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

Jason Vargo, Ph.D[a,b,*], Brian Stone, Ph.D[c], Dana Habeeb[c], Peng Liu, Ph.D[d], Armistead Russell, Ph.D[d]

[a] University of Wisconsin-Madison, Global Health Institute, 1070 Medical Sciences Center, 1300 University Avenue, Madison, WI, 53706, United States
[b] University of Wisconsin-Madison, Nelson Institute for Environmental Studies, Center for Sustainability and the Global Environment, United States
[c] Georgia Institute of Technology, School of City and Regional Planning, Atlanta, GA, United States
[d] Georgia Institute of Technology, School of Civil and Environmental Engineering, Atlanta, GA, United States

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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 × 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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* Corresponding author at: University of Wisconsin-Madison, Global Health Institute, 1070 Medical Sciences Center, 1300 University Avenue, Madison, WI, 53706, United States.
E-mail address: javargo@wisc.edu (J. Vargo).

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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.

2. Methods

To describe the distribution of benefits from climate adaptive land use planning and design strategies we rely on modeled estimates of mortality in the year 2050. Much of the work was performed as part of the Climate, Urban Land use and Excess Mortality (CULE) study sponsored by the US Centers for Disease Control and Prevention. Here, we briefly review the methods employed through the CULE project to associate land cover change with future climate and heat-related morality in Atlanta, Philadelphia, and Phoenix by 2050. Earlier analyses and published methodologies discuss the specifics of projecting future land cover (Vargo et al., 2013), refining climate models (Liu et al., 2012), and estimating health impacts of temperature changes (Stone et al., 2014).

2.1. Population

Underlying population estimates come from the economic forecasting firm Woods & Poole and were extended to 2050 using linear regression of the county-level trends between 1990 and 2040, with the census tract's percentage of the total county population in the year 2000 held constant to arrive at 2050 estimates.

2.2. Land cover

Per capita rates of land conversion were empirically estimated previously by combining US Census population numbers and temporally proximate land cover change details available from the National Land Cover Dataset (NLCD) 1992/2001 Retrofit Land Cover Change Product (Fry et al., 2009). Population projections were considered with land cover conversion rates to produce per capita land conversion rates and estimates of seven (7) land cover classes within each tract for the year 2050. For each metropolitan area in the study, this estimate provided the 'Business As Usual' (**BAU**) land cover, to which we applied policies to manage urban heat (Stone et al., 2014; Vargo et al., 2013).

2.3. Mitigation policies

As part of previous work, 2050 BAU land cover at the tract scale was manipulated to 1) increase reflectivity of impervious surfaces, 2) increase the amount of vegetation, or 3) do both in combination. In the **'ALBEDO'** scenario, we simulated the effects of policies designed to enhance the albedo of all surface paving – from 0.15 to 0.45–and roofing – from 0.15 to 0.9–throughout each metropolitan area. Modified albedo values were obtained from those associated with commercial cool roofing and paving products available today (Wan and Hien, 2012).

Simulated new vegetation was then added to each census tract under the **'GREEN'** scenario according to policies requiring private non-residential, private residential, and public parcel areas to meet minimum green area standards by zoning class. Private, non-residential parcels were first required to convert roof areas to grass, and then to add additional green material until achieving a minimum green area of 50%. Residential parcels and public lands were required to meet an 80% green area standard, which was achieved through variable combinations of street tree planting, parking lot conversions to tree canopy, and residential roof conversions to green roofs.

In a third scenario the ALBEDO and GREEN strategies were modeled in combination by applying the green area standard first and then increasing the albedo of any remaining impervious surfaces. This final climate simulation is referred to as the **'COMBINED'** scenario. Additional details can be found in Table 1 of Stone et al., 2014.

2.4. Simulated future climate

The underlying weather for the year 2050 (May-September) was simulated using the Weather Research and Forecasting (WRF) model. Additional model details can be found in previously published CULE documentation (Liu et al., 2012; Stone et al., 2014; Trail et al., 2013). Simulations for BAU, ALBEDO, GREEN, and COMBINED scenarios produced hourly temperature and humidity metrics at a 4 km spatial resolution. Daily minimum temperatures for each scenario were averaged for the entire summer and compared against BAU (Medina-Ramón and Schwartz, 2007; Voorhees et al., 2011). Daily average temperatures were used to identify heat waves – 2 or more consecutive days with values above the 95th percentile of 1987–2005 summer average – in each scenario (Brooke Anderson and Bell, 2011).

2.5. Health impacts modeling

Differences between BAU and other scenarios, in terms of both average summer temperatures and number of heat waves, will produce differences in mortality relative to the BAU 2050 summer. Earlier studies using the US EPA's Benefits Mapping and Analysis Program (BenMAP) combined information on weather, population, and baseline mortality to estimate changes in health outcomes between scenarios. The resultant number of avoided (or increased) deaths in each tract was estimated for three scenarios depicting urban heat management policies. Consistent with underlying health studies, BenMAP scales annual mortality to approximate daily changes to health outcomes. These results are then aggregated for the period of interest, in this case summer months. This measure of "avoided mortality" is the difference in deaths expected to occur in 2050 under BAU and the alternative (ALBEDO, GREEN, and COMBINED) scenario due to changing summer temperatures. The result of this computation is an estimate of the health benefit, or heat-related deaths that can be avoided, due to the implementation of vegetation and/or albedo enhancement strategies region-wide.

These methodologies used epidemiological studies to define associations between summer temperatures and changes in baseline mortality (the number of deaths from all causes, as defined by the pertinent epidemiological studies), which were age and county specific. Based on those studies, mortality was expected to increase by 3.74% for each additional summer heat wave day (Anderson and Bell, 2011), and by 0.43% for each 1 °C increase in average summer minimum daily temperature (Medina-Ramón and Schwartz, 2007).

Results from previous CULE work including population projections and avoided mortality estimates, were compiled and processed using R Statistical Software version 3.0.3 (R Foundation for Statistical Computing, 2014).

2.6. Vulnerability factors

In this work we assess the distribution of health benefits from urban heat management policies using the population distribution data stratified by age, race, and income. Tracts are classified based on median income, median age, and majority race (white or non-white). Three classes of income and age are selected and breakpoints identified such that each grouping contains more than one tract in all metro areas.

2.7. Health outcomes

BenMAP provides modeled estimates for changes in avoided mortality resulting from our land cover-based urban heat management strategies. BenMAP estimates a total for the change in mortality from daily estimates for summer months. In each tract, we combined BenMAP's estimates of total tract population and the number of avoided deaths to calculate avoided mortality rates (avoided deaths/100,000 persons). We reduced the number of outliers by removing tracts with fewer than 500 people and those with avoided mortality rates more than five standard deviations from the mean avoided mortality rate for all tracts and scenarios.

Rates for avoided mortality represent a standardized effectiveness of each heat management strategy holding population constant. Using population-normalized rates allows us to make comparisons between different locations within a metropolitan area, as well as between different metropolitan areas. Avoided mortality rates were inspected through visual inspection of Q–Q plots. Average rates were computed for each category with 95% confidence intervals, which are used to compare group means within and across metros.

Local climate affects avoided mortality rates through its influence on regional humidity, air movements, and dominant vegetation types. Historic land use also affects avoided mortality rates by determining the amount of existing vegetation and thus the application of land cover change decision rules. Finally, population characteristics influence avoided mortality rates. Modeled avoided mortality is responsive to some of these characteristics through variability in baseline mortality and population age captured in the underlying data.

3. Results

3.1. Population

The projected 2050 distributions of income, race, and age are presented for each metro area in Fig. 1. Colors are arranged such that the category with anticipated higher vulnerability is shown in darker shades. The direction of this scheme is informed by the literature on extreme heat risk (Kovats and Hajat, 2008). In 2050 the Atlanta, Philadelphia, and Phoenix metros were projected to be home to roughly 9.1 M, 6.0 M, and 7.6 M people, respectively. A majority of the growth in areas is expected to occur beyond the fringes of the historic Central Business District (CBD) (Stone et al., 2014). After processing data and applying criteria to remove outliers, more than 96% of the original tracts remained included in the analysis.

3.1.1. Age

The metro areas differ with respect to their demographic compositions and spatial distributions. Tracts with higher median age are likely to contain more people considered vulnerable to extreme heat because of their age. The median age represents the midpoint of all people's ages for a given tract, thus higher median age tracts have larger populations of older people. The large confidence intervals around estimates for older tracts limited our

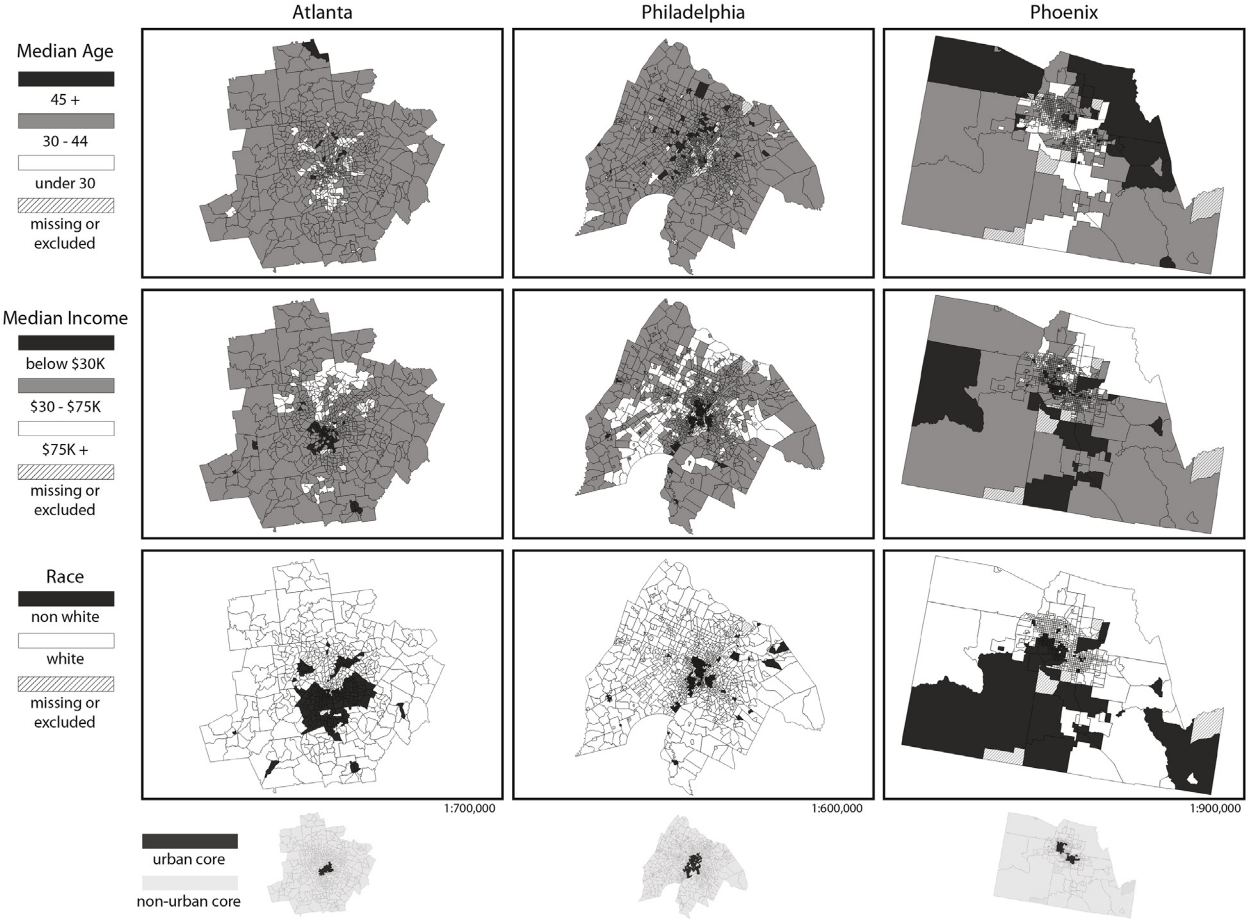

Fig. 1. Projected 2050 distribution of income, race, and age (with urban core tracts shown) for Atlanta, GA, Philadelphia, PA, and Phoenix, AZ.

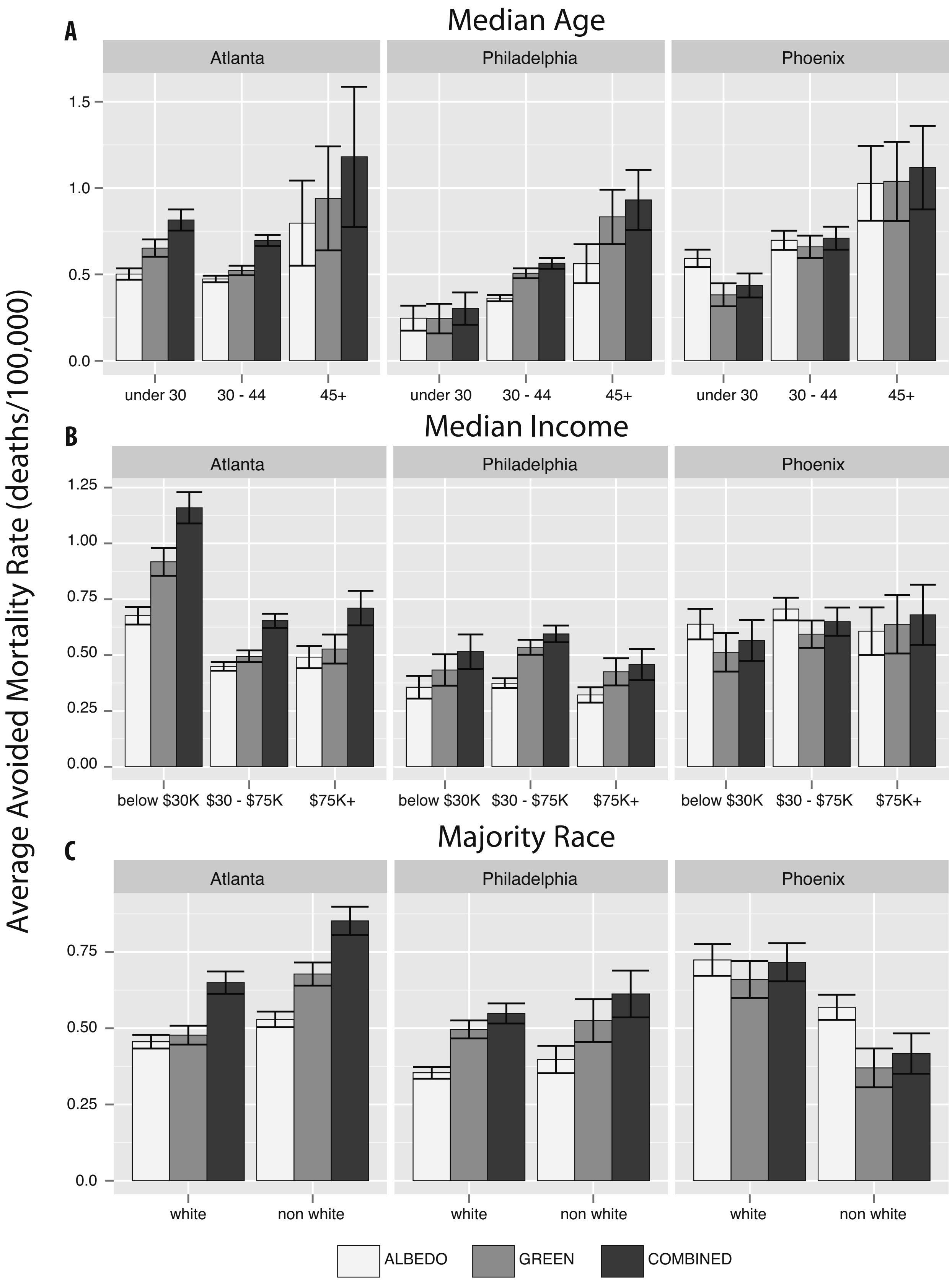

Fig. 2. Average avoided mortality rates by vulnerability factor ((A) age, (B) income, (C) race) and scenario in Atlanta, GA, Philadelphia, PA, and Phoenix, AZ.

ability to draw strong conclusions about differences with these tracts. In general younger tracts are found closer to central city urban cores (Fig. 1). Phoenix will be both the oldest and youngest metro by fraction of its total population, with 8.7% of its population living in tracts with a median age over 44, and 34.8% living in tracts with median age under 30. Atlanta will have less than 1% of its total metro population in 45 and over tracts; 11.5% will live in under 30 tracts. Philadelphia will have nearly 5% of the metro population in the oldest and youngest categories of tracts while Phoenix's projected age distribution is much wider.

3.1.2. Income

Lower income populations and tracts are expected to experience increased vulnerability to heat because of limited adaptive capacity to deal with this environmental exposure. Phoenix is projected to have the largest share of its population living in tracts with a median annual income below $30,000 (15.5%), and the smallest share in tracts with median income above $75,000 (11.6%). Only 4.5% of Atlanta's residents are expected to live in tracts with median income below $30,000. Over 10% of Philadelphia's projected population lives in tracts with the lowest median income, with a much higher share of the metro population in more affluent tracts (22.1%); nearly double that of Phoenix. In all three metros, pockets of low-income tracts in and around the city center are expected. In Phoenix there are also large tracts with concentrated poverty in the southern portions of the metro area.

3.1.3. Race

Race and ethnicity are often discussed in works studying heat wave and health risk factors due to their ability to capture variation in poverty, educational attainment, and social isolation (O'Neill et al., 2005; Uejio et al., 2011; Whitman et al., 1997). All three metros are expected to have more majority white tracts than majority non-white; however, Philadelphia will have less of its population in majority non-white tracts (13.1%) than Atlanta (22.1%) and Phoenix (26.1%). The patterns of non-white settlement in the regions also follow noticeable spatial patterns (Fig. 1). In Atlanta, non-white tracts tend to be to the south of the historic CBD, clustered in areas that are still relatively central and urban in character. In Phoenix, non-white populations are dispersed closer to the fringe of the metro area, away from the city center with denser more urban character.

3.2. Age and avoided mortality

There are differences in the average avoided mortality rate between the oldest and youngest tracts in Philadelphia and Phoenix (Fig. 2, Panel A). In these two metros, for each urban heat management strategy – ALBEDO, GREEN, and COMBINED – older tracts benefited more from the policies in terms of reduced rates of mortality. A similar trend is observed in Atlanta, but the small number of tracts with a median age of 45 or older (< 1%) affected the confidence to distinguish rates in these tracts from others.

In Phoenix's tracts with median age over 44 there is no difference in avoided mortality rate between different scenarios. This implies that cheaper and more easily implemented albedo strategies – due to their immediate effectiveness and shorter payback periods (Stone, 2012) – may be prioritized to achieve health protections. In Philadelphia's oldest tracts, GREEN and COMBINED strategies provide higher average avoided mortality rates than ALBEDO policies alone. In Atlanta, there is no difference between differently aged tracts, though for the majority of the metro area the COMBINED strategies are more effective at lowering rates of mortality than either policy alone.

3.3. Income and avoided mortality

In Atlanta, urban heat management strategies reduced mortality rates more in low income than in middle and high income tracts while the reverse was true between middle and high income groups in Philadelphia (Fig. 2, Panel B). In Atlanta, the poorest tracts had an average avoided mortality rate that was 1.5 times greater than the average rate in middle income tracts when following ALBEDO policies, 1.9 times greater under GREEN policies, and 1.8 times greater with both sets of policies implemented. In all income categories of Atlanta tracts, the rate for COMBINED strategies was higher than for either policy alone. In Philadelphia, there was an advantage to GREEN and COMBINED urban heat management strategies over ALBEDO alone, but not in the poorest tracts. There were no differences in mean avoided mortality rates along income categories in Phoenix.

3.4. Race and avoided mortality

The distribution of benefits to different races varied between metro areas (Fig. 2, Panel C). For Atlanta, urban heat management strategies tend to benefit majority non-white tracts more than majority white tracts. This was true for each urban heat management policy, with the largest difference observed under the GREEN scenario, where average reduction in mortality rates for non-white tracts was 42% higher than in majority white tracts. In Phoenix the reverse was true for all strategies: majority white tracts tended to benefit more from urban heat management than non-white tracts. The highest average avoided mortality rates in Phoenix were under ALBEDO policies, and majority white tracts enjoyed a rate 27% higher than non-white tracts. The disparity was even greater under GREEN policies, where average avoided mortality rates for white tracts were 78% higher than non-white tracts. In Philadelphia, there were differences between the impacts of ALBEDO and other policies, but no difference along lines of race for any specific policy.

4. Discussion

The results of our analysis suggest disparities in the effectiveness of the urban heat management strategies by age, income, and race with varying results depending on the region and the strategies pursued. While previous work demonstrates that climate adaptive land use planning and design can produce reductions in projected rates of mortality over time (Stone et al., 2014), this study finds clear differences in the demographic distribution of these benefits. As temperatures in urbanized areas continue to rise in response to both global and regional scale warming phenomena, municipal and regional governments may require and/or incentivize heat management strategies involving enhanced vegetative cover and surface reflectivity. For these and other strategies to maximally benefit population health, it is necessary that the distribution of characteristics affecting population vulnerability to climate change impacts be considered.

Disparities in avoided mortality rate by age, income, and race differ across the three metropolitan regions examined through this study, however some consistencies can be identified. First, for most metro-scenario combinations, there is clear evidence that tracts with a higher median age benefit more from physical heat management strategies than younger portions of the metro areas. Though the precise mechanisms of these protections must still be explored further, this is an important finding. It is supportive of efforts to protect what are typically the populations most at risk for heat-related illness. Such efforts include targeted physical land cover interventions, which result in enhanced vegetative cover and cool materials at the neighborhood scale.

While emergency response plans for extreme heat often focus on weather emergency information, the siting of cooling centers, and, in the most extreme cases, evacuation efforts for elderly populations, our work suggests that built environment interventions designed to lessen the intensity and duration of extreme temperatures are protective of these populations across a diversity of urban and climatic settings. Municipal and regional governments should consider broadening conventional emergency response planning for heat waves to include mitigation strategies focused on cool land covers in neighborhoods characterized by large or concentrated elderly populations. Analyses like this one, which are based on scenario-based climate and health modeling, shed important light on the effectiveness of specific strategies and for particular populations (Huang et al., 2011).

Next, heat management strategies focused on increasing vegetative cover and albedo are most protective of lower income populations in regions in which these populations are disproportionately located in close proximity to the historic urban core. In Atlanta, lower income populations benefited more from heat management strategies than middle and upper income Atlantans. Tracts containing low-income populations are more concentrated within high density areas of Atlanta than in Philadelphia or Phoenix. Phoenix, in particular, provides a strong counterpoint to Atlanta, with a larger percentage of low income households concentrated in lower density, suburban census tracts than in close proximity to the urban core (Fig. 3, Panel D). As a result of this pattern, heat management strategies – as applied here with greater impact on modifying highly impervious zones such as downtown districts characterized by high building densities and extensive surface parking – may be less effective in Phoenix at reducing heat risk for populations with limited access to air conditioning and other resource-dependent protective measures.

The spatial association between income and imperviousness observed across Atlanta and Philadelphia is even more pronounced with respect to disparities in race and avoided heat mortality in these two regions. Under all of the land cover scenarios simulated, non-white residents benefit more in Atlanta, while white residents disproportionately benefit in Phoenix. This finding contrasts previous studies in Phoenix, which demonstrated larger cooling effects of similar land cover conversions in more impervious neighborhoods (Gober et al., 2009; Jenerette et al., 2011; Middel et al., 2014). Our finding that Phoenix's white residents benefit more may be due in part to our larger unit of analysis and approach used in modifying hypothetical land cover. Earlier Phoenix modeling exercises examined much finer-scale and highly targeted land cover modifications with the outcome of temperature reductions. Here, we are testing the efficacy of policies, albeit policies tied to land cover modifications, applied uniformly across the region and thus to differing degrees in different locations. Also, the outcome of a health endpoint is novel and introduces a new factor impacting the non-linearity of relationships between land cover modifications and tested outcomes.

Patterns of race and avoided heat mortality are closely associated with the spatial distribution of non-white populations, with a large and predominantly African American population principally situated in the southern reach of the urbanized core in Atlanta and, to a less concentrated extent, in Philadelphia (Fig. 1). Atlanta is one US city where a stronger relationship between weather variables and health impacts among non-whites has been observed previously (Kalkstein and Davis, 1989). Phoenix has a higher percentage of non-white population overall with a large Hispanic population and several majority non-white tracts housing Reservations for First Nations' peoples. These tracts are situated to the south and east of the central business district and characterized by very low built densities. As a result, heat management strategies designed to mitigate the heat production of concentrated imperviousness appear to be less protective of health for that group.

Our analysis relies on temperature as the sole predictor of a strategy's effectiveness. It is important to note that temperature is only one of several variables important to the human energy balance (Barnett et al., 2010; Zhang et al., 2014, 2012). Also, our estimates of avoided summer mortality rely on an annual baseline mortality scaled to approximate daily deaths. An update and refinement to the mortality modeling underlying this work could improve our results by providing more accurate baseline mortality in summer months, by more precisely assessing the impact of daily temperature rather than summer averages, and by more closely defining the mortality-temperature relationship for specific locations. Certainly regional differences in the temperature-mortality relationship would be expected to affect results (Wu et al., 2014). Importantly these relationships may also change over

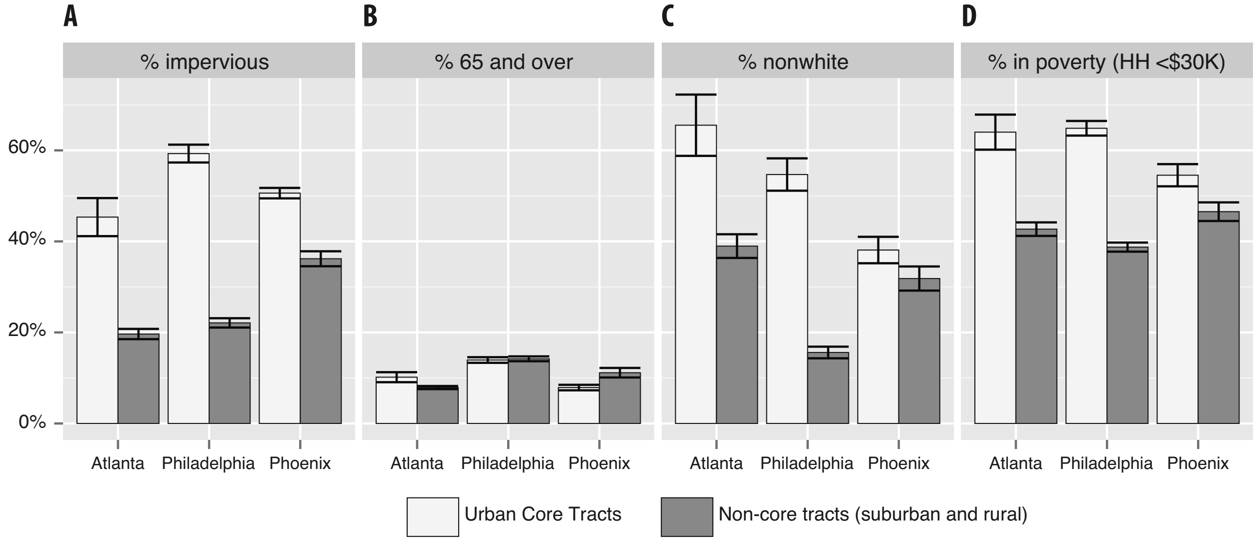

Fig. 3. Average tract composition ((A) impervious surface, (B) age, (C) race, (D) poverty) for urban core and the rest of the metropolitan area in Atlanta, GA, Philadelphia, PA, and Phoenix, AZ.

time as populations adapt to warming conditions within locations. Studies can make use of improved epidemiological data on heat and use regional substitutes to approximate future adaptive capacity of, say northern latitude populations to respond to heat as current more southerly populations (Gasparrini et al., 2015; Greene et al., 2011). Finally, the non-parametric nature of some of these data — specifically Philadelphia's middle age and income groups — require larger studies with more observations to reach more concrete conclusions.

In concert, these findings support the conclusion that to be maximally beneficial for health, climate-adaptive land use planning and design strategies must consider, reflect, and respond to variation in population vulnerability. Where urban thermal hotspots and population vulnerability spatially overlap, such as in Atlanta and, to a lesser extent, Philadelphia, physical heat management strategies designed to enhance neighborhood vegetation and albedo are expected to produce greater human health benefits than in other areas. Where urban thermal hotspots and heat vulnerability are less spatially aligned, as observed in Phoenix, uniformly-applied physical climate-adaptive strategies are likely to be less effective for protecting health and may need to be combined with a wider array of non-physical strategies, such as heat wave early warning systems, the siting of cooling centers, and other emergency response measures (Bradford et al., 2015). In short, the results of our study support the development of region-specific urban heat management plans responsive to the unique demographic (age, income, race) and material (urban form, urban design, climate zone) composition of metropolitan regions. The public health community, together with urban planners, city arborists, and developers, have shared interests and responsibilities to respond to extreme heat events not only through emergency response planning but in the adoption of mitigation strategies designed to lessen the frequency and intensity of extreme heat at the urban scale (Rosenzweig et al., 2011).

By building on prior work that focused on climate adaptation and heat-related mortality, this study examined whether conventional heat mitigation strategies designed to increase the region-wide coverage of green and cool materials disproportionately benefit some portions of metropolitan regions. The results of this work suggest that the spatial association between built density and the regional location of vulnerable populations is a key indicator of the potential effectiveness of physical heat mitigation strategies in large urbanized areas. As climate adaptation planning is further integrated into the routine planning functions of cities, municipal governments may choose from an array of 1) heat mitigation and 2) emergency response strategies to lessen the risk of extreme heat to urban populations. The findings from this work add to a body of evidence suggesting a combination of these two approaches in response to the unique physical and demographic characteristics of a metropolitan area to protect public health against the impacts of climate change.

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