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# Mitigating Urban Heating in Dryland Cities: A Literature Review

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## Abstract

This review analyzes literature regarding urban heating and urban heat islands (UHIs) in dryland cities. This topic is of widespread importance in the era of climate change since many global cities are in arid, semiarid, or Mediterranean regions. We first analyze the literature on dryland UHIs, finding major differences with those for temperate cities. We then review research on cooling strategies involving vegetation, built form, and materials. Finally, we consider planning dimensions. Overall, we find that the most sustainable cooling approach for dryland cities is likely to combine low-water tree species with dense, shade-producing built form and high-albedo materials.

## Keywords

design, energy, sustainability, urban design, urban form, environment, heat islands, climate adaptation, cooling cities, dryland cities

## Introduction

One goal of climate adaptation efforts worldwide has been to cool cities and reduce urban heat island (UHI) effects. Such steps can improve human comfort, protect human health, and reduce energy use. However, cooling strategies for dryland cities will likely be different from those for wetter, temperate cities. Little water is available in the former locations to irrigate vegetation, and other characteristics such as humidity, latitude, cloud cover, and degree of heating are often different too. In this article, we review several bodies of literature to examine urban heating and heat island dynamics for dryland cities and to ask how these urban regions might best be cooled through vegetation, built form, and use of heat-reflecting materials.

"Dryland" environments include arid, semiarid, steppe, and Mediterranean landscapes. These regions make up 41 percent of the earth's land surface and are home to more than 2.1 billion people (see Figure 1). They exist primarily in two latitude belts around 30° north and south of the equator and include many rapidly growing cities in the developing world. For arid regions, rainfall is generally under 200 millimeter (7.9 inches). For semiarid regions, rainfall may be greater but annual evapotranspiration still exceeds precipitation. Semiarid Mediterranean landscapes are characterized by wet winters and dry summers, while steppe landscapes feature dry continental climates with high seasonal temperature differences. There is thus a large range of dryland climate types. However, all have a similar shortage of water, and most feature low latitudinal position, consistently clear skies, intense solar radiation, and very hot temperatures at least some times during the year.

Mitigating high urban temperatures through vegetation is challenging in dryland regions due to the lack of water. Climate change also threatens many existing sources of water: in many dry regions, precipitation will decrease, ground water aquifers recharge at slower rates, and nearby snowpacks shrink. Dryland regions are at disproportionate risk from climate change along with Arctic ecosystems, small-island developing states, and less developed countries (Intergovernmental Panel on Climate Change 2018, 11). Such differences make the literature on dryland urban heating and UHIs worth detailed and specific review.

UHIs in dryland locations often behave differently from those in temperate contexts. Surrounding desert soils may heat up rapidly in the day, leading cities to become daytime "urban cool islands." These same soils may then cool rapidly after dark, leading UHI effects for dryland cities to be most pronounced at night.

Although reducing urban temperatures may be the overall planning goal, understanding UHI dynamics is an important step toward meeting that goal. The impact of planning strategies on immediate heating or cooling may be different from their effect on UHI cycles. For example, deep street canyons in

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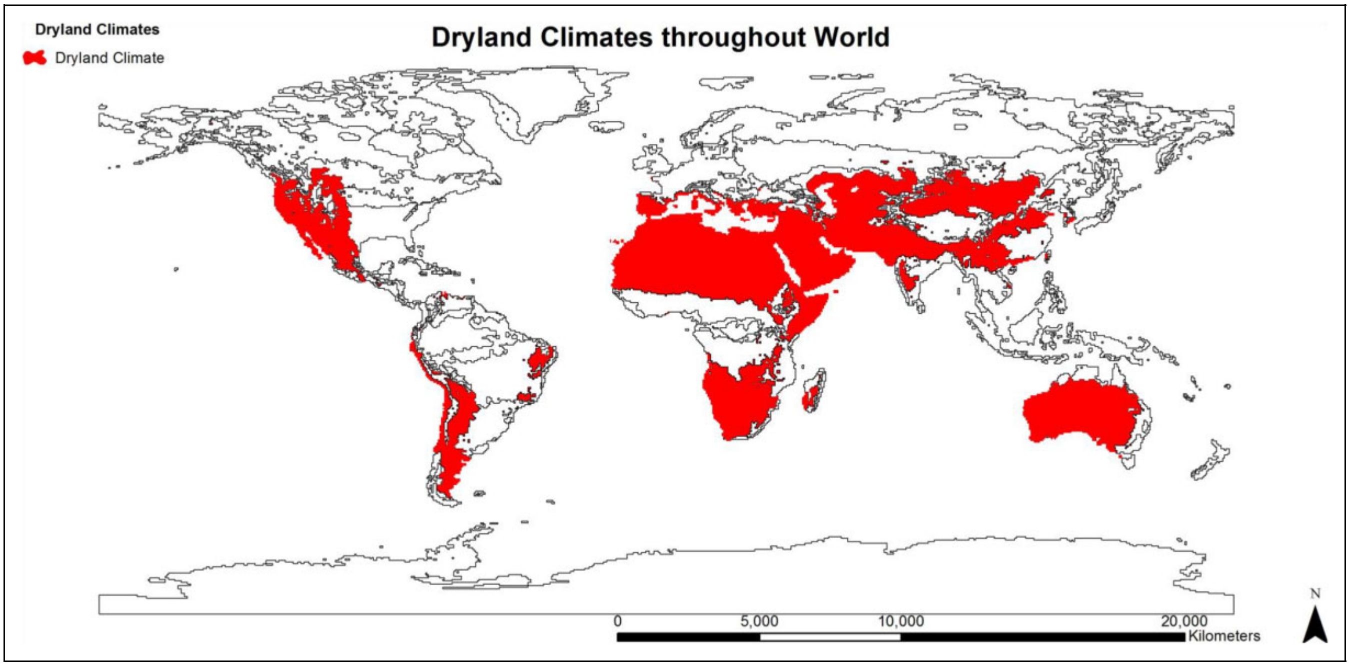

**Figure 1.** Dryland climates throughout the world, based on the Köppen climate classification.

dryland cities appear to contribute to daytime cooling but nighttime heating (since reduced sky view can trap heat). Their immediate, local daytime cooling benefit for street users is partially offset by contributions to a nighttime citywide UHI. So our aim is to help readers understand how many factors including UHIs interrelate to affect temperatures and the potential for cooling in these urban regions.

Research on interactions between urban heating, vegetation, urban form, and materials has expanded greatly during the past decade, capitalizing on the increased availability and quality of remote sensing data and modeling software. Indeed, more than 80 percent of the 120 articles included in this review date from the past ten years. Our method to identify literature related to this subject began with exhaustive searches of electronic databases including Web of Science and Google Scholar using a variety of search terms such as "arid cities," "dryland cities," and "semiarid cities" in combination with "urban heating," "urban heat islands," "urban greening," "green infrastructure," "vegetated green infrastructure," "built form," "cool materials," and the like. We reviewed the references used within each article to develop a larger database of literature and consulted with experts to obtain their recommendations. We then sought to identify emerging themes within this body of work. The first section of this review considers the dynamics of dryland urban heating and UHIs. The second examines mitigation and cooling strategies, with attention to different types of vegetated green infrastructure (VGI), built form, and surface materials. The third section considers urban planning challenges related to these strategies, such as issues of greenspaces planning, public acceptance, maintenance, shade-maximizing built form, and the use of high-albedo roofing and paving materials. We conclude by suggesting future planning directions for cooling dryland cities and reducing dryland UHIs.

Our review of the literature on UHIs in dryland cities and vegetative strategies to cool cities is quite comprehensive and includes a large amount of literature. However, much less work exists on urban form strategies for cooling neighborhoods or cities, and so this information is more limited. We've given less emphasis to the literature on the use of low-albedo materials to cool cities, since this strategy (emphasizing light-colored roofing) is relatively straightforward and benefits from strong scientific agreement.

## Urban Heating and Heat Island Dynamics in Dryland Regions

The replacement of vegetation by hardscape during urbanization often results in urban heating and an UHI effect in which cities are warmer than suburbs and rural landscapes (Myint et al. 2010; Wong et al. 2011). Mechanisms include the higher thermal inertia of urban environments and reduced convection and evapotranspiration. Exact impacts and dynamics of urban heating depend on the level at which temperatures are measured: land surfaces, the canopy level (ambient air around buildings and trees), or the boundary layer above the canopy (Oke 1976). Land surfaces typically show the greatest variation, since materials such as asphalt readily absorb solar radiation while light-colored or vegetated surfaces remain cooler. Air temperatures within the canopy layer are influenced by the geometry and characteristics of buildings, trees, and other vegetation. The boundary layer blends lower-level heating or cooling across a larger area.

Researchers use three main means to investigate urban heating: remote sensing data from satellite sources such as LANDSAT or ASTER; on-site measurement, often of air temperatures at a two-meter height; and computer modeling. Remote sensing data can only provide land surface temperature that tends to show heating more strongly than air temperature measurements and operates at relatively coarse scales of resolution such as thirty meters. However, satellite data are relatively easy to obtain and can be analyzed across broad geographical areas and so are most frequently used. Surface temperatures generally correlate with air temperatures but vary due to atmospheric mixing and materials properties as well as technical measurement issues (Zhou et al. 2019).

On-site air temperature measurements can shed light on interactions between temperature, land cover, and built form at smaller scales. However, such measurements are time-consuming and issues of sensor placement and shielding can skew results. Finally, urban planners and landscape architects frequently use software such as ENVI-MET to model such effects. Modeling software has improved over time and has the advantage of providing a wide range of microclimate, energy use, and air pollution mitigation projections for specific sites without the labor of on-site measurement. However, models may not always predict unique characteristics of sites. For example, Chow et al. (2011) found that ENVI-MET overpredicted daytime air temperatures and underpredicted nighttime temperatures for a small park in Tempe, Arizona, and failed to predict a strong near-surface inversion over nonurban surfaces. In the end, each of these techniques must be used with an awareness of its limitations.

Urban heating dynamics for dryland cities are often different than those for wetter, temperate urban regions. Urban cool island effects, in which vegetation and built form keep cities cooler than surrounding desert soils, have been observed by researchers such as Brazel et al. (2000), García-Cueto et al. (2007), Buyantuyev and Wu (2010), Cao et al. (2010), Chow et al. (2011), Peng et al. 2011, Giannaros and Melas (2012), and Chakraborty and Lee (2019). The cool island effect can be of large magnitude. Lazzarini, Marpu, and Ghedira (2013) found downtown Abu Dhabi 5–8°K cooler during the daytime than surrounding desert areas.

However, within these regions, some landscapes are hotter than others. Dialesandro, Abunnasr, and Wheeler (in review) found surface temperatures for neighborhoods that maximize paved surfaces, bare dirt, or xeriscape (low-water vegetation) frequently 2–3°C hotter than the urban mean, while urban forest, turf-and-tree, or multistory building landscapes often 2–6°C cooler.

Moreover, cool island effects for dryland cities are relative to the often-scorching arid landscapes outside their boundaries. Daytime temperatures will still frequently be high enough to threaten human health and place high demands on energy systems. The intense solar radiation that most of these cities experience, due to low latitude and lack of cloud cover and humidity, exacerbates human impacts. At night, UHIs often appear since city surfaces typically retain heat longer than natural ones (Connors, Galletti, and Chow 2013). For example, Muscat, Oman, experiences the peak of its UHI differential with surrounding areas six to seven hours after sunset (Charabi and Bakhit 2011). Whereas Haashemi et al. (2016) found mean monthly daytime temperatures of bare soils outside Tehran up to 4°K hotter than those of the urban area, at night, the situation reversed, with the urban mean up to 4°K hotter. Hot nighttime temperatures give vulnerable populations little respite during long periods of heat and mean that the energy demands of building cooling systems may continue around the clock. Night hours are also a time that residents of hot cities can use to exercise outside, participate in outdoor public events, and shop in pedestrian-oriented urban districts (Gober et al. 2012). Reducing nighttime heating may thus become an important planning goal, especially for those cities in which humidity may hold in heat.

Many factors influence the extent of heating and UHIs for dryland cities, including time of day, season, latitude, elevation, humidity, cloud cover, prevailing winds, and other contextual features. Such factors appear more important than sheer size of the city in exacerbating heat islands (Heinl et al. 2015; Zhou et al. 2014). Geographical factors related to terrain can be particularly important. For example, Makido et al. (2016) found that Doha's, Qatar, heat island features a gradient of warming from the coast inland and travels throughout the day to different parts of the city depending on the radiation absorption capacity of different land covers.

The typically lower humidity of arid cities means that daily temperature changes may occur more rapidly than for temperate cities, without humidity "holding in" heat. At the same time, low humidity means that evaporative cooling from vegetation or mechanical devices in buildings (referred to as "swamp coolers" in the southwestern United States) may be more effective. However, arid cities such as Dubai and Lima are next to oceans that produce humidity. While the oceans may create local cooling, as their humidity travels inland, it may create more intensive heat islands and reduce cooling effects from vegetation (Sailor 1998; Saneinejad, Moonen, and Carmeliet 2014). Humidity also reduces convection efficiency, meaning that air currents may be lighter and do less to dissipate heat within the city (Zhao et al. 2014).

The complex dynamics of heat islands in dryland cities mean that local context must be taken into account when designing cooling strategies. This context includes the character of urbanization as well as geographical factors. For example, dryland cities with low buildings and little vegetation may have relatively small differences between surface and canopy temperatures, meaning that residents will have little respite from the heat as surface temperatures warm quickly each day. Cities with taller, shade-producing built form and large trees are likely to have a deeper canopy layer, improving human comfort. But dissipating heat at night may then become a problem. Further research will be needed to shed light on such trade-offs.

**Table 1.** Research Findings Related to Strategies to Cool Dryland Cities.

| Category | Finding (Study Cities in Parentheses) | Authors |
|---|---|---|
| Vegetation | Trees have greater daytime cooling benefit than lawns (Phoenix) | Wang et al. (2016) |
| | Lawns can increase daytime air temperatures and humidity compared to surrounding urban areas (Tel Aviv) | Potchter, Cohen, and Bitan (2006) |
| | Irrigated turf leads to lower air temperatures than desert vegetation (Phoenix) | Hall et al. (2016) |
| | Tree canopy has strong cooling benefits in daytime but not at night (Tel Aviv and Cairo) | Cohen, Potchter, and Matzarakis (2012); Mahmoud (2011); and AboElata (2017) |
| | Tree canopy has only small air cooling benefit on very hot days (Athens) | Tsiros (2010) |
| | At night dense, low tree canopies decrease wind and increase air temperatures and humidity (Tel Aviv) | Potchter, Cohen, and Bitan (2006) |
| | Tree canopies that leave sky view can increase nighttime cooling (Cairo) | AboElata (2017) |
| | Total area of vegetation matters more than distribution (Denver) | Rhee, Park, and Lu (2014) |
| | Clustered vegetation cools surface temperatures more than dispersed vegetation (Phoenix and Las Vegas) | Fan, Myint, and Zheng (2015) and Myint et al. (2015) |
| | Parks in dryland cities typically produce park cool island effects | Bowler et al. (2010) |
| | The cooling impact of parks extends well beyond their borders | Dimoudi and Nikolopoulou (2003) and Akbari et al. (2016) |
| Built form | Shade-producing built form (close buildings with narrow streets) can cool dryland cities | Emmanuel and Fernando (2007) and Nassar et al. (2016, 2017) |
| | Street canyons (narrow streets and tall buildings) reduce daytime air temperatures through shade and reduced sky view | Johansson (2006) |
| | Street canyons lead to warmer nighttime temperatures since heat escapes more slowly with reduced sky view | Nassar, Blackburn, and Whyatt (2016, 2017) and Jamei et al. (2016) |
| | Replacing pavement with buildings leads to lower nighttime temperature (Phoenix) | Gober et al. (2012) |
| | The roughness of urban landscapes leads to less wind and more heating | Golden (2004) |
| | Tall buildings and straight streets can promote air flow and redirect wind | Golany (1996) |
| Materials | Cool roof materials reduce urban heating in all climate zones | Roman et al. (2015) and Santamouris (2014) |
| | Phase change materials can spread heating out through the daily cycle | Roman et al. (2015) |
| | Highly reflective surfaces may heat other spaces nearby | Vardoulakis, Karamanis, and Mihalakakou (2014) |

## Mitigation Strategies

Vegetation, built form, and materials interact to affect surface, canopy, and boundary layer temperatures within urban regions (Buyantuyev and Wu 2010). Careful design of these elements holds the potential to optimize cooling and reduce UHI effects within dryland cities (Myint et al. 2015) (see Table 1).

### *Vegetation*

Two main mechanisms help vegetation cool cities: evapotranspiration and shading. The former reduces air temperatures through evaporative cooling. The latter cools urban environments by shading surfaces (pavement, walls, etc.) that might store or reflect heat (Shashua-Bar, Pearlmutter, and Erell 2011) and also improves human comfort by protecting people from the sun.

Mesic (moderately moist), oasis (localized water), and xeric (low-water) vegetation strategies differ in their provision of evapotranspiration and shading. With their broad-leaf trees and irrigated lawns, mesic landscapes maximize both forms of cooling (Akbari 2009; Abunnasr 2013), although at the cost of high water consumption and increased humidity. Oasis landscapes also offer both forms of cooling but only for small, localized areas. Xeric landscapes minimize evapotranspiration since their plant species are adapted to conserving water. Thus, they lack the first vegetative cooling method, although they can potentially meet other goals of twenty-first-century greenspaces planning such as habitat value and on-site drainage (Cranz and Boland, 2003). Potentially, xeriscapes can provide the benefit of shade. However, native dryland tree species are often short and have thin canopies, and no native trees at all exist in many arid locations. So the number of shade-maximizing, low-water tree species from which to choose is limited.

The extent of vegetation in an urban neighborhood appears highly important for dryland urban cooling. In a study of Denver, Rhee, Park, and Lu (2014) found that total area of green space, particularly trees, had a stronger relationship with decreasing land surface temperature than the distribution of vegetation. The latter appears to matter as well, though. In studies of Phoenix and Las Vegas, respectively, Fan, Myint, and Zheng (2015) and Myint et al. (2015) found that clustered vegetation cooled surface temperatures more than dispersed vegetation. Studying arid Aksu City, an oasis town in western China, Maimaitiyiming et al. (2014) found that a combination of patch density and the total length of greenspace edges had the most significant impacts on lowering land surface temperature. Thus, a balance between clustering and dispersion may be desirable. This latter set of researchers hypothesized that "the increase of total patch edges may enhance energy flow and exchange between green space and its surrounding areas, and provide more shade for surrounding surfaces" (p. 64).

Extensive tree canopies can be effective at reducing dryland heat islands during the day, since they cool through shade as well as evapotranspiration. Wang et al. (2016, 443) conclude that "trees have an overall more significant cooling effect due to shading than the [evapotransporation] cooling of lawns," although their conclusions for Phoenix are based on modeled rather than measured temperature reductions. Potchter, Cohen, and Bitan (2006) and Cohen, Potchter, and Matzarakis (2012) measured strong cooling benefits from trees in Tel Aviv, while Mahmoud (2011) and AboElata (2017) found the same for Cairo. Tsiros (2010), surprisingly, found lesser effects for very hot days in Athens, which may be attributable to lower levels of tree shading and irrigation. Bencheikh and Rchid (2012) measured an air cooling benefit of up to 10°C provided by palm trees in the urban area of Ghardaia, Algeria, with the greatest impact at dawn. However, heat island benefits will be less at night, and low tree canopies may reduce local air movement and increase air temperatures and humidity compared to surrounding urban areas (Potchter, Cohen, and Bitan 2006).

Studies have found variable cooling benefits from turfgrass alone (which of course must be irrigated in most dryland environments). Potchter, Cohen, and Bitan (2006) found air temperatures above unshaded park grass in Tel Aviv to be slightly warmer than the urban average in the day and slightly cooler at night. Chow et al. (2011) measured nocturnal temperature reductions of more than 3°C in air temperature readings from a small park in Tempe, Arizona, compared with surrounding urban areas. Cooling from grass is especially pronounced when temperatures are compared with surrounding desert landscapes. Hall et al. (2016) found daytime air temperatures of Phoenix residential landscapes with turf 6°C cooler than surrounding areas with native Sonoran Desert vegetation.

As the most extensive VGI location within dryland cities, parks often produce a park cool island effect and have consistently lower temperatures than surrounding areas independent of climate. In a synthesis of twenty-six studies across all climates, Bowler et al. (2010) found parks to be 1.15°C cooler on average than surrounding areas. However, the cooling impact of parks is more pronounced in dryland environments, where air temperatures in parks can be 5°K cooler than elsewhere in the city (Skoulika et al. 2014). In Tunis, Charfi, Krout, and Dahech (2014) found park surface temperature differences of 7°C during the day and 10°C at night, with corresponding air temperature differences of 1–2°C and 3°C. The cooling impact of a park can extend up to 1,000 meters beyond its borders depending on orientation, density, and configuration of the urban area (Dimoudi and Nikolopoulou 2003; Akbari et al. 2016). One study modeling thermal cooling using parks found that the simplest way to increase the cooling effect was to increase the size of the park (Dimoudi and Nikolopoulou 2003).

Little literature yet exists on thermal effects of xeric. Since these provide relatively little evapotranspiration and shade, it might be expected that their urban heating or cooling impacts would be close to those of bare soil. Exact impacts would probably depend on the density and nature of xeric plantings.

Green roofs and walls—whether containing xeric or more intensively irrigated mesic landscapes—are a final dimension of urban vegetation. Such plantings are more difficult in dryland climates than in temperate ones due to the lack of water and intense solar radiation. To date, green walls and roofs have been relatively little studied within dryland climates, and what studies exist look mainly at effects on building energy use rather than UHI mitigation. However, in a modeling study of different roof treatments in a Mediterranean landscape in southern Italy, Gagliano et al. (2016) determined that a green roof would stay substantially cooler than traditional roofs and so have potential microclimate cooling effects.

Overall, the literature suggests that a vegetative strategy to cool dryland cities while minimizing water use would rely on low-water, shade-producing tree and shrub species. These plantings would likely be most intensive within urban parks, since those typically offer the largest available land area for planting, but could also be clustered around buildings and along streets citywide. Such dispersion would have benefits as suggested by Maimaitiyiming et al. (2014). Shading asphalt pavement and rooftops would be important goals due to the contribution of those surfaces to UHIs. Although the literature shows turfgrass also to be effective at urban cooling, irrigated lawns lack the benefit of shade and are dependent on extensive irrigation and so might be a secondary strategy for limited areas.

## Built Form

Many authors agree with Li et al. (2016, 241) that cities are best cooled by "increasing the compactness and concentration of vegetation covers and decreasing the same for buildings and impervious surfaces." However, such analysis neglects potential cooling from shaded walkways and courtyards, narrow and/or shaded streets, reduced parking surfaces, green roofs, and high-albedo materials on buildings or ground surfaces (Yan et al. 2014; Middel et al. 2014; Ali-Toudert and Mayer 2007). Consequently, authors such as Emmanuel and Fernando (2007) argue that high-density urban environments (closely packed mid-rise buildings with narrow streets) are desirable in order to cool cities in hot climates.

Cities in dry regions such as the Mediterranean have historically relied on shading from buildings for human comfort (Martinelli, Lin, and Matzarakis 2015). Nassar, Blackburn, and Whyatt (2016, 2017) found that increased building height, density, and shade are all correlated with reduced urban temperature in Dubai, although the reduced sky view associated with urban density also leads to greater heat retention and warmer nighttime temperatures. Gober et al. (2012) used an urban energy balance model for Phoenix to show that replacing impervious surfaces with buildings achieved similar benefits to vegetation in terms of nighttime cooling (relative to hardscape) without the increased water consumption. They speculated that “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” (Gober et al. 2012, 1046).

Urban canyons along streets (created by keeping street widths narrow and allowing multistory buildings) provide shade and reduce the daytime sky view factor, both of which reduce ambient air temperatures (Lehmann and Sharifi 2014). Deep, narrow canyons reduce temperatures the most—by up to 6°C for ambient air temperatures within dryland cities and up to 12°C for land surface temperatures (Johansson 2006). In Algeria, Bourbia and Boucheriba (2010) found that the smaller the sky-view factor of an urban building, the cooler its temperature and measured differences of up to 12°C. However, Jamei et al. (2016) found that high street canyon walls (buildings) compared to widths (streets) lead to nighttime retention of heat. Depending on climate, these features may also produce more shade and coolness than residents want in the winter (Lin, Matzarakis, and Hwang 2010).

At a regional scale, the roughness of urban landscapes typically leads to slower winds and reduced convection, compounding the heat island effect (Golden 2004). However, high-rise buildings and linear street patterns may strengthen citywide airflows and direct wind into different parts of the urban area than otherwise (Golany 1996). Local air movements influenced by buildings and vegetation can reduce temperatures and improve human comfort. Airflows can also spread the cooling benefits of greenspaces, as Oliveira, Andrade, and Vaz (2011) determined through a study of Lisbon, Portugal.

Because desert soils tend to heat up quickly, if empty lots and other large areas of bare soil exist within the city, these are likely to add to daytime heating. (In temperate cities, vegetation is likely to naturally cover those lots, contributing to cooling.) It may become important to reduce these open areas within the city or to shade them with low-water tree species. A policy of relatively intense urbanization that minimizes vacant or skipped-over lots may thus be useful to reduce urban heating.

Besides buildings, other types of structural cooling are possible. Middel et al. (2016) found that a photovoltaic canopy over an area on the Arizona State University campus improved user perceptions of heat as well as reducing actual temperatures for all seasons except winter. Vanos et al. (2016) found that a shade sail reduced measured surface temperatures on an Arizona playground from 56 to 39.3°C, nearly as much as the shade from dryland trees like palo verde, western cedar, and mesquite that have sparse foliage. Walls made of porous materials in Cyprus have been found to provide evaporative cooling benefits with or without associated vegetation (Saneinejad et al. 2011).

Overall, such evidence suggests that dense built form can help reduce UHIs for dryland cities at least during the daytime. Deep urban canyons and urban design devices such as colonnades, building overhangs, and planted trellises can help maximize shade. Large, pillar-mounted photovoltaic canopies over parking areas, walkways, or public spaces may be a further useful shade-producing device. In addition to human comfort and cooling benefits, the shade produced by such structural elements allows the establishment of vegetation in places where it would be difficult otherwise.

### Materials

Increasing the albedo of urban surfaces through light-colored materials or paint represents a third main set of strategies to reduce UHI effects (Santamouris, 2014). Roman et al. (2015) found in a modeling study of five roof types in seven US climatic zones that cool roof technologies reduced UHIs in all climate zones. In a similar modeling study, Synnefa et al. (2008) found that increasing roof albedo could lead to a 2°C reduction in urban air temperature over Athens. Cool roofs have been required by the California building code since 2005 and are promoted by US cities ranging from San Antonio to New York.

Cool materials are relatively cheap and involve few development trade-offs. Akbari et al. (2016) argue that increasing the albedo of roofs through cool roof materials results in no increase in cost to the builder. Highly reflective surfaces should be avoided in locations where the sun’s reflected rays might more strongly heat other spaces nearby (Vardoulakis, Karamanis, and Mihalakakou 2014).

The technology of high-albedo materials is developing rapidly. In recent years, phase change materials (which can temporarily store heat or cool) have been shown to have cooling benefits apart from high-albedo materials by spreading thermal storage and release out through the day or night (Roman et al. 2015). Retro-reflective materials, which reflect solar energy directly backward toward the source rather than onto neighboring structures and spaces, may offer substantial advantages (e.g., Rossi et al. 2015). Researchers are also exploring many issues around the weathering, soiling, and cleaning of high-albedo roofing materials (e.g., Morini et al. 2018).

There is an ongoing controversy over whether urban geometry (“configuration”) or types of materials and surfaces (“composition”) are more important in mitigating UHIs for dryland cities. Li et al. (2016) and Emmanuel and Fernando (2007) found the former in their analysis of Phoenix. However, Connors, Galletti, and Chow (2013) identified the opposite in their study of the same city. Both sets of authors agree that the strongest impacts occur when both composition and configuration are considered together. Thus, planning efforts to cool dryland cities should consider both built form and use of heat-reflecting paving and roofing strategies.

## Planning Challenges

Comprehensive strategies to cool cities will likely require planners to consider environmental justice, public health, economic, and water systems issues. If such strategies include changes to built form, then growth management and urban design considerations would come into play as well. Here, we will restrict our discussion to planning challenges most centrally related to the implementation of vegetative, built form, and materials strategies.

### Strategic Greenspaces Planning

How might officials prioritize locations and types of vegetation to cool dryland cities? What mixture of park improvements, street trees, green roofs, green facades, incentives for greening private property, and regulation should be proposed? How should residents and other stakeholders be involved? Such questions will need to be answered to implement vegetative strategies for cooling cities. Abunnasr (2013) and Abunnasr and Hamin (2012) suggest that greening strategies can be linked to a rural–urban gradient of urban form. In dense central cities, planners can emphasize green roofs, green facades, street trees, and small pocket parks. In the suburbs, they can aim for larger patches of VGI within parks, watershed lands, along streets, and within residential yards. Norton et al. (2015) suggest a different strategic framework emphasizing neighborhood risk (neighborhoods with old, young, or disadvantaged populations) and neighborhood context (including existing vegetation, whose cooling benefit should be maximized). Relation to regional greenspaces planning (e.g., filling gaps in the large-scale mosaic of landscape ecology), stormwater management needs (e.g., vegetating floodplains so as to slow runoff), and microclimates (e.g., mitigating hot spots within the city) could also be considered. Further research is needed to help develop strategic greenspaces planning strategies and to give planners information and tools so as to balance context, location, heat distribution, the needs of vulnerable communities, and ecological performance.

### Minimizing Water Use and Choosing Plant Species

Traditional urban greening programs rely on water-intensive mesic landscapes, often combining broad-leaf trees with large areas of turfgrass. However, in dryland cities, mesic landscapes consume large volumes of water most of which are then lost through evapotranspiration, increasing urban humidity. McPherson (1990) found that in Phoenix, mesic landscapes took four to five times as much water as xeric landscapes. Al-Ajlouni, Vanleeuwen and Hilaire (2012) found in a study of two New Mexico communities that a turfgrass site used an estimated 40,000 gallons of water a year compared to 15,000 gallons for a similarly sized landscape emphasizing native trees.

To minimize water use, a growing number of dryland cities in the United States mandate water-conserving landscape treatments. For example, Santa Fe, New Mexico, limits yards to 25 percent temperate-climate grasses such as Kentucky Bluegrass and starting in 2003 prohibited recreational fields and golf courses from using turfgrass. Albuquerque, New Mexico, limits lots to 20 percent turfgrass, while Tucson, Arizona, allows only 5 percent of residential plots and 2.5 percent of commercial plots to use water-intensive plants. Shading turfgrass with trees can further reduce water use. Litvak, Bijoor, and Pataki (2014) and Litvak et al. (2017) determined that shading Los Angeles lawns with trees saved over 1,200 millimeter a year in evapotranspiration. Such strategies can make a substantial difference in urban water consumption. Aggarwal et al. (2012, 06518) report that building water use efficiencies, smaller lots, fewer pools, and increased use of xeriscapes in Phoenix have held residential water consumption relatively stable for nearly twenty years, despite the population increasing by over 25 percent.

Instead of irrigated turfgrass, many dryland cities are creating xeriscaped public spaces, often emphasizing native plants. In virtually every arid region native plant communities exist that are suited to multiple microclimates (shade, sun, arroyos, oases, canyons, etc.). Such dryland plant communities are typically characterized by ephemeral annuals, succulent perennials, nonsucculent perennials, shrubs, and trees. Ephemeral annuals appear after a wet period and complete their cycle within a brief time (± eight weeks). Succulent perennials store water for use during dry periods. Nonsucculent perennials include hardy grasses, woody herbs, shrubs, and trees that resist the strain of the arid climate. A combination of these xeriscape plant types can potentially create landscapes that maximize habitat value; accommodate stormwater on-site; and provide an aesthetically pleasing diversity of plant shapes, textures, and colors.

For urban cooling, however, xeriscapes that provide shade will probably be necessary, and in arid regions, few if any large, shade-producing native trees exist. In any case, choosing native species may not always be the most water-conserving choice. Pincetl (2010) points out that as a street tree in Los Angeles, the California Sycamore (native to riparian areas in the state) would require far more water than certain Australian species. The most appropriate species will depend on an understanding of the context. For inland southern California, for example, McPherson et al. (2017) recommends a selection including an Australian acacia, Netleaf Hackberry, Rosewood, Palo Blanco, a Palo Verde hybrid, and two species of drought-tolerant oaks.

An increasing number of planting guides for xeric species now exist, developed by agencies such as the US Forest Service, the US Environmental Protection Agency (Akbari 2009), the Indian Ministry of Urban Development (2014), and the Inter-American Development Bank (1997). The Saudi government has emphasized native and climate-adapted plants in a reference plant manual for Riyadh (High Commission, 2014). Other professional resources include Morrow's (2016) and Phillips' (2015) guides to best plants for New Mexico, Wasowski and Wasowksi's (1995) guide for the southwestern United States, Dvorak and Volder's (2010) and Tolderlund's (2010) guides for green roofs in arid climates, Jubran and Hizon's (1999) guide to plants in the Gulf countries, Houdeshel, Pomeroy, and Hultine's (2012) analysis of species and bioretention strategies for the US Southwest, and Asgarzadeh et al.'s (2014) guide for Tehran.

A growing number of online resources also exist. The US Forest Service's i-Tree software provides tools for finding and prioritizing tree location, estimating carbon load, and calculating impacts on water use and quality (United States Forest Service 2014). The Urban Forest Ecosystems Institute (2017) at Cal Poly, San Luis Obispo, offers tools for choosing urban trees while the University of California and the California Department of Water Resources provide Water Use Classification of Landscape Species, an online assessment tool aimed to help water managers create water-efficient green landscapes (Costello and Jones 2014). The University of California at Davis houses a climate-ready tree list for portions of California (McPherson et al. 2017).

Regulation and incentives may be required to bring about shade-producing dryland urban forestry. Cities such as Sacramento have enacted ordinances requiring that 50 percent of parking lot surfaces be shaded by trees within ten to fifteen years (McPherson 2001). Electric utilities such as San Diego Gas & Electric have underwritten the distribution of free shade trees for residential lots. Denver and Los Angeles (as well as the wetter cities of New York and Chicago) initiated "million-tree" programs in the 2000s in order to green streets and public spaces. McPherson et al. (2011) modeled two scenarios for the Los Angeles program (high and low tree mortality) and found that urban tree-planting programs could raise tree canopy from 21 percent to as much as 33 percent, with both scenarios showing substantial economic benefits for the city.

### Public Acceptance of Xeric Greenspaces

Although they may save water and help cool dryland cities, xeric plant communities including shade trees may face public resistance. Many people worldwide equate urban greening with turf-and-tree landscapes originating from Northern European traditions. A rapid move to xeric plant communities may be welcomed in some places, while in others, oasis or mesic landscapes may need to be retained for cultural reasons while being made more water-efficient. However, rising environmental awareness may increase acceptance of xeric landscapes over time, and in places public embrace of turfgrass removal is already high. For example, Hurd, Hilaire, and White (2006) found that 92 percent of homeowners in three New Mexico cities supported limiting turfgrass to below 25 percent of the area around public buildings.

Public expectations of green spaces depend on factors such as culture, age, socioeconomic status, recreational interests, and historical exposure to landscapes of different types (Van den Berg and Koole 2006; Fernandez-Cañero et al. 2013). Public values regarding vegetation vary significantly across cultures. Giannakis et al. (2016) found that residents of Nicosia, Cyprus, valued green space for exercise, nature, social interaction, cleaner air, and cooler temperatures. Zhang et al. (2013) determined that Chinese park users most valued accessibility, ambiance, security, and good maintenance. Park (2017) found that in Arizona, the public desired greening for shade, urban agriculture, and water features. In the Netherlands, Buijs, Elands, and Langers (2009) found that native Dutch residents prioritized wild elements of greenspaces, whereas Islamic immigrants from Turkey and Morocco valued well-managed and controlled spaces. Makhzoumi (2002) argues that due to the harsh conditions of desert environments, many Middle Eastern cultures value calm, secure, and controlled green areas. Planners will need to take local or regional public attitudes into account when designing both vegetative and architectural urban cooling solutions.

Oases have played important roles in many dryland cultures historically and can be replicated through landscape design. Within the city of Ghardaia, Algeria, for example, the Mzad settlements have for centuries maintained palm tree gardens for both climatic and cultural benefits (Bencheikh and Rchid 2012). Within the Muslim religion, prayer is done five times a day and urban green spaces provide locations for this ritual to be carried out. In Karachi, Pakistan, more than 60 percent of residents requested spaces for prayers within parks (Qureshi, Breuste, and Jim 2013). Islamic religious concepts of paradise are strongly associated with lush green landscapes (Kafafy 2010), and the Arab word for garden, "jenna," also means paradise. Historically land was divided between *amir* and *mawat*, meaning developed and dead land, respectively (Makhzoumi 2002). Members of the public may see xeriscape designs as falling into the latter category. In some places, landscape planners may need to slowly introduce members of the public to new vegetative strategies and educate them about native desert vegetation.

### Maintenance Practices

Conventional turf-and-tree landscapes have been relatively simple to maintain through regular mowing, fertilization, application of herbicides to kill weeds, replacement of annual plants, and occasional tree and shrub pruning. Maintenance of xeric landscapes is likely to be quite different, especially if they are to be managed sustainably in forms likely to be most acceptable to the public (i.e., neatly maintained rather than wild in appearance). Little research exists on this topic. Labor-intensive weeding and mulching will likely be needed to keep down invasive annual species, and drip or micro-spray irrigation will likely be required to establish plants initially. Careful pruning and removal of debris may be necessary to avoid creating habitat for rodents or hidden spaces that can raise safety issues. Such maintenance is likely to require retraining of parks staffs and acquisition of detailed knowledge of plant species and communities by local professionals. A related problem may be that many native or drought-tolerant species may not be available through local commercial growers. Changes in the nursery industry will be needed to ensure adequate supply of species for public landscapes in some urban regions.

### UHI-reducing Built Form

As previously discussed, dense, shade-maximizing built form can be a main strategy to cool dryland cities. In some parts of the world, including many Mediterranean cities, vernacular architecture has followed this path for millennia. Contemporary authors such as Ratti, Raydan, and Steemers (2003) argue that a multistory courtyard building form performs best in hot arid climates at maximizing features such as shadow density. However, twentieth-century development practices typically aimed for lower, more spread-out built landscapes with wide roads, low buildings, and extensive surface parking. Metropolitan regions such as Phoenix and San Diego primarily follow this more suburban model. Rapidly urbanizing regions such as Dubai and Cairo also include many such landscapes that are more likely to exacerbate UHIs than mitigate them.

Planners could use many mechanisms to produce more climate-adaptive built form. These include minimum heights for buildings; urban design guidelines that encourage courtyards, arcades, and shade structures; requirements for passive solar design of buildings; and standards that minimize street width and surface parking while requiring trees and/or buildings to shade road and parking surfaces. Municipal, state, or national regulations could also require light-colored, high-albedo paving and roof materials, as indeed has already occurred in some locales.

However, bringing about such changes will not be easy. Urban densification is politically controversial in many parts of the world. Architects and builders tend to follow conventional building and site design formats and are not necessarily trained in producing alternatives. Existing zoning and subdivision codes may work against new urban forms. Business owners and local residents frequently want to maximize motor vehicle parking and roadway capacity. Development economics frequently makes it difficult to place parking within structures or below ground, leading to expansive surface parking lots. Our review will resist delving into such issues but will instead point out that movements such as the New Urbanism and Smart Growth have been seeking to change such established practices for nearly thirty years now, with some success. Just as acceptance of concepts such as pedestrian friendliness has had to grow over time, so understanding and encouraging climate-adaptive built form is likely to be an ongoing process that planners and public officials can encourage.

## Conclusion

Planning strategies to cool dryland cities and reduce UHI effects are still in the early stages. However, they hold the potential to provide many benefits related to health, comfort, recreation, habitat, stormwater management, and economics. No single strategy will apply across the diversity of dryland urban regions and cultures. But in each location, vegetation, built form, and heat-reflecting materials can work together to create cooler and more climate-adapted cities. Cost, maintenance, and public acceptance issues are likely to diminish over time with greater experience.

Strategies will vary not just by location but by scale as well. At a regional scale, our analysis indicates the importance of maximizing the sheer amount of vegetation within the urban region, of developing plant palettes of appropriate low-water species, and of coordinating vegetation strategies with shade-producing built landscapes and high-albedo materials. At neighborhood and site scales, more specific planting and built form strategies come into play. Tree canopies coordinated with tall and closely spaced buildings and narrow street canyons can potentially maximize shading, cool ambient air temperatures, and increase human comfort. At both regional and local scales, regulatory changes, urban design guidelines, educational materials, and technical support to property-owners and builders can help new, more climate-appropriate landscapes come about.

Since many dryland locations have few if any native trees and global warming will alter local climates in any case, professionals may need to use drought-tolerant species from many locations worldwide to help green arid cities. More research is needed to develop effective plant palettes for particular sorts of dryland environments and to avoid unintended consequences from importing species into new contexts. Additional knowledge about maintenance strategies will likewise be needed, and educational campaigns may be necessary to gain public acceptance. Although much remains to be done, dryland cities appear to be at the start of a new era in which more sophisticated combinations of vegetation, built form, and materials improve thermal performance, human comfort, and sustainability. Urban planners and designers will have a significant role in advancing these notions through research and practice.

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