Environmental Science & Technology

Article

pubs.acs.org/est

Climate Change Adaptation Through Urban Heat Management in Atlanta, Georgia

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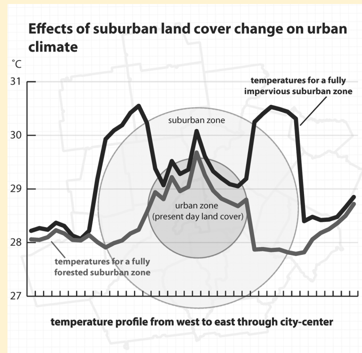
ABSTRACT: This study explores the potential effectiveness of metropolitan land cover change as a climate change adaptation strategy for managing rising temperatures in a large and rapidly warming metropolitan region of the United States. Through the integration of a mesoscale meteorological model with estimated land cover data for the Atlanta, Georgia region in 2010, this study quantifies the influence of extensive land cover change at the periphery of a large metropolitan region on temperature within the city center. The first study to directly model a metropolitan scale heat transfer mechanism, we find both enhanced tree canopy and impervious cover in the suburban zones of the Atlanta region to produce statistically significant cooling and warming effects in the urban core. Based on these findings, we conclude that urban heat island management both within and beyond the central developed core of large cities may provide an effective climate change adaptation strategy for large metropolitan regions.



INTRODUCTION

The rapid pace of climate change in large cities is presenting new planning challenges to urban governments confronted with a growing threat to public health and critical infrastructure. Recent work finds that most large U.S. cities are warming at double the rate of the planet as a whole, a trend attributed to rapid growth in the urban heat island phenomenon.[1] Concurrent with this urban warming is an increase in heat wave activity across the most populous cities since the 1960s. All measured characteristics of heat waves in U.S. cities, including the frequency, duration, and intensity of heat waves have increased, while the time elapse to the first annual event has decreased by an average of almost two weeks between the 1960s and 2000s.[2] Concurrent with rising heat wave activity is a growing incidence of heat related health effects among urban populations and more frequent failures of critical infrastructure, such as electrical power generation and transmission systems.[3,4]

Confronted with these trends, many urban governments have revised or developed anew heat wave emergency response plans, as part of broader climate change adaptation strategies. Since the Chicago heat wave of 1995, and more recent heat waves in Europe (2003) and Russia (2010)—events during which tens of thousands of heat related fatalities are estimated to have occurred—emergency response plans developing more robust early warning systems, establishing public cooling centers, and creating directories of high-risk individuals, among other response strategies, have become more widespread.[5]

In this article, we explore the potential for an additional class of climate change adaptation planning—metropolitan land cover changes designed to moderate urban heat island formation—to reduce the extremity of heat in large cities, as opposed to simply responding to extreme heat events once they occur. To do so, we model regional meteorological responses to extensive reforestation and deforestation scenarios throughout the Atlanta, Georgia metropolitan region.

In particular, this article poses a question largely unexplored by the literature on urban climate change adaptation: To what extent do land cover changes outside of the central core of a large metropolitan region influence temperatures within the core itself? Our purpose in examining this question is to assess the extent to which a regional climate change adaptation policy focused on forest conservation and reforestation beyond the municipal boundaries of a city can be undertaken by a region to slow the pace of warming in the city center—in concert with or independent of reforestation strategies undertaken within the municipal area itself. Our findings highlight the potential for a comprehensive heat management strategy, focused on increased forest cover both within and beyond the municipal boundaries of a large U.S. metropolitan region, to significantly reduce warm season temperatures.

THE URBAN HEAT ISLAND

The urban heat island (UHI) effect is a well-documented phenomenon wherein a thermal anomaly exists in urban areas

Received: October 25, 2012
Revised: March 29, 2013
Accepted: June 4, 2013
Published: June 4, 2013

   dx.doi.org/10.1021/es304352e | Environ. Sci. Technol. 2013, 47, 7780−7786

when compared with proximate rural landscapes.[6−8] The UHI is created by alterations to the surface energy balance that, in combination with waste heat from buildings and vehicles, are the result of land cover conversions that replace natural vegetated land covers with anthropogenic surfaces. These conversions have three important effects on energy in cites. First, they decrease through reduced absorption and enhanced runoff the amount of water available to provide evaporative cooling. Second, replacement materials—often asphalt and concrete—absorb more incoming solar energy due to decreased reflectance and release energy as heat slowly well into the night. Finally, urban morphology decreases turbulent airflows and increases the surface area for the absorption and emittance of long wave radiation. This work models the first two of these three conversions—altered vegetative and mineral-based land cover materials—to assess the intraregional consequences of large scale land cover change.

The enhanced warming associated with urban heat islands entails direct implications for a range of environmental, economic, and health-related outcomes in cities and is large enough to warrant a management response from urban governments. The magnitude of the heat island has been estimated to be in the range of less than 1 °C to over 8 °C in cities around the world.[9,10,24] While site-specific measurements of heat islands tend to vary greatly, larger data sets can describe urban and rural trends more generally. Warming attributable to land cover change in large cities has been found to be equivalent to that from other anthropogenic climate forcings,[1,11] with decadal trends in UHI growth measured to be around 0.05 °C.[12,13] Others studies attribute about half of the observed warming over the past half century to urban land cover changes.[14,15]

Modeling studies focused on heat island mitigation demonstrate the potential for significant reductions in localized warming to be achieved through extensive tree planting. One such study focused on Los Angeles, California found the simulated planting of 11 million trees throughout the metropolitan region to reduce summer afternoon temperatures by 1.5 °C, accounting for roughly half of the region's average afternoon heat island at the time of the study.[16] When modeled in concert with city-wide albedo enhancement strategies, such as the installation of cool roofing materials, tree planting strategies have been shown to reduce heat island intensity across the largest U.S. cities by between 25 and 75%.[17]

While numerous studies have been conducted to date on the potential for reforestation to moderate local temperatures, focused on both urban and rural environments, few studies have examined the intraregional climatic effects of reforestation. Characterized across larger, typically hemispheric scales as "teleconnections", a number of studies have addressed the potential for surface changes in one region of the planet to influence climate in another. For example, Pielke et al. (2002) summarize evidence of geographically distant changes in cloud formation and precipitation in response to tropical land cover change.[18]

The potential for a similar intraregional climatic effect at the metropolitan scale is significant for cities interested in moderating the urban heat island effect as an urban climate adaptation strategy. Due to the fact that most of the available land for extensive reforestation is found at the periphery of heavily urbanized downtown cores, as opposed to within city centers themselves, reforestation efforts targeted to lower density, suburban zones will be less costly to urban governments than greening efforts in the urban core. In addition, these peripheral suburban areas are typically experiencing the most rapid rate of tree canopy loss in large metropolitan areas of the United States.[19]

To date, very little work has sought to quantify the relative climatic benefits of reforestation strategies undertaken in the urban and suburban zones of large metropolitan regions. In exploring the influence of urban morphology on heat island formation, Golany (1996) posits that land cover changes peripheral to the urban core may influence center-city climates, where temperatures are maximized, through regional wind patterns.[20] Yet neither Golany nor any subsequent authors, to our knowledge, are able to demonstrate the existence of such intraregional energy exchanges or their potential magnitude.

In recognition of the growing need for cities to manage rising temperatures, we explore three questions through this study related to urban reforestation as a climate change adaptation strategy. First, how effective is extensive reforestation within the urban core of a major U.S. metropolitan region in moderating warm season temperatures within the city-center itself? Second, how effective is extensive reforestation within adjacent suburban zones in moderating warm season temperatures in the urban core of Atlanta? Finally, what are the relative climatic effects of continuing extensive deforestation within and around the urban core of Atlanta?

■ STUDY APPROACH

As noted above, the purpose of this study is to gain an understanding of the benefits of metropolitan scale "greening" strategies for moderating the pace of warming in urban areas. To accomplish this, we assess several hypothetical land cover scenarios in the Atlanta metropolitan region during the summer of 2010. Each scenario involves the uniform replacement of existing (base case) land cover with forested or impervious materials for a portion of the Atlanta metro area. The modeling exercises were conducted using the Weather Research and Forecasting (WRF) mesoscale meteorological model. The results of the model runs from each scenario are evaluated to determine the impact of regional heat island mitigation strategies on city-center temperatures throughout the month of July 2010.

Land cover within the 20-county Atlanta Metropolitan Statistical Area (2000) was derived from the National Land Cover Dataset (NLCD), a land cover database compiled from satellite data by a consortium of federal agencies.[21] As a component part of a related project focused on multidecadal land cover change and climate trends, we associate land cover changes measured in the NLCD between 1992 and 2001 with population growth at the census tract level and then project such changes forward based on observed and anticipated population growth. In this study, we make use of the resulting land cover estimates for 2010. Seven general classes of land cover were used to describe the 2010 base case for the 20-county area at the scale of the census tract, including open water, developed land, forest, barren, grassland/shrub, agriculture, and wetlands.

Scenarios. To simulate the effects of metropolitan land cover change on urban temperatures, the Atlanta metro area was divided into two distinct zones using radii of 24 and 48 km from the central business district—linear distances roughly corresponding with the size of the municipal area. The "center" section of the region is approximately 1800 km^2 and contains slightly more than 36% of the region's population. Surrounding the urban center is a suburban "ring" spanning from 24 to 48 km outside the city center and accounting for about 50% of the total metropolitan population. Figure 1 illustrates the three zones included in the scenario modeling: (1) the urban center; (2) the suburban ring; and (3) an exurban zone extending beyond 48 km of the city center.

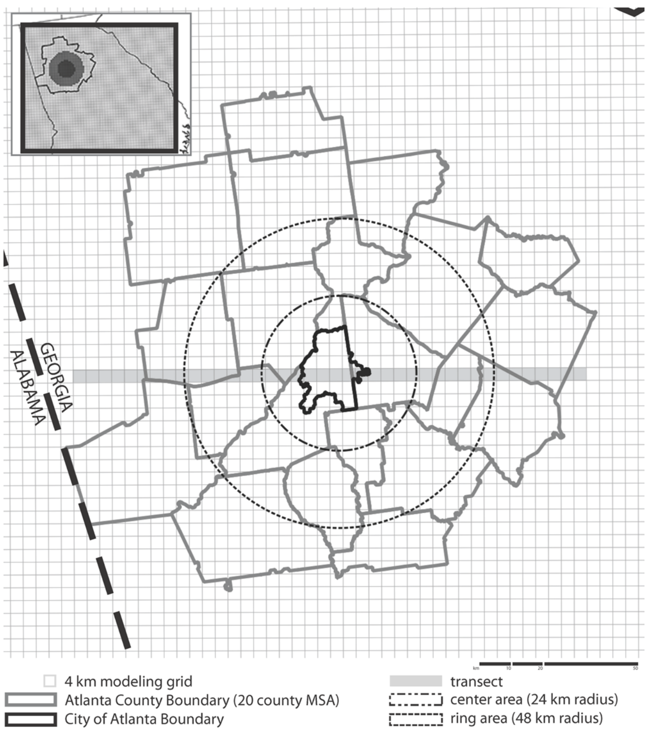


Figure 1. Schematic of the study area domains.

Land cover change scenarios are simulated by holding 2010 land cover fixed under the base case scenario or by fully substituting the base case land cover in the center and ring zones with one of two alternative land covers: forest and asphalt. These surface materials represent two extremes with respect to potential land cover influences on climate—one theoretically associated with a cooling effect and the other with a warming effect. The forested and asphalt substitutions are taken to represent the most extreme land cover conditions attainable across the region in response to heat management policies. Alternating the center and ring zones with base case, fully forested, or fully impervious land cover types allows for the construction of nine potential scenarios. All scenario combinations will be evaluated with respect to their effects on temperatures in the city center zone only—the zone in which the urban heat island effect is maximized.

WRF Setup. Meteorological modeling was performed using the WRF model with three nesting domains of 36, 12, and 4 km^2 grid-spacing, respectively. Initial conditions were set with the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset for the month of July 2010, with a one day spin-up period. The final 4 km modeling domain (shown in Figure 1) consists of 8715 grid cells. The base case land cover inputs for the Atlanta region were derived at the census tract level and assigned to the 4 km grid dimension using spatial weighting.

Energetic parameters of different land cover types were supplied by the default WRF land surface model. This set of parameters provides characteristics including albedo, soil moisture, surface roughness height, leaf area index, and surface emissivity, among other parameters. The "deciduous broadleaf forest" class was used for simulating zonal reforestation in the scenario modeling. A separate "asphalt" land cover class was created to represent complete zonal imperviousness. Roughness height for the new impervious class came from WRF's default "urban and built-up land" class. Factors for the albedo, emissivity, specific heat, and soil moisture availability of the "asphalt" category were obtained from previous work modeling surface temperatures over asphalt and concrete.[22,23]

Models of each scenario were run for the entire month of July 2010. Results were aggregated to produce hourly average 2m temperatures over the month and then compared to regional observations from the Research Data Archive maintained by the National Center for Atmospheric Research. Using a commonly employed index of agreement (IOA), we found a high level of correspondence throughout the modeling domain between simulated and observed temperatures (mean IOA = 0.9, with 1 indicative of perfect agreement over the modeling period). Temperatures for the grid cells in the urban center and suburban ring zones were averaged and compared between scenarios at 5 am, 1 pm, and 7 pm. Times were selected to capture differences in solar incidence and heat retention in the urban heat island. In addition, temperatures across a single west-to-east "transect" of grid cells were measured to analyze intrazonal temperature distributions (Figure 1).

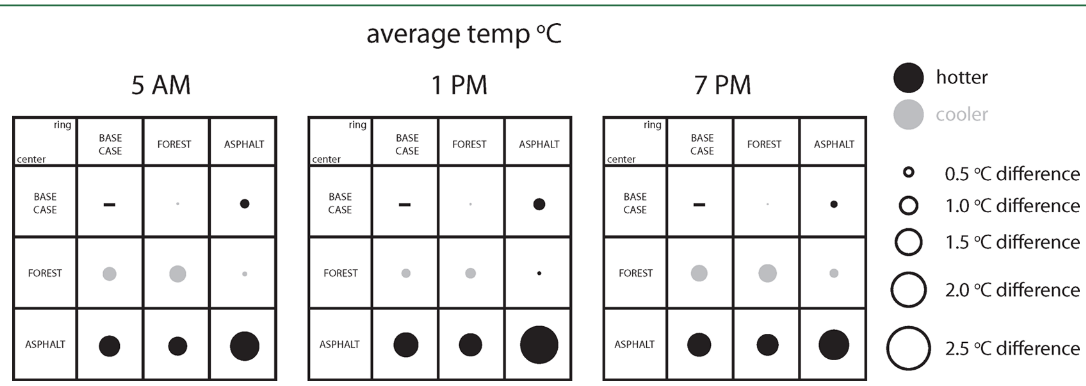


Figure 2. Differences in urban center temperature between scenarios.

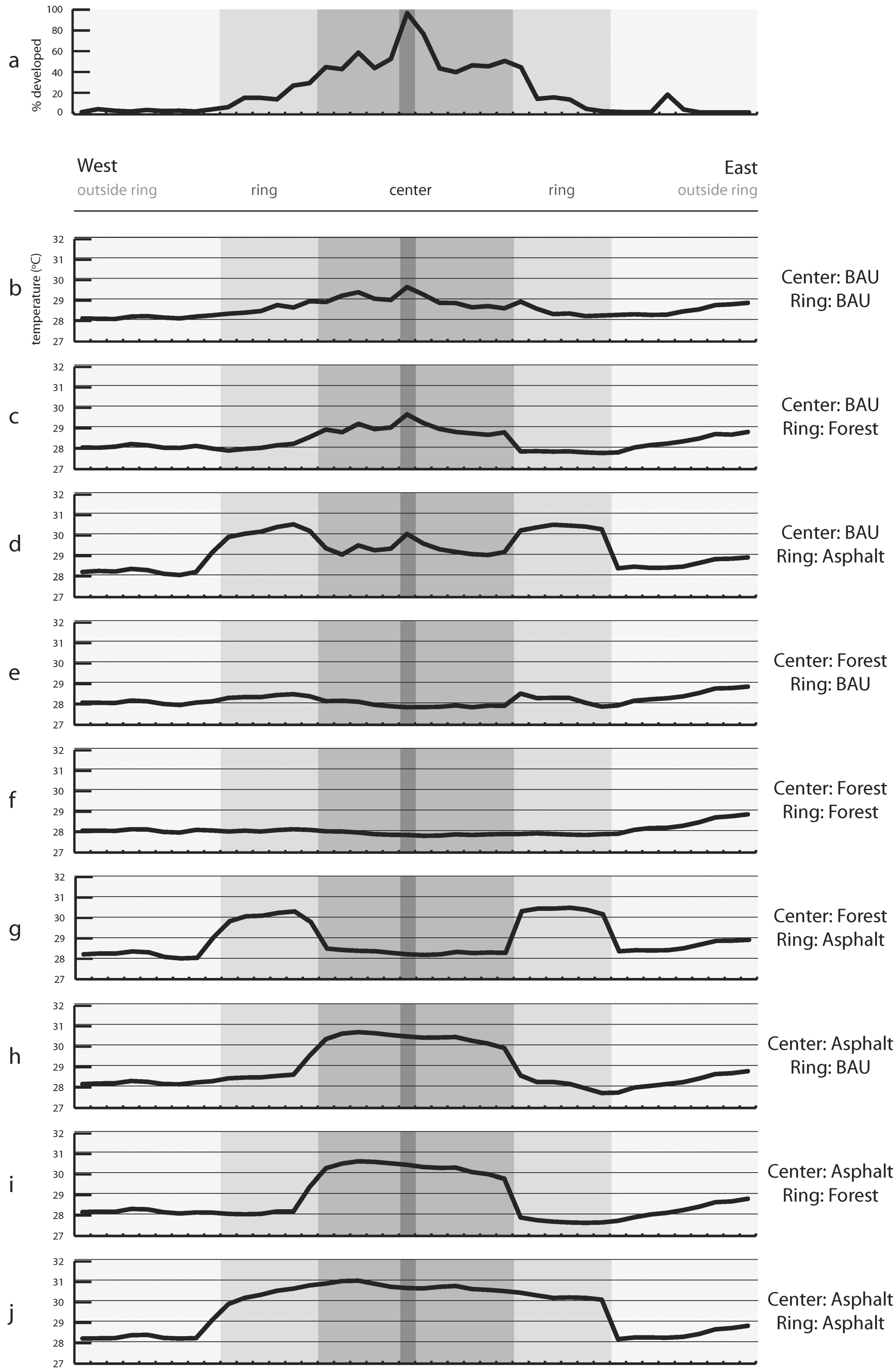


Figure 3. Evening (7 PM) Temperatures across a horizontal transect. Note: Horizontal axis divisions correspond to 4km model resolution.

■ RESULTS

The results of the WRF modeling process are reported as both zonal averages (center vs ring) and as a regional transect. For the zonal analysis (Figure 2), the average temperature changes resulting from various combinations of the reforestation and impervious land cover scenarios are reported in separate scenario matrices for the three modeled time periods: early morning, early afternoon, and early evening. In each cell of a time-of-day matrix, the change in average monthly temperature for July relative to the base case scenario is reported for the various ring and center zone land cover changes corresponding to the selected row and column of the matrix. All changes in average July temperatures are reported for the center zone only, as we are interested in the impact of heat mitigation strategies undertaken in any part of a metropolitan region on urban center temperatures, where the heat island is most consistently maximized.

We first consider how center area temperatures are impacted by land cover changes within the central zone itself. Consistent with both theoretical and measurement studies of the urban heat island, a transitioning from base case conditions in the central zone to complete impervious cover is found to increase center area temperatures at all time periods and under all ring scenario combinations, including a base case, fully forested, and fully impervious ring zone. The greatest magnitude effects of a transition to center imperviousness are found to occur in the early afternoon, although the changes in early evening temperatures across the various scenario combinations are only marginally smaller, on average. As to be expected, the greatest shift in temperatures is brought about from a combination of impervious cover in both the center and ring zones, resulting in a change in average July temperatures of 2.3 °C ($p < 0.0001$) in the early afternoon.

In direct contrast to impervious land cover, a transition to a fully forested center is found to lower average July temperatures across all ring scenarios in the early morning and early evening time periods. The magnitude effects of reforestation are found to be consistently lower than those of full imperviousness, resulting in a maximum cooling effect of 1.1 °C ($p < 0.0001$). This lower magnitude effect can be linked to the less extensive land cover changes resulting from the reforestation scenarios; given that the central zone is 46% forested under the base case and only 22% impervious, a transition to a fully forested center changes less total area than a transition to full impervious cover. As a result, we expect the impacts of reforestation to be greater in less heavily forested urbanized areas.

An important exception to the finding that central zone reforestation lowers average July temperatures is the instance of central zone forestation combined with ring zone imperviousness in the early afternoon. As illustrated in the middle matrix of Figure 2, a transition to full impervious cover around the periphery of Atlanta's central zone has the effect of raising center-city temperatures, even when combined with a full reforestation of the central zone itself. This finding suggests that when insolation is maximized in early afternoon, the advecting heat from peripheral zones can overwhelm the cooling effects of heat mitigation strategies in the center city.

Further evidence of a regional heat transfer mechanism is provided by the effects of land cover transitions in the ring zone on base case center area temperatures. While the magnitude of effect is small—ranging from a 0.10–0.15 °C temperature reduction—a transition to full forest cover around the urban periphery is found to produce in all time periods a statistically significant cooling effect ($p < 0.01$) in center area temperatures when combined with base case land cover conditions in the center area. Likewise, a transition to a fully impervious ring zone when combined with a base case center is found to increase center area temperatures across all time periods—a statistically significant warming effect ranging from 0.4 to 0.7 °C ($p < 0.001$). These findings support our central hypothesis: center-city heat island intensity is directly influenced by suburban land cover conditions.

Transect Analysis. The preceding analysis of average temperature differences between suburban and urban zones of Atlanta illustrates well how land cover change can influence heat island formation across major land cover divisions of a metropolitan region. Two additional sets of questions require a more highly resolved analysis to address: (1) How does land cover change alter the distribution of temperature within urban and suburban zones? (2) How rapidly do temperatures change when moving from one distinct land cover zone to another? To address these questions, we plot a 168 km temperature transect running west to east across the central business district of Atlanta, reporting average temperatures at a spatial resolution of 4 km (shown in Figure 2). As illustrated in the top panel of Figure 3 (panel a), such a transect analysis captures a wide diversity of development intensity. A west-to-east orientation is used to minimize elevation changes across the study area.

The transect analysis reveals relatively little spatial change in temperatures within the urban and suburban zones under base case conditions (panel b in Figure 3). Despite a substantial change in the percentage of each transect grid cell occupied by developed land covers under the base case scenario—ranging from 40 to almost 100% across the center zone (see panel a)—grid cell temperatures only vary within a range of roughly 1 °C under this scenario across the central city. As to be expected, this range diminishes further in response to the spatially uniform forestation and imperviousness scenarios. The relatively narrow range in temperature within zones is likely a product of the 4 km spatial resolution of the analysis, which serves to smooth the temperature distribution relative to the point location measurements of in situ measurements.

The transect analysis illustrates the potential for rapid transitions in temperature to occur over relatively small distances in response to extensive land cover change. While panel b in Figure 3, corresponding to base case conditions, shows a gradual rise and fall in average temperatures at transition points between suburban and urban zones, sharper transitions are revealed as suburban or urban zones are modeled as fully impervious (panels d, g, h, i, and j). Likewise, increased forest cover along the transect is associated with more rapid spatial changes in temperature at transition points than the base case scenario, with the exception of fully forested center and ring zones (panel f).

The transect temperatures further illustrate how land cover changes peripheral to the central zone of the city can influence climate in the downtown district, independent of land cover changes within the zone itself. For example, a transition to fully impervious suburban zones in combination with a base case center has the effect of raising city-center temperatures at all points along the transect in the urban zone, pushing the maximum temperature above 30 °C (panel d). A transition to fully forested suburban zones likewise lowers BAU center temperatures at all points along the transect (panel c); however, the magnitude of these changes remains small.

DISCUSSION

The study results are suggestive of several important policy directions for climate change adaptation in cities with climates similar to the Atlanta region. Chief among these is further confirmation of the potential for extensive land cover change within downtown districts to significantly reduce urban heat island formation. As demonstrated in previous modeling studies,[17] urban reforestation in naturally forested regions carries the potential to significantly offset elevated temperatures in downtown districts. As illustrated in panel e of Figure 3, a transition to a fully forested urban center brings temperatures along the transect in line with those exhibited far outside the city center under base case conditions. While a reversion to full forest cover in an urban environment is not possible, increased forest cover in combination with other greening strategies, such as green roofs, carries the potential to significantly increase total green cover in urbanized areas, with resulting benefits for heat management.

Novel to the literature on heat island mitigation, and urban heat management more generally, are the demonstrated impacts of suburban land cover changes for city-center climate. While the magnitude of modeled changes was found to be modest, a transition to full forest or impervious cover in suburban zones of the Atlanta study area, holding land cover conditions in the core itself unchanged, was found to significantly influence temperatures in the center-city zone.

This is a key finding for climate management policy in cities in that it demonstrates the heat island phenomenon to be responsive to metropolitan scale land cover conditions and thus is suggestive of the need for regionally coordinated policies. Consistent with most large U.S. cities, the vast majority of land cover change in the Atlanta metropolitan region in recent decades has occurred outside of the central-city core. Yet, despite this growth pattern, temperatures in the core have continued to increase at a higher pace than rural areas beyond the urbanized zone, resulting in rapid growth in the city-center heat island in the absence of significant land use change. Our results suggest a periphery-to-center heat transfer mechanism, similar to that posited by Golany (1996), may be partially responsible for this observed outcome. Such a hypothesis is supported by an analysis of wind field and energy balance data from the WRF simulations, which finds modified windspeeds around the urban center and evidence of advection driven by differences in energy balance partitioning by zone. While higher resolution analysis is needed to accurately characterize the influence of urban morphology and land cover on heat transfer, there is evidence to suggest, at the very least, that continued deforestation outside of urban cores may offset the effectiveness of heat management strategies implemented within the urban core.

Overall, the intensity of heat island formation demonstrated by this study is generally lower than that of observational studies.[24−26] As illustrated in Figure 3 (panel b), the difference in temperatures between the base case city center and the exurban periphery is about 1.5 °C. Interpreted as a proxy for heat island intensity, this modeled intensity is at the low end of the roughly 1−8 °C range observed across a large number of observational studies. A key distinction between this study and previous work concerns the scale and timing of heat island measurement. In contrast to the point location temperature measurements of observational studies, the mesoscale meteorological model used in this study averages near surface air temperatures across 4 km resolution grid, serving to smooth the point location extremes across each grid cell. In addition, we measure heat island intensity as a monthly average, as opposed to the more conventional measurement of the maximum daily heat island—a further departure from conventional studies that may account for lower heat island intensity.

Most important from a theoretical perspective is that mesoscale meteorological models such as WRF are not well designed to capture anthropogenic heat emissions across heterogeneous urban surfaces. Found in previous work to account for 30% or more of heat island intensity in downtown districts,[24,27] anthropogenic heat is an important component of heat island formation that, while often omitted from modeling studies, is captured in observational studies. However, given our focus on the land cover drivers of heat island formation alone, the omission of anthropogenic heat from our analysis holds only limited implications for our findings.

In conclusion, the results of this study are suggestive of the potential for land cover change to play a measurable role in moderating the extremity of heat in urbanized regions. While the average heat island intensity measured by this study is lower than most observational studies, the extent to which modeled land cover change within and outside of the central urban zone of Atlanta influences the heat island is substantial. A transition to a fully forested center creates a negative heat island (i.e., center-city temperatures fall below that of the far periphery), while a transition to a fully impervious center increases heat island intensity by more than 60%. Even land cover changes limited to the urban periphery were found to have a measurable influence on city-center temperatures, with a fully impervious suburban zone found to increase evening base case heat island intensity by more than 22%.

While there is no expectation that a transition to a fully forested landscape within or at the periphery of cities is achievable, these findings highlight the potential for strategic land cover change to moderate the rapid pace of climate change presently underway in large cities. In concert with emergency response plans designed to minimize heat-related illness during heat wave events, investments in heat island mitigation at the metropolitan scale may provide a viable climate change adaptation strategy for cities situated in naturally forested regions.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was supported by the US Centers for Disease Control and Prevention (#1U01EH000432-01).

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