1.931	1.847
Heating rate	0.768	0.644
Cooling rate	–0.171	0.236
Cooling efficiency index	–0.073	0.156
Assumption 1 (HadCM3)		
Total ET	10309.295	10800.55
Average daily ET	1.975	1.957
Heating rate	0.761	0.632
Cooling rate	–0.139	0.330
Cooling efficiency index	–0.054	0.198
Assumption 2 (IPSL-CM)		
Total ET	10267.24	10558.5
Average daily ET	1.967	1.913
Heating rate	0.762	0.637
Cooling rate	–0.145	0.292
Cooling efficiency index	–0.058	0.182
Assumption 3 (PCM)		
Total ET	10204.46	10356.25
Average daily ET	1.955	1.876
Heating rate	0.764	0.641
Cooling rate	–0.154	0.260
Cooling efficiency index	–0.063	0.168

simulated through 2040. A warmer climate raised ET more in Portland than in Phoenix (Table 5)—5.9% versus 2.2% in Assumption 1, 3.6% versus 1.8% in Assumption 2, and 1.7% versus 1.2% in Assumption 3. Results did not include precipitation data from the climate models, and therefore did not account for possible precipitation changes and their feedback effects on ET. Uncertainties associated with precipitation in the climate models and problems in downscaling precipitation to an hourly time step led us to focus only on temperature, where there is greater agreement about hourly temperature regimes and the prospect of warmer future temperatures.

Results were consistent with House-Peters and Chang's (2011a) interpretations that Portland's more vegetated landscape (47.1% versus 36.3%) would be more difficult to maintain in a warmer climate. The relative insensitivity of ET to temperature change in Phoenix was consistent with an earlier study of the sensitivity of water use to changes in temperature. Balling and Cubaque (2009) related recorded water use in Phoenix to historical temperature variations and found that the average change in monthly water use for single-family households was 648 liters (171 gallons) for a 1°C change in temperature. They also estimated changes in temperature and precipitation for 50 statistically downscaled climate model/scenario combinations and determined that the mean water consumption would increase by an average of 3% by 2050.

Simulations showed that a warmer climate would have only minimal effects on daytime heating rates (which would be moderated by the increased ET) but larger impacts on nighttime cooling rates. Cooling efficiencies from the model were impaired by a combination of higher ET and less favorable cooling rates. These findings suggested that, without adaptation strategies, cities of the future will be warmer and more humid; they will heat and cool more slowly, and the tradeoff between water conservation and heat management (as reflected in the cooling efficiency index) will be more difficult to resolve.

That LUMPS metrics were far less responsive to changes in the climate inputs than in the land use changes implied that it may be possible for cities to adapt to a warmer climate with modifications in land use that are well within the purview of human action and public policy. Reducing impervious surfaces accelerates cooling rates, and increasing vegetated landscapes can reduce daytime temperatures, especially in poorly vegetated industrial areas.

CONCLUSIONS

The idea for this project originated at a City of Phoenix UHI Task Force meeting in which water planners, recognizing the relationship between vegetated landscapes and urban cooling, asked how much water it would take to cool the city. Results of an earlier study (Gober et al., 2010) indicated that it would, in fact, be possible to mitigate temperatures using vegetated landscapes, but it would take substantial quantities of additional water under today's water and land use practices. The current study arose from the desire to generalize this tradeoff between cooling and water use and determine how it would function in Portland with different climate conditions and urban structure. Salient differences between the cities included Portland's cooler and more humid climate, greater vegetated coverage, and denser urban core.

Despite the perception that Phoenix is short of water, the use of vegetation for cooling makes sense from an UHI mitigation standpoint because accelerated cooling is possible in a hot, dry climate, greening strategies could be targeted to the most arid parts of the city, and decided advantages can be achieved during early evening hours with obvious benefits for human health, comfort, and activity. Increased densification (matched with reductions in impervious surfaces) would enhance cooling with modest water consequences, but would come with increased heating rates during midday in a city that is already scorching in the summer. Outdoor water conservation, without changing key urban design features, would accelerate daytime heating and depress and delay nighttime cooling during the critical early evening hours, especially in arid industrial and downtown neighborhoods.

Difficult choices also confront Portland, although they play out in a cooler, more humid climate and an urban setting with higher vegetation and building densities. Key differences include the delayed cooling that occurs in a city with a smaller diurnal variation in temperatures, cooler temperatures overall, and more natural precipitation. As a result, the

UHI may be a less significant issue overall. Daytime heating is less sensitive to changes in vegetated fraction in Portland; thus adding vegetation to drier industrial areas makes less sense than in Phoenix. Nighttime cooling is sensitive to the vegetated fraction in Portland, but the human comfort benefits of enhanced cooling in industrial areas are limited by the fact that few people reside in these areas to benefit from cooling.

Results also highlight the challenge of climate adaptation in Portland, given its greater vegetated coverage and more humid climate. Warmer temperatures will raise ET and thus lead to higher demand for outdoor water use to maintain current landscape treatments in July. Efforts to reduce outdoor water use would compromise the cooling capacity of neighborhoods, especially drier ones, unless they are accompanied by urban design strategies to mitigate UHI effects. Phoenix would experience smaller increases in ET and smaller temperature gains under climate change assumptions, but the loss of cooling capacity may be far more impactful, given already hot baseline conditions.

There are obvious feedback effects between population growth and heat management and water conservation in Phoenix and Portland. As cities warm from UHI effects and climate change, they may become less desirable places for people to live. The growth of Phoenix and Portland has been facilitated by the availability of vegetated landscapes, both for their ability to moderate temperatures and enhance city attractiveness and land values. With plentiful water supplies, these cities have not until recently faced the possibility that current landscape practices are unsustainable—now and in a future climate. Residents of Phoenix regularly ask whether and when their hot, desert city will become uninhabitable or at least at what point growth rates will abate from UHI effects. And even though Portland starts from much cooler baseline conditions, climate change may limit its capacity to grow in ways that require heavy outdoor water use.

There are caveats in any study of this nature, and three must be noted. First, presentation and interpretation of the modeling results do not do justice to interactions that are embedded in the model and their implications for results. We viewed LUMPS as a vehicle to explore alternative urban futures rather than as a method to predict the future. Interactions between changes in land cover fractions are, in fact, the subject of more detailed analysis in Middel et al. (2011a). Second, ET is not strictly the equivalent of outdoor water use, especially in Portland. The choice of July targeted the month when the correlation between ET and outdoor water use was highest, but the assumption that vegetation relies on artificial water ignored longer-term soil fluxes. And third, adding outdoor landscaping (thus increasing outdoor water needs) and reducing impervious surfaces are not the only strategies for UHI mitigation. Other strategies include Low Impact Development (LID) approaches that encourage soil infiltration and using recycled water from harvested storm water to support ET and thereby cooling. Portland would be better positioned than Phoenix to take advantage of these strategies because of higher overall precipitation.

Ultimately, cities will choose climate adaptation strategies based on their values about continued growth, the risk of water shortage in the face of climate change, the importance of outdoor lifestyles and evening activities, and comfort in downtown spaces. This research exposed the multi-dimensionality of these choices as expressed in heat management and water conservation policies. Focusing on just one of these issues may have unintended consequences for the other. Sustainable decisions acknowledge inherent tradeoffs between urban resource systems, and challenge us to think more strategically about the future—to decide what kind of city we value and want, and then use modeling strategies such as the one presented here to figure out how to achieve that end.

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