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The social and spatial distribution of temperature-related health impacts from urban heat island reduction policies

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ABSTRACT

Cities are developing innovative strategies to combat climate change but there remains little knowledge of the winners and losers from climate-adaptive land use planning and design. We examine the distribution of health benefits associated with land use policies designed to increase vegetation and surface reflectivity in three US metropolitan areas: Atlanta, GA, Philadelphia, PA, and Phoenix, AZ. Projections of population and land cover at the census tract scale were combined with climate models for the year 2050 at 4 km $\times$ 4 km resolution to produce future summer temperatures which were input into a comparative risk assessment framework for the temperature-mortality relationship. The findings suggest disparities in the effectiveness of urban heat management strategies by age, income, and race. We conclude that, to be most protective of human health, urban heat management must prioritize areas of greatest population vulnerability.

1. Introduction

Cities, given their concentrated populations, outsized contributions to carbon emissions, and impacts on surface energy balances, are crucial sites for addressing climate change and avoiding associated health impacts. Urbanized regions produce the majority of greenhouse gas emissions, and are the places most vulnerable to human health impacts resulting from climate change due to concentrated poverty and inequality (Bulkeley and Betsill, 2005; Revi et al., 2014). Urban environments further elevate the rate of warming in cities through the urban heat island effect, a phenomenon where the impervious materials of urban construction absorb, store, and release heat energy. Urban warming has been shown in large US cities to be as great, or greater than, the impact of global climate change on local temperature trends (Georgescu et al., 2014; Stone et al., 2012).

While municipal governments are taking actions on climate change, there remains scarce evidence for how the potential health benefits of climate-adaptive land use planning and design (or urban heat management) — additional urban vegetation, reduced impervious surface, and increased reflectivity of built surfaces — are distributed. In this work we assess the distribution of environmental health benefits from alternative climate adaptation scenarios in Atlanta, GA, Philadelphia, PA, and Phoenix, AZ. These planning scenarios involve urban land cover changes designed to increase the spatial extent of vegetation and cool building and paving materials across these metropolitan areas by 2050. Using the combination of high resolution output from a regional climate model – the Weather Research and Forecast (WRF) model – and a health modeling software – USEPA's Benefits Mapping and Analysis Program (BenMAP) – temperature-related changes in mortality resulting from alternative development scenarios were modeled. Here, we evaluate the distribution of resulting health benefits. Specifically, we test the effectiveness of planning strategies to lower summer ambient temperatures and thereby reduce mortality for different races, ages, and income levels in the three metropolitan areas.

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1.1. Planning actions to cool cities

Some cities are experiencing a higher rate of warming than proximate rural areas, with recent work finding the frequency, intensity, and duration of heat waves to be increasing rapidly in many large cities (Habeeb et al., 2015). Results of studies comparing urban and rural warming trends demonstrate that many large cities are warming at a rate more than double that of the planet as a whole (Fujibe, 2009; Ren et al., 2007; Stone, 2007). With the incidence of extreme heat constituting a leading climate-related threat to human health (Confalonieri et al., 2007), the higher rates of warming in cities poses a substantial challenge to municipalities and public officials at all levels of government (Stone et al., 2012). Four specific changes in urban environments drive the urban heat island effect: 1) the loss of natural vegetation, 2) the introduction of urban construction materials that are more efficient at absorbing and storing thermal energy, 3) the creation of "urban canyons" which trap solar radiation and reduce air flow, and, 4) the emission of waste heat from buildings and vehicles (Arnfield, 2003; Oke, 1982; Rizwan et al., 2008). As this elevated rate of warming in large cities is directly influenced by their own patterns of land use, climate adaptive land use planning provides a potential strategy for local action to mitigate extreme heat and its impacts.

The benefits of increased urban vegetation, through tree planting, increased park space, and the construction of green roofs, has been demonstrated in a large number of modeling studies (Akbari, 2005; Dimoudi and Nikolopoulou, 2003; Taha et al., 1997). In one such study, tree planting alone reduced summer afternoon temperatures by as much as 1.5 °C, diminishing the region's average summer heat island by more than half (Rosenfeld et al., 1998). Similarly, studies modeling the large-scale conversions of urban surfaces to higher albedo materials show reductions in afternoon temperatures. Numerous studies on the Los Angeles basin find that extensive albedo enhancement of building rooftops and paved surfaces could result in a reduction in afternoon summer temperatures of between 1.5 °C and 2 °C (Rosenfeld et al., 1998; Sailor, 1995; Taha et al., 1997). In a study of Athens, Greece, climate models parameterizing citywide roofing with baseline (0.18), moderate (0.63), and extreme (0.85) albedos demonstrated a reduction in ambient temperatures of between 1 and 2 °C, with results varying by neighborhood (Synnefa et al., 2008).

Previous analysis of the simulations informing this work showed additional tree canopy and green roofs in Atlanta, Philadelphia, and Phoenix lowered summer temperatures (Stone et al., 2014). Such greening strategies alone in Atlanta, for example, offset projected mid-century warming by about 30% across the metropolitan region as a whole, with greater reductions resulting in specific areas. Albedo enhancement in Atlanta, Philadelphia, and Phoenix offset mid-century projections of the increases in warm season temperatures by about 11–20% at the metropolitan level (Stone et al., 2014).

In this work we assess the distribution of health benefits resulting from policies aimed at lowering urban summer temperatures by increasing vegetative cover or increasing surface albedo. Underpinning our analysis are simulated changes in vegetative cover over time; the result of a "green area ratio" (GAR) policy in each metropolitan region. A longstanding zoning tool in Germany, and more recently adopted in Seattle and Washington, DC, GARs specify minimum vegetative cover requirements for privately owned property, but provide wide flexibility in meeting these cover standards. GARs identify a menu of greening options from which property owners can choose, including tree planting and green roofs, among other greening strategies and allow property owners to combine multiple strategies to meet the minimum requirements.

1.2. Vulnerability to heat

Lowered summer temperatures are expected to result in lower overall mortality. In general, the temperature-mortality relationship for a given location follows a u-shaped curve with steep increases in the relative risk of mortality at severe high temperatures (Curriero et al., 2002; Gasparrini et al., 2015). Several factors determine the effectiveness of planning strategies to protect human health from heat. Implementing municipal policies designed to increase vegetation and/or the use of cool materials have implications for potential cooling benefits which may be unequally distributed. An important factor in determining a policy's effectiveness to reduce heat mortality depends on characteristics of the population affected by the land cover, and resulting temperature, changes.

Population vulnerability to heat-related mortality has been found to vary greatly by metropolitan region in the United States, with several explanations including differences in the biophysical ability of populations (Bonner et al., 1976; Senay et al., 1976), cultural practices, and the character of physical and technical infrastructures such as air conditioning (Greenberg et al., 1983). Air conditioning is among the most effective adaptation strategies but remains one of the most costly, particularly when individuals are directly responsible for costs through utility expenses (The Royal Society Policy Centre 2014). Architects and planners have begun to factor heat relief into designs (Davis et al., 2003; Santamouris and Kolokotsa, 2013), but air conditioning remains a heavily relied-upon and immediate means of protecting human health from thermal hazards (Bouchama et al., 2007; Davis et al., 2002; Semenza et al., 1996).

Individual factors such as age and pre-existing health conditions also affect physiological ability to adapt to high temperatures. Advanced age reduces the function of the body's thermoregulatory system (Flynn et al., 2005; Grundy, 2006). Older individuals, particularly those over the age of 65, are recognized to have a higher risk and in some instances elevated mortality is observed among populations less than 1 year of age following heat waves (Basu and Samet, 2002).

Income also is an important correlate of adverse health outcomes during periods of extreme heat (Madrigano et al., 2015). Poorer populations experience more ill effects of heat waves (Jones, 1982; Martinez, 1989), have less neighborhood vegetative resources (Harlan et al., 2006), and reside in more urban inner cities with elevated temperatures (Applegate et al., 1981; Martinez, 1989).

Race had been shown to be associated with increased heat mortality as it was correlated with urban living and poverty (Applegate et al., 1981; Jones 1982). More recent studies have not found an association between health impacts of heat and race, and the findings on race and heat-related health effects have been inconsistent (Basu and Samet, 2002; Kovats and Hajat, 2008), perhaps suggesting that findings manifest as the product of spatial arrangement in certain urban areas (Martinez, 1989; Smoyer, 1998). Cultural adaptations related to racially-defined groups, however, have been suggested to be important for influencing health outcomes during extreme heat events (Whitman et al., 1997). Race and income are common proxies for other factors including social isolation (Semenza, 1999), poor housing quality (Uejio et al., 2011), and lack of air conditioning (Bouchama et al., 2007) known to increase risks of extreme heat.

While the potential for vegetation and albedo enhancement to lower ambient summer temperatures is well supported by the technical literature, only a handful of studies have examined the direct health-related implications of these approaches to climate management, and none to our knowledge has addressed the likely demographic distribution of potential benefits.

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