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Abbreviations and Definitions:

CBSA Core-based statistical area

CI Confidence interval

D_m	Multigroup Dissimilarity Index
HRRLC	Heat risk-related land cover
NLCD	National Land Cover Dataset
U. S.	United States

ABSTRACT

Objective: To examine the distribution of heat risk-related land cover (HRRLC) characteristics across racial/ethnic groups and degrees of residential segregation.

Methods: Block group-level tree canopy and impervious surface estimates were derived from the 2001 National Land Cover Dataset for densely populated urban areas of the United States and Puerto Rico, and linked to demographic characteristics from the 2000 Census. Racial/ethnic groups in a given block group were considered to live in HRRLC if at least half their population experienced the absence of tree canopy *and* at least half of the ground covered by impervious surface (roofs, driveways, sidewalks, roads). Residential segregation was characterized for metropolitan areas in the United States and Puerto Rico using the multigroup dissimilarity index.

Results: After adjusting for ecoregion and precipitation, and holding segregation level constant, non-Hispanic blacks were 52% more likely (95% confidence interval (CI): 37% to 69%), non-Hispanic Asians 32% more likely (95% CI: 18% to 47%), and Hispanics 21% more likely (95% CI: 8% to 35%) to live in HRRLC conditions compared to non-Hispanic whites. Within each racial/ethnic group, HRRLC conditions increased with increasing degrees of metropolitan area-level segregation. Further adjustment for home ownership and poverty did not substantially alter these results, but adjustment for population density and metropolitan area population attenuated the segregation effects, suggesting a mediating or confounding role.

Conclusions: Land cover was associated with segregation within each racial/ethnic group, which may be partially explained by the concentration of racial/ethnic minorities into densely populated neighborhoods within larger, more segregated cities. In anticipation of greater frequency and duration of extreme heat events, climate change adaptation strategies, such as planting trees in

urban areas, should explicitly incorporate an environmental justice framework that addresses racial/ethnic disparities in HRRLC.

INTRODUCTION

In the U. S., extreme heat events are responsible for about 1 in 5 natural hazard deaths (Borden and Cutter 2008). Because of climate change, many cities are expected to become warmer (IPCC 2007) with "more intense, more frequent, and longer lasting" heat waves (Meehl and Tebaldi 2004). Furthermore, studies of extreme heat have shown large racial disparities in heat-related deaths (Greenberg et al. 1983; Jones et al. 1982; Kaiser et al. 2007; O'Neill et al. 2005; Schwartz 2005), although this is not universally the case (Ramlow and Kuller 1990; Weisskopf et al. 2002), and in at least one case, whites have been more affected than minority groups (Ellis et al. 1975). Land cover characteristics may contribute to these disparities (Uejio et al. 2011). Urban tree canopy is an important local mitigating factor for extreme heat (Oke et al. 1989; Hart and Sailor 2009), while impervious surfaces play a primary role in creating urban heat island effects (Oke 1982).

Urban trees provide several environmental amenities (Givoni 1991), including shade on hot days (Scott et al. 1999), reductions in wastewater loads on treatment facilities (Keim et al. 2006), and reduced air pollution (Hwang et al. 2011; Nowak 1994) and noise pollution (Samara and Tsimoni 2011) from vehicular traffic. Research also suggests that urban trees are associated with reduced all-cause mortality after adjustment for neighborhood deprivation (Mitchell et al. 2011), and green spaces are associated with many positive health outcomes (Lee and Maheswaran 2010), including improved pregnancy outcomes (Dadvand et al. 2012). Studies in the United States have documented racial/ethnic disparities in urban tree canopy, usually in the direction of racial/ethnic minorities living in neighborhoods with lower tree coverage (Heynen et al. 2006, Landry and Chakraborty 2009, Lowry et al. 2011, Ogneva-Himmelberger et al. 2009, Perkins and Heynen 2004, Zhang et al. 2008), but some counter-examples exist (Boone et al. 2010, Troy

with both of these characteristics. Thus, using this approach, Hispanics living in rented homes could have a different measure of HRRLC than Hispanics living in owner-occupied homes, depending on their relative distribution across the blocks within the block group.

Segregation measure

We used a multi-group dissimilarity index, D_m (Sakoda 1981), to characterize the unevenness of the residential distribution of the four racial/ethnic groups described above, plus a residual category consisting of all other residents, at the core-based statistical area (CBSA) level. CBSAs consist of counties or groups of counties closely linked by commuting patterns (Office of Management and Budget, 2000) and we refer to them here as metropolitan areas. D_m ranges from zero (i.e. no segregation where every census block group within the CBSA has the same racial/ethnic makeup) to one (i.e. complete segregation where each census block group within the CBSA consists only of a single racial/ethnic group). D_m describes the proportion of racial/ethnic minority populations that would need to move within the metropolitan area so that each census block group would have the same racial/ethnic makeup. Specifically,

$$D_m = 0.5 * \{ [\sum_r \sum_i |N_{ir} - (N_i N_r / N)|] / [\sum_r N P_r (1 - P_r)] \} \quad [2]$$

where r indexes each racial/ethnic group, i indexes the block groups, N is the number of residents, and P_r is the proportion of residents of racial/ethnic group r in the entire CBSA.

We treated D_m as a continuous variable in the main analysis, but also performed sensitivity analyses with D_m modeled as a categorical variable.

Biophysical variables

Tree growth is dependent on ecological (or biophysical) parameters that we wanted to control for when comparing tree cover across areas of the country. Therefore, we classified each census

block group according to Level I ecoregions developed by Omernik (Commission for Environmental Cooperation 1997) to classify regions with similar ecological characteristics and environmental resources. We combined ecoregions that included < 5 metropolitan areas (temperate Sierras and northwestern forested mountains, and southern semi-arid highlands and North American deserts)] and assigned Hawaii and Puerto Rico to the tropical wet forests ecoregion, resulting in a variable with 8 possible categories. We also considered local-area climatic variation in average annual precipitation and average precipitation during the driest month of each year for each census block group using layers developed by the United States Department of Agriculture's Natural Resources Conservation Service (USDA NRCS 2011). We calculated these parameters for each block group using the same projection as for the land cover characteristics.

Analytic approach

We used robust Poisson models to estimate prevalence ratios (Deddens and Petersen 2008) for the co-occurrence of two dichotomous heat risk-related measures: whether at least half of a sub-population of a census block group lived in census blocks with no tree canopy reported in the NLCD and at least half of a sub-population of a census block group lived in census blocks with at least 50% impervious surface.

We used a generalized estimating equation approach for all models to account for the fact that up to eight sub-populations might be assessed within each block group, and thus there were closely correlated measures for each block group. We weighted sub-populations within each block group by population, with a sum equal to the number of block groups in the analysis:

$$\text{weight}_{rti} = (\text{Number of block groups} * \text{population}_{rti}) / N, \quad [3]$$

where r indexes the racial/ethnic group, t indexes whether they live in a rented or owner-occupied housing unit, i indexes the block group, and N indicates the total size of the eligible population, 81,517,417.

The first set of models we examined contained only race/ethnicity, and an interaction term between race/ethnicity and racial/ethnic residential segregation, to yield four estimates of the association between segregation and HRRLC within each racial/ethnic group.

$$\text{HRRLC}_{irt} = \exp(\alpha + \beta X_r + \gamma X_r D_{mi} + \varepsilon_{irt}) \quad [4]$$

where i , r , and t represent the same indices described above, X represents the racial/ethnic groups relative to whites, β parameterizes racial/ethnic differences relative to whites, and γ parameterizes the association of segregation with HRRLC within each racial/ethnic group.

In the second set of models, we adjusted for biophysical covariates: average annual rainfall (as 6 categories; under 10"/year, then in 10"/year increments, with rainfall averages above 50"/year grouped together), average rainfall in the driest month of the year (in 5 categories; none, under 1", 1-2", 2-3", and 3" or greater), and Omernik's level I ecoregions (eight categories after collapsing 2 sparsely populated ecoregions).

In further modeling exercises, we considered variables that could alter the observed association between segregation and land cover characteristics through confounding or mediation. Home ownership and poverty have often been linked to the likelihood of having trees on both private and public lands (Heynen 2006; Heynen and Lindsey 2003; Heynen et al. 2006; Iverson and Cook, 2000). These factors might theoretically be part of the causal pathway between

segregation, race/ethnicity, and land cover characteristics, especially given *de jure* and *de facto* discrimination in historical and contemporary home mortgage lending that restrict where racial minority populations live (Ghent et al. 2011; Hillier 2003). We added categorical terms for housing tenure (renter vs. home-owner) and household income relative to poverty (under poverty, near poverty, or household income at least twice poverty) to the model containing the biophysical variables to assess whether associations between land cover, race/ethnicity and residential segregation seen in models controlling only for biophysical variables changed with adjustment for these variables. In sensitivity analyses, we also examined adding housing tenure terms or poverty terms separately.

In more segregated metropolitan areas, racial/ethnic minority groups tend to be clustered in densely populated neighborhoods near the central business district, and/or in ‘wedges’ extending outwards from this central point (Berry and Kasarda 1977, p. 90), while a ring of almost exclusively white suburban areas surrounds the metropolitan area at or near the limits of tolerable commuting distances. It is quite possible that the main effect of segregation on the distribution of land cover experienced by racial minority groups is mediated through the phenomenon of concentrating minority groups into densely populated neighborhoods. Moreover, more populous metropolitan areas tend to have a more segregated character (Iceland et al. 2002). Metropolitan area population size may precede residential segregation on the causal pathway affecting the distribution of land cover. Therefore, we examined models that included these two factors in addition to the biophysical variables.

We conducted sensitivity analyses with D_m modeled as a categorical versus continuous variable to assess the assumption of a linear relationship between D_m and the HRRLC outcome variables in the robust Poisson model, and to explore whether associations between land cover and

race/ethnicity or segregation varied depending on the method we used to classify HRRLC. We also examined associations with tree canopy and impervious surface as separate components.

RESULTS

There were 63,436 block groups that met our eligibility criteria. These were distributed across 304 metropolitan areas, and contained 81,517,417 eligible residents, about 29% of the U. S. population in the 2000 Census. Supplemental Material Figure S1 shows a national map of the metropolitan areas included in our analysis by level of segregation. Table 1 shows the distribution of the population across race/ethnicity, housing tenure, household income relative to poverty, and categories of D_m . Twenty six percent of our study population was Hispanic (of any racial identity), 19% were black, 7% Asian, and the remaining 48% were white.

Overall, 42% of the entire study population lived in block groups where at least half the population sub-group lived in blocks with no tree canopy in the NLCD, 62% lived in block groups where at least half the population sub-group lived in blocks with $> 50\%$ impervious surface, and 36% lived in block groups that met both heat risk-related land cover criteria. Overall, racial/ethnic minority groups were more likely to live in areas with heat risk-related land cover than whites, particularly Hispanics and Asians. For example, 29% of whites lived in block groups with no tree canopy and mostly covered with impervious surface, as did 31% of blacks, 50% of Hispanics, and 54% of Asians. Residents of rented housing units were more likely to live in areas with both HRRLC characteristics than residents of owner-occupied housing units, and those with a household income below poverty were more likely to live in these areas than those with higher levels of household income.

Residents of metropolitan areas with a D_m between 0.50 and 0.60 were the most likely to have HRRLC characteristics (Table 1).

Table 2 shows modeling results for the joint occurrence of low tree canopy and high levels of impervious surface by race/ethnicity and segregation level. In the baseline models, the association between HRRLC and segregation was largest among whites (12% increased prevalence per 0.10 increase in D_m , 95% CI: 10% to 13%), and was slightly negative among blacks. In addition, the prevalence of HRRLC for blacks, Asians, and Hispanics was about twice that of whites [e.g., a 100% increased prevalence (95% CI: 84, 118%) for Hispanics relative to whites] after adjustment for D_m . Racial/ethnic disparities in HRRLC remained after adjustment for Omernik ecoregion and rainfall patterns, although the magnitude of these disparities was diminished, with prevalence increased by only 21 to 52% (for Hispanics and blacks, respectively) relative to whites. In contrast, associations between segregation and HRRLC were stronger and positive for all 4 racial/ethnic groups (27 to 37% increased prevalence per 0.10 unit increase in D_m). Further adjustment for housing tenure and household income relative to poverty had very little impact on the effect estimates; no estimates changed by 10% or more. However, adjustment for block group population density and metropolitan area population size in addition to Omernik ecoregion and rainfall shifted estimates for the association between HRRLC and segregation toward the null by more than 10%. The disparity between Hispanics and whites increased by more than 10% with this adjustment, while associations between black and Asian race/ethnicity and HRRLC were not substantially affected.

Sensitivity Analyses

Models of associations with > 50% impervious surface or no tree canopy as separate outcomes (Supplemental Material, Table S1) suggest that segregation is more strongly associated with a

lack of tree canopy cover than with impervious surface. Separate models adjusted for the biophysical variables (Omernik ecoregion and rainfall) plus either home ownership, poverty, block group population density, or metropolitan or population size (Supplemental Material, Table S2) indicated that adjustment for both population density and metropolitan area population size decreased associations between land cover disparities and segregation levels towards the null.

Results of models in which segregation, represented by the multigroup dissimilarity index D_m , was modeled as a categorical variable defined using "round number" cut-points (0.40, 0.50, 0.60), quartiles of the population-weighted distribution (0.467, 0.526, 0.606), and cut-points between four groups of 76 metropolitan areas (0.381, 0.4571, 0.523) were generally consistent with models of D_m as a continuous variable (Supplemental Material, Table S3.) Specifically, in most cases HRRLC increased monotonically with increasing segregation in each race/ethnicity group, though there was some heterogeneity depending upon which cut-point schema is used. Using alternate cut-points to dichotomize tree canopy (i.e., < 10% or < 20% instead of no tree canopy versus any) or impervious surface (> 70% or > 80% versus > 50%) also did not qualitatively alter the results (Supplemental Material, Table S4).

DISCUSSION

At a national scale, we found racial/ethnic disparities in heat risk-related land cover characteristics. We anticipated that these disparities might be due to confounding by biophysical factors that strongly influence tree growth, but found that racial disparities remained after adjustment for these factors.

Adjusting for home ownership and household poverty did not substantially alter associations between HRRLC and race/ethnicity or metropolitan area segregation levels within each racial/ethnic group. However, adjusting for block group population density and metropolitan area population size substantially attenuated effect estimates for segregation, suggesting that these variables either precede or are in the causal pathway between segregation and HRRLC characteristics. This is consistent with previous work indicating that segregation tends to concentrate racial/ethnic minority groups into densely populated neighborhoods, particularly in larger cities (Iceland et al. 2002; Lichter 1985; Massey and Denton 1989), which in turn are likely to have fewer trees and more impervious surfaces (Iverson and Cook 2000, Pozzi and Small 2001).

Given that the degree of segregation between blacks and whites is generally larger than between whites and either Asians or Hispanics (Iceland et al. 2002), we anticipated that the largest disparity in HRRLC characteristics would be between blacks and whites. At first glance, blacks and whites appeared nearly equally likely to share these adverse built environment characteristics on a national level (Table 1); the largest disparities in land cover characteristics were between whites and Asians, and between whites and Hispanics. However, after adjustment for Omernik ecoregion, precipitation patterns, and segregation (Table 2), the largest racial/ethnic disparity in HRRLC characteristics was between blacks and whites.

Living in a neighborhood with high HRRLC may not necessarily translate to greater risk of heat-related illness. Our finding of comparable prevalences of HRRLC in blacks and whites without adjustment for segregation or other factors (31% and 29%, respectively, versus 50% for Hispanics) is not entirely consistent with evidence of higher risk of heat-related mortality among African-Americans compared to whites (Basu and Ostro 2008; Greenberg et al. 1983; Kaiser et

al. 2007; O'Neill et al. 2005; Schwartz 2005), and lower risk among Hispanics relative to whites (Basu and Ostro 2008; Whitman et al. 1997) . However, consistent with our finding that Asians had the highest prevalence of HRRLC (54%), Asians were more likely to go to an emergency department for heat-related illnesses during California's 2006 heat wave (RR of 11.4 [95% CI: 5.5 to 27] relative to a comparison period) than were whites (RR=6.3, 95% CI: 5.4 to 7.3), Hispanics (RR=6.5, 95% CI: 5.3 to 8.0), or blacks (RR=5.3, 95% CI: 3.8 to 7.4) (Knowlton et al. 2009).

Some of this inconsistency may be explained by other risk factors that are also associated with heat-related illness. Existing racial/ethnic disparities in chronic diseases that increase susceptibility to heat such as cardiovascular disease and diabetes (Bouchama et al. 2007; Schwartz 2005), differential representation in physical and outdoor occupations (Greenberg et al. 1983), unequal access to air conditioning (O'Neill et al. 2005, English et al. 2007), and social isolation (Klinenberg 2002) may explain a good deal of the observed disparate health outcomes despite relatively similar land cover characteristics between blacks and whites.

Limitations

The NLCD assessment of tree canopy and impervious surface was part of a project to categorize land cover across the United States; adaptation of these measures to assess local variation in heat risk introduces misclassification. An analysis of the accuracy of tree canopy and impervious surface estimates in the 2001 NLCD revealed that there was a consistent undercount of tree canopy in all regions of the country. Misclassification ranged from an 11.3% overcount to a 34.7% undercount in developed areas (Nowak and Geenfield 2010). Because the NLCD used smoothing techniques to characterize 30 meter pixels, areas with sparsely planted trees might be classified as having no trees whatsoever, which may tend to overestimate heat risk in densely-

populated neighborhoods. The degree of misclassification of impervious surface was also quite variable, from a 29.0% undercount to a 19.7% overcount across developed regions of the country. It is difficult to predict how this misclassification would bias our results.

The NLCD classification of impervious surface is mainly intended to distinguish between urbanized and non-urbanized areas, whereas the albedo of paved and roofed areas is a dominant consideration for urban heat (US EPA 2011). Harlan and colleagues (2006) examined 8 select neighborhoods in Phoenix and found that areas with higher proportions of minority residents tended to have housing with darker roofs. In the absence of systematic evidence about the racial/ethnic distribution of the albedo of impervious surfaces, we are hesitant to speculate as to how accounting for albedo in addition to the presence of impervious surface would alter our observations.

Our analysis also does not account for any differences in pavement permeability, which can have a large impact on local surface temperatures (Haselbach et al. 2011), or other contributions to heat risk, including waste heat from energy consumed by cars and buildings (Rizwan et al. 2008) and the “urban canyon” effect created by tall buildings (Oke 1982).

Although the NLCD has produced more recent data on impervious surface (Fry et al. 2011), the 2001 dataset remains the most recent nationally consistent assessment of tree canopy. We elected to match the impervious surface data and Census data closest in time to the tree canopy data. It is possible that tree planting efforts in metropolitan areas in the intervening years may have altered the patterns we observed. It is difficult to predict whether these tree planting efforts would have reduced or exacerbated racial disparities in heat-risk related land cover on a national level.

The biophysical variables we used as controls may not have captured important factors that affect tree growth and are independent of the built environment. We did not account for soil composition, ground slope or aspect, proximity to riparian areas, or temperature characteristics (Lowry et al. 2011). However, unless these factors were distributed in a very different manner than the three biophysical variables we did consider, they would be unlikely to offset the dramatic differences in model results we observed after controlling for these biophysical variables.

Several analyses have attempted to predict the likely frequency of future extreme heat events (Lau and Nath 2012; Meehl and Tebaldi 2004), and some have attempted to assess the likely differential impact of these extreme heat events on specific populations, such as the elderly (Jackson et al. 2010). Our analysis did not incorporate heat-related morbidity and mortality data or climatic projections to assess potential racial/ethnic disparities in health risks from climate change; this would be an area worthy of future research.

CONCLUSION

The U. S. Environmental Protection Agency recommends both increased tree canopy and changes in roof and pavement characteristics to reduce urban heat intensity (US EPA 2011). Many cities have developed plans to mitigate future heat risks, largely through adopting strategies that promote tree planting and high albedo roofs and pavements (US EPA 2011). Results of this analysis highlight the idea that urban planning to mitigate future extreme heat should proactively incorporate an environmental justice perspective and address racial/ethnic disparities in land cover characteristics.

REFERENCES

- Basu R, Ostro BD. 2008. A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *Am J Epidemiol* 168:632-637.
- Berry BJL, Kasarda JD. 1977. *Contemporary Urban Ecology*. New York:Macmillan Publishing Company.
- Boone CG, Cadenasso ML, Grove JM, Schwarz K, Buckley GL. 2010. Landscape, vegetation characteristics, and group identity in an urban and suburban watershed: why the 60s matter. *Urban Ecosyst* 13:255-271.
- Borden KA, Cutter SL. 2008. Spatial patterns of natural hazards mortality in the United States. *Int J Health Geogr* 7:64.
- Bouchama A, Dehbi M, Mohamed G, Matthies F, Shoukri M, Menne B. 2007. Prognostic factors in heat wave–related deaths: a meta-analysis. *Arch Intern Med* 167:2170-2176.
- Collins CA, Williams DR. 1999. Segregation and mortality: the deadly effects of racism? *Sociol Forum* 14:495-523.
- Commission for Environmental Cooperation (CEC). 1997. *Ecological Regions of North America: Toward a Common Perspective*. Commission for Environmental Cooperation, Québec. Available: http://www.cec.org/Storage/42/3484_eco-eng_EN.pdf [Accessed 24 February 2012].
- Dadvand P, Sunyer J, Basagaña X, Ballester F, Lertxundi A, Fernández-Somoano A, et al. 2012. Surrounding greenness and pregnancy outcomes in four Spanish birth cohorts. *Environ Health Persp* 120:1481-1487.
- Deddens JA, Petersen MR. 2008. Approaches for estimating prevalence ratios. *Occup Environ Med* 65:501-506.
- Ellis FP, Nelson F, Pincus L. 1975. Mortality during heat waves in New York City July, 1972 and August and September, 1973. *Environ Res* 10:1-13.

- English P, Fitzsimmons K, Hoshiko S, Kim T, Margolis HG, McCone TE, et al. 2007. Public Health Impacts of Climate Change in California: Community Vulnerability Assessments and Adaptation Strategies: Heat-Related Illness and Mortality: Information for the Public Health Network in California. Richmond, CA:Climate Change Public Health Impacts Assessment and Response Collaborative, California Department of Public Health.
- Fry J, Xian G, Jin S, Dewitz J, Homer C, Yang L, et al. 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States. *Photogramm Eng Rem S* 77:858. Available: <http://www.asprs.org/PE-RS-Journal/2011-PE-RS-Journals.html> [Accessed 29 February 2012].
- Gee GC, Payne-Sturges DC. 2004. Environmental health disparities: a framework integrating psychosocial and environmental concepts. *Environ Health Persp* 112:1645-1653.
- Ghent AC, Hernández-Murillo R, Owyand MT. 2011. Race, redlining, and subprime loan pricing. Working Paper 2011-033A. Research Division, Federal Reserve Bank of St. Louis. Available: <http://research.stlouisfed.org/wp/2011/2011-033.pdf> [Accessed 1 October 2012].
- Givoni B. 1991. Impact of planted areas on urban environmental quality: a review. *Atmos Environ* 25B:289-299.
- Greenberg JH, Bromberg J, Reed CM, Gustafson TL, Beauchamp RA. 1983. The epidemiology of heat-related deaths, Texas—1950, 1970-1979, and 1980. *Am J Public Health* 73:805-807.
- Harlan SL, Brazel AJ, Prashad L, Stefanov WL, Larsen L. 2006. Neighborhood microclimates and vulnerability to heat stress. *Soc Sci Med* 63:2847-2863.
- Hart M, Sailor DJ. 2009. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theor Appl Climatol* 95:397-406.
- Haselbach L, Boyer M, Kevern JT, Schaefer VR. 2011. Cyclic heat island impacts on traditional versus pervious concrete pavement systems. *Transport Res Rec* 2240:107-115.
- Heynen NC, Lindsey G. 2003. Correlates of urban forest canopy cover: implications for local public works. *Public Works Management & Policy* 8:33-47.
- Heynen N. 2006. Green urban political ecologies: toward a better understanding of inner-city environmental change. *Environ Plann A* 38:499-516.
- Heynen N, Perkins HA, Roy P. 2006. The political ecology of uneven urban green space: the impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. *Urban Aff Rev* 42:3-25.

- Hillier AE. 2003. Redlining and the Home Owners' Loan Corporation. *J Urban Hist* 29:394-420.
- Homer C, Huang C, Yang L, Wylie B, Coan M. 2004. Development of a 2001 National Land Cover Database for the United States. *Photogramm Eng Rem S* 70:829-840.
- Huang G, Zhou W, Cadenasso ML. 2011. Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhoods socioeconomic characteristics in Baltimore, MD. *J Environ Manage* 92:1753-1759.
- Hwang HJ, Yook SJ, Ahn KH. 2011. Experimental investigation of submicron and ultrafine soot particle removal by tree leaves. *Atmos Environ* 45:6987-6994.
- Iceland J, Weinberg DH, Steinmetz E. 2002. U.S. Census Bureau, Series CENSR-3, Racial and Ethnic Residential Segregation in the United States: 1980-2000. Washington, DC:U.S. Government Printing Office.
- Intergovernmental Panel on Climate Change (IPCC), 2007. Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* (Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, Eds). Cambridge:Cambridge University Press, pp. 7-22.
- Iverson LR, Cook EA. 2000. Urban forest cover of the Chicago region and its relation to household density and income. *Urban Ecosyst* 4:105-124.
- Jackson JE, Yost MG, Karr C, Fitzpatrick C, Lamb BK, Chung SH, et al. 2010. Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climatic Change* 102:159-186.
- Jones TS, Liang AP, Kilbourne EM, Griffin MR, Patriarca PA, Fite Wassilak SG, et al. 1982. Morbidity and mortality associated with the July 1980 heat wave in St Louis and Kansas City, Mo. *J Am Med Assoc* 247:3327-3331.
- Kaiser R, Le Tertre A, Schwartz J, Gotway CA, Daley R, Rubin CH. 2007. The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. *Am J Public Health* 97:S158-S162.
- Keim RF, Skaugset AE, Weiler M. 2006. Storage of water on vegetation under simulated rainfall of varying intensity. *Adv Water Resour* 29:974-986.

- Klinenberg E. 2002. Race, place, and vulnerability: urban neighborhoods and the ecology of support. In: *Heat Wave: a Social Autopsy of Disaster in Chicago*. Chicago:University of Chicago Press.
- Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, Solomon G, et al. 2009. The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environ Health Persp* 117:61-67.
- Landry SM, Chakraborty J. 2009. Street trees and equity: evaluating the spatial distribution of an urban amenity. *Environ Plann A* 41:2651-2670.
- Lau N-C, Nath MJ. 2012. A Model Study of Heat Waves over North America: Meteorological Aspects and Projections for the 21st Century. *J Climate* 25:4761-4784.
- Lee ACK, Maheswaran R. 2010. The health benefits of urban green spaces: a review of the evidence. *J Public Health* 33:212-222.
- Li G, Weng Q. 2007. Measuring the quality of life in city of Indianapolis by integration of remote sensing and census data. *Int J Remote Sens* 28:249-267.
- Lichter DT. 1985. Racial concentration and segregation across U.S. counties, 1950-1980. *Demography* 22:603-609.
- Lowry JH, Baker ME, Ramsey D. 2012. Determinants of urban tree canopy in residential neighborhoods: household characteristics, urban form, and the geophysical landscape. *Urban Ecosyst* 15:247-266.
- Lu D, Weng Q, Li G. 2006. Residential population estimation using a remote sensing derived impervious surface approach. *Int J Remote Sens* 27:3553-3570.
- Martin CA, Warren PS, Kinzig AP. 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighborhoods and embedded small parks of Phoenix, AZ. *Landscape Urban Plan* 69:355-368.
- Massey DS, Denton NA. 1989. Hypersegregation in U.S. metropolitan areas: black and Hispanic segregation along five dimensions. *Demography* 26:373-391.
- Meehl GA, Tebaldi C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st Century. *Science* 305:994-997.
- Mitchell R, Astell-Burt T, Richardson EA. 2011. A comparison of green space indicators for epidemiological research. *J Epidemiol Community Health* 65:853-858.

- Morello-Frosch R. 2002. Discrimination and the political economy of environmental inequality. *Environ Plann C* 20:477-496.
- Morello-Frosch R, Jesdale BM. 2006. Separate and unequal: residential segregation and estimated cancer risks associated with ambient air toxics in U.S. metropolitan areas. *Environ Health Persp* 114:386-393.
- Morello-Frosch R, Lopez R. 2006. The riskscape and the color line: examining the role of segregation in environmental health disparities. *Environ Res* 102:181-196.
- Morton TA, Yuan F. 2009. Analysis of population dynamics using satellite remote sensing and US census data. *Geocarto Int* 24:143-163.
- Nowak DJ. 1994. Air pollution removal by Chicago's urban forest. Chapter 5 in: *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, McPherson EG, Nowak DJ, Rowntree RA, Eds. US Department of Agriculture, Forest Service, Northeastern Forest Experimental Station. General Technical Report NE-186.
- Nowak DJ, Greenfield EJ. 2010. Evaluating the National Land Cover Database tree canopy and impervious cover estimates across the conterminous United States: a comparison with photo-interpreted estimates. *Environ Manage* 46:378–390.
- Office of Management and Budget. 2000. Standards for defining metropolitan and micropolitan statistical areas. *Federal Register* 65:82228-82238.
- Ogneva-Himmelberger Y, Pearsall H, and Rakshit R. 2009. Concrete evidence & geographically weighted regression: A regional analysis of wealth and the land cover in Massachusetts. *Appl Geogr* 29:478-487.
- Oke TR. 1982. The energetic basis of the urban heat island. *Q J Roy Meteor Soc* 108:1–24.
- Oke TR, Crowther JM, McNaughton KG, Monteith JL, Gardiner B. 1989. The micrometeorology of the urban forest. *Philos T Roy Soc B* 324(1223):335-349.
- O'Neill MS, Zanutti A, Schwartz J. 2005. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *J Urban Health* 82:191-197.
- Perkins HA, Heynen N. 2004. Inequitable access to urban reforestation: the impact of urban political economy on housing tenure and urban forests. *Cities* 21:291-299.
- Pozzi F, Small C. 2001. Exploratory analysis of suburban land cover and population density in the U.S.A. *IEEE/ISPRS Joint Workshop on Remote Sensing and Data Fusion over Urban Areas*, pp 250-254. 8-9 November, Rome, Italy.

- Ramlow JM, Kuller LH. 1990. Effects of the summer heat wave of 1988 on daily mortality in Allegheny county, PA. *Public Health Rep* 105:283-289.
- Rizwan AM, Dennis LYC, Liu C. 2008. A review on the generation, determination and mitigation of urban heat island. *J Environ Sci* 20:120-128.
- Sakoda JM. 1981. A generalized index of dissimilarity. *Demography* 18:245-150.
- Samara T, Tsitsoni. 2011. The effects of vegetation on reducing traffic noise from a city ring road. *Noise Control Eng J* 59:68-74.
- Schwartz J. 2005. Who is sensitive to extremes of temperature? A case-only analysis. *Epidemiology* 16:67-72.
- Scott KI, Simpson JR, McPherson EG. 1999. Effects of tree cover on parking lot microclimate and vehicle emissions. *J Arboriculture* 25:129-142.
- Shonkoff SB, Morello-Frosch R, Pastor M, Sadd J. 2011. The climate gap: environmental health and equity implications of climate change and mitigation policies in California--a review of the literature. *Climate Change* 109:S485-S503.
- Stathopoulou M, Synnefa A, Cartalis C, Santamouris M, Karlessi T, Akbari, H. 2009. A surface heat island study of Athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials. *Int J Sust Energy* 28:59-76.
- Troy AR, Grove JM, O'Neil-Dunne JPM, Pickett STA, Cadenasso ML. 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. *Environ Manage* 40:394-412.
- Uejio CK, Wilhelmi OV, Golden JS, Mills DM, Gulino SP, Samenow JP. 2011. Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health & Place* 17:498-507.
- US Census Bureau. 2001. Census 2000 Summary File 1 Technical Documentation. Available: <http://www.census.gov/prod/cen2000/doc/sf1.pdf> [Accessed 19 April 2013].
- US Census Bureau. 2002. Census 2000 Summary File 3 Technical Documentation. Available: <http://www.census.gov/prod/cen2000/doc/sf3.pdf> [Accessed 19 April 2013].

- US Census Bureau. 2004. Metropolitan and Micropolitan Statistical Areas and Components, December 2003, with Codes. Available: <http://www.census.gov/population/metro/files/lists/2003/0312mfips.txt> [Accessed 1 October 2012].
- US Census Bureau. 2010. 2010 TIGER/Line[®] Shapefiles Technical Documentaion. Available: <http://www.census.gov/geo/www/tiger/tgrshp2010/TGRSHP10SF1.pdf> [Accessed 19 April 2013].
- US Environmental Protection Agency. 2011. Reducing Urban Heat Islands: Compendium of Strategies. Available: <http://www.epa.gov/heatisland/resources/compendium.htm> [Accessed 2012 Jan 30].
- US Department of Agriculture, Natural Resources Conservation Service, Geospatial Data Gateway. Available: <http://datagateway.nrcs.usda.gov/> [Accessed 15 September 2011].
- Weisskopf MG, Anderson HA, Foldy S, Hanrahan LP, Blair K, Török TJ, et al. 2002. Heat wave morbidity and mortality, Milwaukee, Wis, 1999 vs 1995: an improved response? *Am J Public Health* 92:830-833.
- Weng Q, Lu D. 2008. A sub-pixel analysis of urbanization effect on land surface temperature and its interplay with impervious surface and vegetation coverage in Indianapolis, United States. *Int J Appl Earth Obs Geoinfo* 10:68-83.
- Whitman S, Good G, Donoghue ER, Benbow N, Shou W, Mou S. 1997. Mortality in Chicago attributed to the July 1995 heat wave. *Am J Public Health* 87:1515-1518.
- Yuan F, Bauer ME. 2007. Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. *Remote Sens Environ* 106:375-386.
- Zhang Y, Hussain A, Deng J, Letson N. 2007. Public attitudes toward urban trees and supporting urban tree programs. 2007. *Environ Behav* 39:797-814.
- Zhang Y, Tarrant MA, Green GT. 2008. The importance of differentiating urban and rural phenomena in examining the unequal distribution of locally desirable land. *J Environ Manage* 88:1314-1319.
- Zhang K, Oswald EM, Brown DG, Brines SJ, Gronlund CJ, White-Newsome JL, et al. 2011. Geostatistical exploration of spatial variation of summertime temperatures in the Detroit metropolitan region. *Environ Res* 111:1046-1053.

Table 1. Proportion of urban residents living in areas with no tree canopy, high proportions of impervious surface, and both conditions, by race/ethnicity, segregation, housing tenure and poverty.

Characteristic	total population ^a		no tree canopy	over 50% impervious surface	both conditions
	n	%			
Total population	81,517,417	100.0%	42.1%	62.2%	36.5%
0.13<D _m <0.40 (97 CBSAs)	7,168,971	8.8%	15.2%	54.9%	10.5%
0.40<=D _m <0.50 (105 CBSAs)	17,696,848	21.7%	40.7%	54.9%	33.9%
0.50<=D _m <0.60 (78 CBSAs)	28,334,868	34.8%	52.4%	60.5%	43.0%
0.60<=D _m <0.76 (24 CBSAs)	28,326,730	34.7%	38.9%	69.2%	37.7%
Hispanics	21,360,877	26.2%	56.8%	72.3%	49.8%
-					
Asians	5,555,510	6.8%	58.8%	76.5%	53.7%
blacks	15,343,325	18.8%	34.2%	61.8%	31.1%
whites	39,257,705	48.2%	34.4%	54.0%	28.6%
rented housing units	39,409,709	48.3%	46.2%	72.0%	42.4%
owner-occupied	42,117,708	51.7%	37.9%	52.2%	30.6%
under poverty	14,038,788	17.2%	46.1%	68.7%	41.3%
near poverty	16,283,421	20.0%	44.8%	65.4%	39.4%
at least twice poverty level	51,205,208	62.8%	39.8%	58.7%	34.0%

^a81,517,417 individuals in 63,436 block groups in 304 metropolitan areas.

Table 2. Estimated prevalence ratios and 95% confidence limits for no tree canopy and at least 50% impervious surface, by race/ethnicity and multigroup dissimilarity index (D_m).

	Model 1 ^a	Model 2 ^b	Model 3 ^c	Model 4 ^d
whites	1.00	1.00	1.00	1.00
per 0.10 D_m , among whites	1.12 (1.10, 1.13)	1.34 (1.30, 1.38)	1.37 (1.33, 1.41)	1.00 (0.96, 1.04)
blacks relative to whites	2.31 (2.09, 2.55)	1.52 (1.37, 1.69)	1.49 (1.34, 1.65)	1.55 (1.39, 1.73)
per 0.10 D_m , among blacks	0.98 (0.96, 1.00)	1.27 (1.23, 1.30)	1.29 (1.25, 1.32)	0.92 (0.88, 0.95)
Asians relative to whites	2.05 (1.84, 2.27)	1.32 (1.18, 1.47)	1.39 (1.24, 1.54)	1.22 (1.11, 1.35)
per 0.10 D_m , among Asians	1.05 (1.03, 1.07)	1.33 (1.29, 1.37)	1.34 (1.30, 1.38)	0.98 (0.94, 1.02)
Hispanics relative to whites	2.00 (1.84, 2.18)	1.21 (1.08, 1.35)	1.23 (1.10, 1.37)	1.42 (1.28, 1.58)
per 0.10 D_m , among Hispanics	1.06 (1.04, 1.08)	1.37 (1.32, 1.41)	1.38 (1.33, 1.42)	0.95 (0.91, 0.99)

^aModel 1 contains terms for race/ethnicity, and the interaction between race/ethnicity and segregation.

^bModel 1 plus Level I Omernik ecoregion; average annual rainfall (under 10", 10"-19", 20"-29", 30"-39", 40"-49", 50" and greater); and average rainfall in driest month (0", under 1", 1" to 2", 2" to 3", 3" and greater).

^cModel 2 plus owner-occupied vs. rented housing units; household income under poverty, between poverty and 2x poverty, or at least twice poverty level.

^dModel 2 plus block group population density (2,000-3,999/km², 4,000-5,999/km², 6,000-7,999/km², 8,000-11,999/km², 12,000/km² and higher); CBSA population size (100,000-249,999, 250,000-499,999, 500,000-999,999, 1,000,000-2,499,999, 2,500,000-4,999,999, 5,000,000 and higher).

Figure legend

Figure 1. Graphical representation of method for assessing heat risk-related land cover (HRRLC) characteristics. (A) Four blocks constituting one block group. (B) National Land Cover Database tree canopy overlay. (C) National Land Cover Dataset impervious surface overlay.

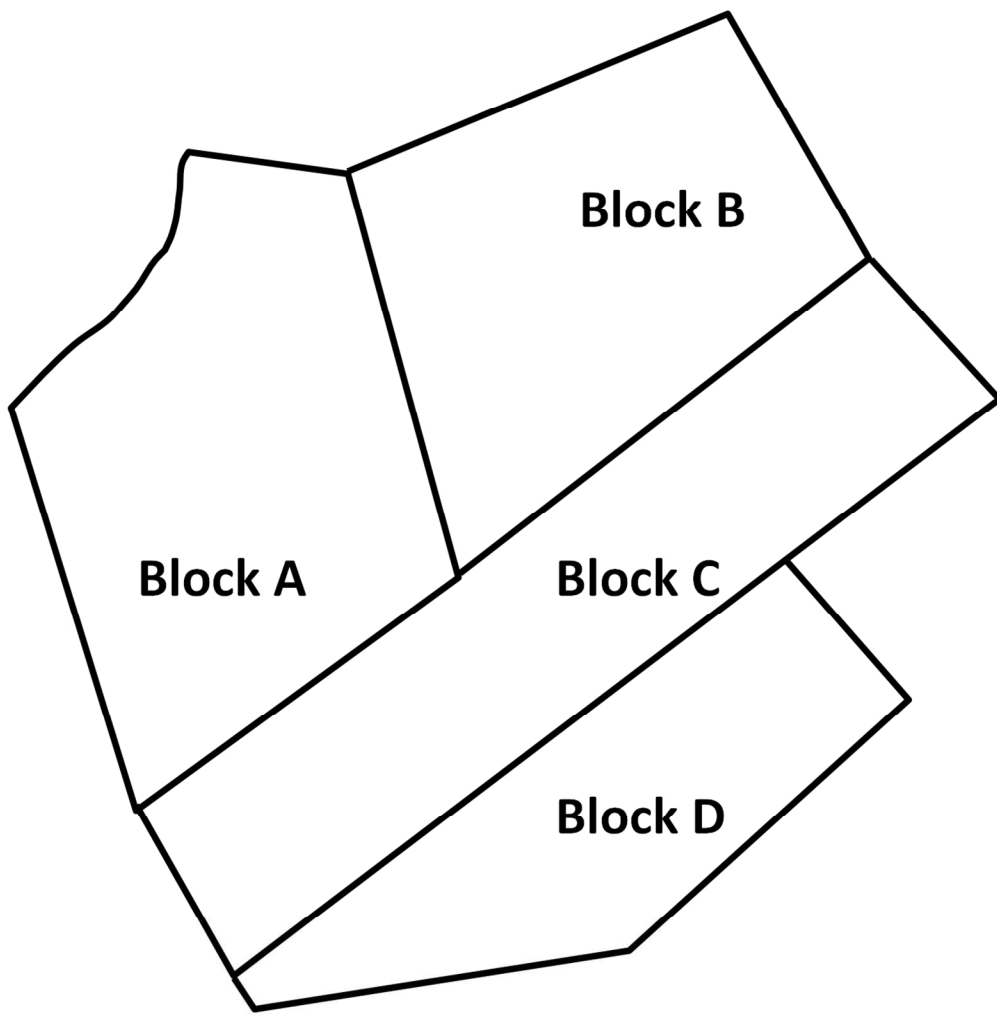


Figure 1A

368x371mm (96 x 96 DPI)

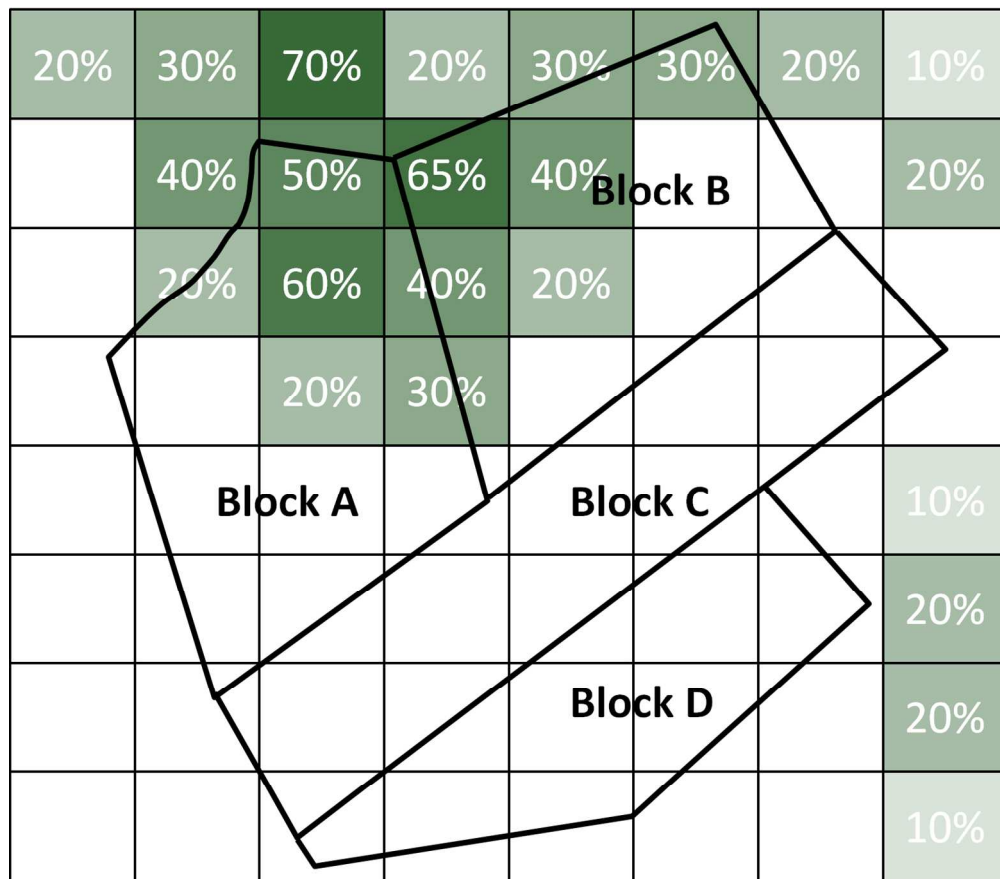


Figure 1B
434x380mm (96 x 96 DPI)

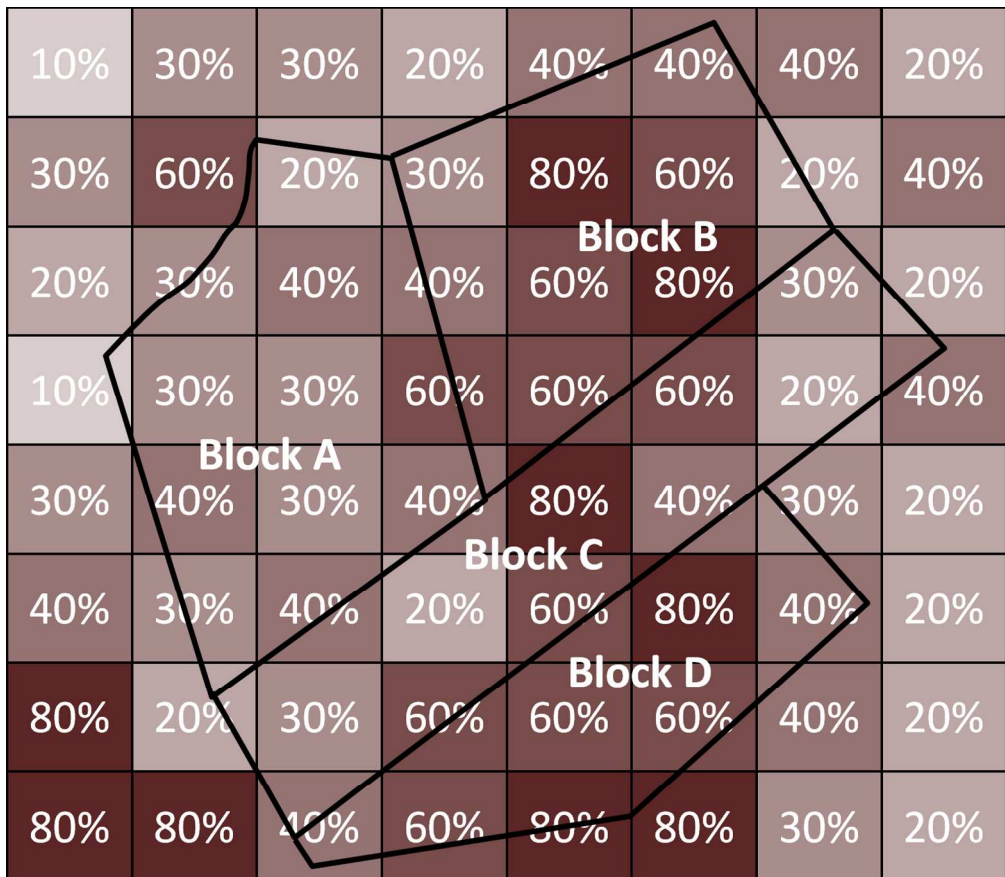


Figure 1C
434x379mm (96 x 96 DPI)