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Land use planning and surface heat island formation: A parcel-based radiation flux approach

Brian Stone[a,*], John M. Norman[b]

[a]City and Regional Planning Program, College of Architecture, Georgia Institute of Technology, Atlanta, GA 30332-0155, USA
[b]Department of Soil Science, University of Wisconsin-Madison, Madison, Wisconsin, 53706, USA

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Abstract

This article presents a study of residential parcel design and surface heat island formation in a major metropolitan region of the southeastern United States. Through the integration of high-resolution multispectral data (10 m) with property tax records for over 100,000 single-family residential parcels in the Atlanta, Georgia, metropolitan region, the influence of the size and material composition of residential land use on an indicator of surface heat island formation is reported. In contrast to previous work on the urban heat island, this study derives a parcel-based indicator of surface warming to permit the impact of land use planning regulations governing the density and design of development on the excess surface flux of heat energy to be measured. The results of this study suggest that the contribution of individual land parcels to regional surface heat island formation could be reduced by approximately 40% through the adoption of specific land use planning policies, such as zoning and subdivision regulations, and with no modifications to the size or albedo of the residential structure.

Keywords: Urban heat island effect; Climate change; Land use; Urban planning; Remote sensing; Surface heat island; Thermal infrared

1. Introduction

Long recognized in the physical sciences as an important climatological phenomenon, the urban heat island effect has only recently gained serious attention in the fields of urban planning and public health. A growing interest in urban temperatures among planners and other social scientists can be attributed to the steadily increasing number of annual heat-related fatalities over the past several decades, which now exceeds the annual mortality rates associated with all other forms of catastrophic weather (National Oceanic and Atmospheric Administration (NOAA), 2000). Also significant to public health is the influence of ambient heat on regional air quality problems. Annual exceedances of the national standard for ground level ozone, for example, have been found to correlate more strongly with ambient temperatures than with annual emissions of ozone precursors (Stone, 2005). The potential for steadily increasing temperatures and air pollution in response to both regional and global climatological mechanisms, coupled with a projected doubling of the global urban population by 2030 (United Nations, 2001, p. 4), greatly elevates the need for planners and

*Corresponding author.

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public health officials to devise effective strategies for managing climate in large cities.

A key question for the field of planning concerns the role of urban spatial structure in the formation of heat islands. While the material composition, form, and configuration of the built environment is known to directly influence the formation of heat islands (Golany, 1996), a consensus regarding the most thermally benign pattern of land development is largely absent from the heat island literature. As demonstrated by a large number of studies, the spatial distribution of urban air temperature maxima appears to correlate strongly with the density of land use, resulting in the classic bell-shaped temperature profile of the monocentric city. Yet, as other studies have shown, lower density patterns of housing are associated with higher per household levels of impervious cover and energy consumption, two important drivers of heat island formation (Stone, 2004; Alberti, 1999). In light of these conflicting observations, should large, mid-latitude cities seek to accommodate future population growth through medium to high density, compact forms, or through lower density, dispersed patterns of development? The answer to this question holds important implications for the practice of urban environmental planning.

To address this issue, this article presents the results of a study of residential parcel design and surface warming patterns in the Atlanta, Georgia, metropolitan region. With the aid of high resolution thermal infrared (IR) imagery and a parcel level geographic information system, the thermal properties of over 100,000 single-family parcels are associated with the spatial structure and material composition of residential development throughout a 900 km^2 study region. In measuring the thermal properties of individual land parcels, we develop an "emissivity adjusted" indicator of the parcel black body flux to account for the influence of variable surface emissivity and sky radiation captured in the thermal IR imagery. Furthermore, we estimate the predevelopment radiant flux and subtract this quantity from the observed, post-development radiant flux to differentiate the warming impacts of urban development from natural, background sources of surface heat. Following a detailed description of our methods and results, the article concludes with a discussion of physical planning strategies designed to mitigate the thermal impacts of existing and future residential development in the Atlanta region and elsewhere.

2. Background

In order to associate remotely sensed thermal IR data with land use planning policies it is essential that a "policy-relevant" indicator of surface warming be developed. While remote sensing technologies can provide a valuable tool for assessing the thermal performance of urban environments, these must be used with great caution to yield reliable information for land use planning. Most importantly, there is a critical need to isolate the influence of specific classes of land use on surface warming patterns. While previous work has demonstrated a clear distinction between the thermal properties of "urban" and "rural" land cover types, each of these broad categories of development is composed of a number of specific land use classes that are subject to an array of development regulations. If we are to mitigate heat island formation through the modification of specific zoning and subdivision regulations, we must be able to isolate the influence of these individual policies on surface warming. To be policy-relevant, an indicator of surface warming must be capable of quantifying the thermal characteristics of distinct and legally defined classes of land use.

In this section of the paper, we discuss three criteria that must be satisfied to derive a policy-relevant measure of heat island formation. These include: (1) the measurement of surface warming at the level of the individual land parcel; (2) the adoption of a flux-based rather than a temperature-based indicator to capture the effects of land area on warming; and (3) the adjustment of the radiant flux to more closely correspond to the sensible flux of heat.

2.1. Measuring thermal performance at the parcel level

In assessing the surface thermal properties of urban and rural land covers, many studies have adopted a unit of analysis consistent with the resolving dimension of a satellite radiometer, such as 1.1 km or 120 m (e.g., Roth et al., 1989; Nichol, 1996). An important limitation of adopting such a spatially uniform unit of analysis, however, is that it fails to conform to the irregularly shaped boundaries of individual land parcels, the unit of area at which land use is controlled. For example, in dense and well-mixed urban districts, a spatially uniform unit of analysis is likely to capture both commercial and residential land uses, confounding any attempt to isolate the thermal properties of a single land use class. Such an outcome may be categorized as a special instance of mixed pixel error—mixed, that is, in terms of land use class rather than land cover type.

The limitation of this type of mixed pixel error for planning analysis is that it obscures the underlying policy drivers of environmental performance. If we are interested in evaluating the environmental impacts of a particular planning policy, such as maximum impervious area regulations, we must first identify those zones subject to the policy. For example, within a square kilometer of urban land there is likely to be a number of unique land use classes, each with its own zoning regulations governing the permissible area of impervious cover per parcel. In measuring the environmental characteristics of an area of land subject to multiple zoning regulations, it is difficult to assess the relative influence of any single policy on environmental performance. For the purposes of planning research, a more methodologically sound approach entails the measurement of surface warming at a dimension compatible with land use regulation, such as a zoning district or individual land parcel. As adopted herein, a parcel-based approach to surface warming analysis permits parcel-specific land use policies, such as zoning regulations, subdivision regulations, and building codes, to be associated with thermal performance at the same spatial dimension.

2.2. Accounting for the effects of land area on surface warming

While parcel-based measures of surface warming are needed to associate heat island formation with land use policies, the adoption of a spatially irregular unit of analysis complicates the use of surface temperature as an indicator of warming. As noted by Price (1979) over 25 years ago, temperature-based measurements, such as the urban–rural temperature differential, often fail to reflect the magnitude of heat islands created by urban areas of different sizes. Price states, "[f]or investigation of urban heating, the peak temperature is less significant than a summation (area integral) of the excess power radiated as a result of the surface temperature elevation" (p. 1557). In other words, a measure of the excess flux of thermal energy from a city provides a more accurate indicator of the total magnitude of warming within an urbanized area than does the urban–rural temperature differential.

We believe the *magnitude* of surface warming between urban and rural zones (defined herein as the excess flux of sensible heat energy) to be more relevant to urban planning policy than heat island *intensity* (the urban–rural temperature differential). The reason for this is that the area-integrated flux of heat energy emitted from a city or parcel provides a more accurate indicator of the volume of the near surface atmosphere influenced by elevated surface temperatures than does the surface temperature differential. In this sense, two cities of similar climate and development type but dissimilar land area are likely to exhibit similar average surface temperatures but different fluxes of energy. As the area of a city expands, the volume of the heat island "dome"—a volume subject to elevated air temperatures and enhanced pollution formation—expands as well. Measures of heat island intensity across cities may not reflect a differential in the volume of heat island domes. While smaller in scale, the same is true when comparing two parcels of different area.

The significance of heat island magnitude to planning policy is clearly illustrated through Price's analysis of heat island formation in a number of New England cities. Through an analysis of thermal IR imagery collected by the Heat Capacity Mapping Mission satellite, the thermal impacts of city size were found to vary substantially based on the indicator of thermal performance selected. As detailed in Table 1, the urban–rural temperature differential and a measure of the excess radiant flux, the "excess power radiated," were found to vary significantly based on city size. For example, while the urban–rural surface temperature differentials for Syracuse, New York, and Waterbury, Connecticut, were found to be equivalent, the quantity of excess radiant energy emitted from Syracuse was found to be over five times greater than that from Waterbury.

Defined by Price as the excess radiant energy (in megawatts) emitted from a city as a product of the urban–rural temperature differential and urban land area, the excess power radiated measure accounts for both the intensity of warming and the area of land impacted by elevated surface temperatures. As the land area of Syracuse is many times greater than that of Waterbury, the total flux of excess radiant energy across this area is greater as well, increasing the spatial magnitude of warming.

Table 1
Population, area, and thermal characteristics for ten New England Cities (adapted from Price (1979))

City	1970 population (× 1000)	Area (km^2)	Population density (km^2)	ΔT (°C)	Excess power radiated (mW)	Excess power radiated per capita (kW)
New York, NY	7895	547.0	14,433	17.0	40,000	5.07
Syracuse, NY	197	6.5	30,307	10.9	417	2.12
Providence, RI	179	48.2	3714	13.2	3190	17.82
Worcester, MA	177	5.1	34,706	11.5	327	1.85
Hartford, CT	158	26.2	6031	15.0	1770	11.2
Bridgeport, CT	157	14.2	11,056	12.1	954	6.08
New Haven, CT	138	5.8	23,793	11.2	372	2.70
Albany, NY	116	3.7	31,351	10.3	227	1.96
Stamford, CT	109	3.2	34,063	11.2	202	1.85
Waterbury, CT	108	1.2	90,000	10.9	74	0.69

Source: Price (1979, Tables 1 and 2).
Note: The population reported for New York, NY, is for the metropolitan area; all other populations are reported for the municipality. We have corrected a typographical error in the original table, in which the unit of excess power radiated was reported as kW rather than as mW, and we have computed the fields of population density and excess power radiated per capita based on the data reported by Price.

Thus, while the temperature differential of these two cities is equivalent, the total land area in Syracuse exposed to elevated surface temperatures, and, by extension, the total volume of the near surface atmosphere, is many times greater.

In the context of planning research, area-integrated measures of heat island magnitude are needed to illuminate the spatial drivers of regional climate change. The significance of heat island magnitude to planning policy is clear from Price's analysis of population size and surface warming in Syracuse and Waterbury. While the population of Syracuse is about 80% greater than that of Waterbury, its excess power radiated is over 500% greater. Why might this be the case? Once we account for any intra-regional variation in climate or land cover types, an important structural distinction between the two cities is the density of development. With a gross population density of about 900 persons per hectare, Waterbury's population density in 1970 was almost three times that of Syracuse. As a result, the average quantity of land developed to support a single Syracuse resident was three times as great as the per capita land requirements of a resident of Waterbury, potentially translating into a greater magnitude of surface warming per resident. For the ten largest cities examined by Price and presented in Table 1, a significant negative correlation was found between population density and the excess power radiated per capita ($r = -0.65$; $p < .001$). These results support the hypothesis that, when controlling for population size and climate, lower density cities in New England are characterized by a greater surface heat island magnitude than higher density cities.

2.3. Approximating the sensible heat flux

While aerial and satellite radiometers provide the most viable means of obtaining continuous surface thermal data across a large study region, a principal limitation of remote sensing studies of the urban heat island effect is a failure to account for the variable distribution of surface emissivity. Given the wide array of surface material types found in urban areas, ranging from heavily canopied areas to the impervious materials of driveways and rooftops, radiant flux densities recorded by thermal sensors are prone to systematically underestimate thermodynamic temperatures from the heterogeneous surfaces of urban environments. As a result, the surface radiant flux density must be adjusted to more closely approximate the black body flux density, which is a better indicator of sensible heat.

The radiant flux density is a reasonable choice for representing heating of the atmosphere by the urban surface for three reasons: (1) it contributes a portion of the heating itself; (2) it can be expressed as a function of the surface-to-air temperature difference, making it roughly proportional to the sensible heat flux density; and (3) it can be measured at the parcel level through the use of remote sensing. Two measures of the surface radiant flux are commonly used: (1) the apparent radiant flux density, which is measured directly by remote sensing instruments, and (2) the black body radiant flux density, which is adjusted for the surface emissivity and represents a maximum emitted flux density proportional to the thermodynamic temperature of the surface. The black body radiant flux density is more closely related to the thermodynamic temperature than the apparent radiant flux density and thus is likely to be more highly correlated to the surface sensible heat flux density. Therefore, we need to adjust the measurements of apparent radiant flux density from a remote sensing instrument using the surface emissivity. To do so, we employ the following equation:

$$\boldsymbol{\Phi}_{\mathrm{BB}} = \frac{\boldsymbol{\Phi}_{\mathrm{measured}} - [(1-\varepsilon)L_{\mathrm{SKY}}]}{\varepsilon}, \tag{1}$$

where $\boldsymbol{\Phi}_{\mathrm{BB}}$ is the black body flux density, $\boldsymbol{\Phi}_{\mathrm{measured}}$ the apparent flux density, ε the parcel composite emissivity, L_{SKY} the emitted sky radiation.

The emissivity value associated with a particular parcel is based on the proportion of the parcel occupied by impervious and vegetative materials. As demonstrated by Carlson et al. (1995), the fraction of vegetative cover (f_{c}) for a particular land parcel may be estimated through the derivation of a normalized difference vegetation index (NDVI). Once computed, the parcel composite emissivity may be estimated through the following equation:

$$\varepsilon_{\mathrm{c}} = \varepsilon_{\mathrm{v}}(f_{\mathrm{c}}) + \varepsilon_{\mathrm{i}}(1-f_{\mathrm{c}}), \tag{2}$$

where ε_{c} is the parcel composite emissivity, ε_{v} the emissivity of vegetative component, f_{c} the fraction of vegetative cover, ε_{i} the emissivity of impervious component.

As a final step, the quantity of radiant energy attributable to predevelopment land characteristics—the rural "background" radiation—must be subtracted from the measured parcel black body flux. As illustrated by Price's measure of the excess power radiated, in deriving an indicator of the urban heat island effect, we are interested in the thermal *differential* between developed and undeveloped land features. When measuring heat island intensity, this variable is quantified as the temperature differential between developed and undeveloped zones. When measuring heat island magnitude, this variable becomes the flux differential between developed and undeveloped zones. To calculate this flux differential at the parcel level, we first calculate the black body flux density for a developed parcel based on the methods described above, and then subtract from this quantity an estimate of the predevelopment black body flux density that would result were the same parcel occupied by a natural land cover, such as forest canopy cover. We then multiply this flux density differential times the parcel area to estimate the parcel *net black body flux*. Eq. (3) demonstrates this calculation:

$$\mathrm{NF}_{\mathrm{BB}} = A_{\mathrm{parcel}}(\boldsymbol{\Phi}_{\mathrm{BB\ urban\ parcel}} - \boldsymbol{\Phi}_{\mathrm{BB\ rural\ parcel}}), \tag{3}$$

where $\mathrm{NF}_{\mathrm{BB}}$ is the parcel net black body flux, A_{parcel} the parcel area, $\boldsymbol{\Phi}_{\mathrm{BB\,urban\,parcel}}$ the black body flux density of post development parcel, $\boldsymbol{\Phi}_{\mathrm{BB\,rural\,parcel}}$ the black body flux density of predevelopment parcel.

In summary, to be useful in planning research, an indicator of the urban heat island effect must be spatially compatible with the legal dimensions of land use control, and must accurately approximate the quantity of energy contributed by a single land parcel to elevated temperatures within cities. The preceding discussion outlines a conceptual basis for deriving such an indicator. What follows in the remainder of the paper is an application of this conceptual approach to the Atlanta, Georgia, metropolitan region and a presentation of policy insights that may be gleaned from this analysis.

3. Methods

In May of 1997, the National Aeronautic and Space Administration (NASA) obtained high resolution multispectral imagery over the Atlanta, Georgia, metropolitan region for the purpose of investigating the influence of land use on urban heat island formation. Recorded from an aerial platform with the Advanced Thermal and Land Applications Sensor (ATLAS) at a ground resolution of 10 m, 15 channels of multispectral data were obtained over the Atlanta study region by NASA and made available to a range of research efforts known collectively as "Project Atlanta." The exceptionally high spatial resolution of this data permits the thermal characteristics of high-density urban parcels to be reliably measured and integrated into a parcel level geographic information system. With the aid of the Project Atlanta data, three principal steps were carried out to develop an integrated surface warming and land use database for the Atlanta region. These included: (1) data processing, (2) construction of a parcel-based land information system, and (3) derivation of the parcel "net black body flux" measure.

3.1. Data processing

Prior to the analysis, a number of steps were performed to atmospherically correct and spatially rectify the ATLAS data. Collected under mostly clear skies and calm conditions in May 1997, the multispectral imagery required corrections for positional accuracy of the sensor, atmospheric radiance, and georectification. To correct for atmospheric radiance, temperature profiles recorded by radiosondes launched during the period of data collection were used in concert with the MODTRAN3 model to account for the effects of water vapor and other atmospheric constituents on atmospheric radiance. Surface measurements recorded with hand held radiometers were employed in validating the ATLAS observations, and positional data recorded continuously during the flights was used to correct the data for positional changes during the period of data collection. Following these atmospheric corrections, each of the eleven flightlines recorded by NASA was georeferenced to Georgia State Plane coordinates and merged into a single image mosaic. Of the 15 channels of multispec tral data obtained from NASA, three were used in this research: a channel in the red (0.63–0.69 μm), near infra-red (0.76–0.90 μm), and thermal IR (9.6–10.2 μm) regions of the electromagnetic spectrum.

3.2. Deriving the parcel black body flux

The first step in estimating the parcel net black body flux requires that the thermal characteristics of individual land parcels be measured. To do so, parcel boundary information for the approximately 104,000 single-family parcels located in the study region was obtained from the City of Atlanta and Fulton County offices of tax assessment. By registering the multispectral imagery and parcel geography data layers to the same coordinate system, it was possible to spatially overlay the two data sets in a geographic information system. Once integrated, the average apparent radiant flux density of each parcel was derived through a zonal summary function. Given the bandwidth of the thermal IR channel, the apparent radiant flux density ($\boldsymbol{\Phi}_{\text{measured}}$) for a parcel can be derived through an application of Planck's model for a black body radiator:

$$\boldsymbol{\Phi}_{\text{measured}} = \int_{9.6\,\mu\text{m}}^{10.2\,\mu\text{m}} \frac{C_1}{\pi\lambda^5[\exp(C_2/\lambda T)]}\,\mathrm{d}\lambda, \qquad (4)$$

where $C_1 = 3.7404 \times 10^8\,\mathrm{W\,\mu^4 m^{-2}}$, $C_2 = 14,387$, T is temperature in Kelvin.

In addition to the apparent radiant flux density, information on the composite parcel emissivity and emitted sky radiation were required to apply Eq. (1), presented above. Employing the method of Carlson et al. (1995), the fraction of vegetative cover for each land parcel was estimated through the derivation of a NDVI with ATLAS bands in the red and near infra-red spectral regions. Based on published data for vegetative and impervious materials characteristic of residential zones, an emissivity value of 0.97 was assigned to the vegetative component of each parcel and a value of 0.90 was assigned to the impervious component (Jensen 2000; Oke, 1987). The composite parcel emissivity was then calculated with Eq. (2). Radiosondes launched during the period of data collections recorded an average value of 2.26 W m^{-2} for the flux density of emitted sky radiation in the 9.6–10.2 μm wavelength band.

As a final step, the parcel net black body flux was calculated by subtracting an estimate of the predevelopment flux density from the post development flux density, and by then multiplying this quantity times the parcel area in square meters to derive an estimate of the area-integrated flux of excess thermal energy at the parcel level (Eq. (3)). It is important to note that, due to the narrow bandwidth of the thermal channel used for this research, 9.6–10.2 μm, the net black body flux indicator derived for this study does not represent the complete flux of excess radiant energy from the surface. Rather, it serves as an indicator of surface warming that should scale closely with the excess blackbody radiant flux across the full spectrum of wavelengths.

3.3. Constructing a parcel design database

In addition to an indicator of surface warming, information on the physical design attributes of single-family parcels was needed to associate heat island formation with variable residential land use patterns. We are interested in residential land use for several reasons: (1) the majority of the developed land area in the Atlanta region is occupied by this land use class; (2) residential land use tends to

Table 2
Parcel design attributes

Variable	Definition	Hypothesized significance
Area of impervious cover	The area of the parcel occupied by the residential structure, ancillary buildings, or paving materials in m^2.	Positive: increments in impervious cover are associated with an increase the net black body flux.
Area of lawn and landscaping	The area of the parcel occupied by lawn and other forms of surface vegetation in m^2.	Positive: increments in the area of lawn and landscaping are associated with an increase in the net black body flux.
Percent tree canopy cover	The percentage of the parcel overlaid by tree canopy cover.	Negative: increments in tree canopy cover are associated with reductions in the net black body flux.
Number of bedrooms	The number of bedrooms in the residential structure.	Control variable: the number of bedrooms serves as a control for the capacity of the residential structure.

constitute the leading edge of urban expansion; and (3) residential land uses are more suitable for modest design changes than commercial or industrial land uses, which tend to be more strictly governed by their function.

Four parcel design variables were derived for this study. These include the area of impervious materials, such as driveways and building footprints, the area of lawn and landscaping, the proportion of the parcel overlaid by tree canopy, and the number of bedrooms in the residential structure. This final variable is used to control for residential capacity. In short, we are interested in comparing the thermal characteristics of parcels varying in size and material composition but similar in the number of residents the parcel was designed to accommodate. The inclusion of this variable in our analysis ensures that differences in thermal performance by region of the city are not attributable to differences in residential capacity.

Information on the area, footprint size of residential buildings (houses and detached buildings), and number of bedrooms in the residential structure was obtained from the City of Atlanta and Fulton County offices of tax assessment.

As driveway areas are not recorded in the property assessment process, a sample of parcels stratified by age and size was selected to estimate the area of these paved surfaces. The driveways of selected parcels were then measured directly to determine how paved areas scale with parcel size throughout the study region. In combination, the estimated area of driveway paving and the area of the building footprint constitute the impervious component of the parcel. The area of lawn and landscaping was derived by subtracting the estimated impervious area from the total parcel area.

Table 3
Descriptive statistics

Variable	Minimum	Maximum	Mean	Standard deviation
Lot size (m^2)	90	4050	1360	800
Impervious area (m^2)	22	1326	208	63
Lawn area (m^2)	46	3863	1152	758
Tree canopy cover (%)	0	100	45	32
Number of bedrooms	1	14	2.9	0.8
Composite emissivity	0.91	0.97	0.96	0.01
Net black body flux (W)	19	22,030	3080	2110

Finally, the proportion of each parcel overlaid by tree canopy was estimated from the NDVI values, discussed above. Table 2 presents the name, definition, and hypothesized significance of each parcel design incorporated into the database.

4. Analysis and result

With the aid of the Statistical Package for the Social Sciences (SPSS), descriptive and explanatory analyses were performed to assess the influence of parcel design on the parcel net black body flux. As detailed in Table 3, the average single-family residential parcel is characterized by a three bedroom house and is approximately 1360 m^2 in area, of which 208 m^2 or 15% is occupied by the impervious components of the house and driveway, with the remaining 85% occupied by lawn and landscaping. Approximately, 45% of the average single-family residential parcel is overlaid by tree canopy cover. In general, the design of the average residential parcel is consistent with a medium to low density pattern of development. As indicated by the range and standard deviation of the lot size variable, the data set includes the full continuum of density levels.

Two measures of thermal performance are reported in Table 3. As described above, the parcel emissivity is a reflection of the relative proportion of impervious and vegetated materials. Values of this variable range from 0.90, reflective of complete impervious cover, to 0.97, reflective of a fully vegetated parcel. The average parcel emissivity is 0.957, indicating a mix of pervious and impervious materials.

The average net black body flux for a single-family residential parcel is 3080 W, or about 2.3 W m^{-2} in the 9.6–10.2 μm wavelength band. This finding suggests that, on average, the conversion of a natural land cover to a single-family residential dwelling results in the emission of an additional 3080 W to the atmosphere within the 9.6–10.2 μm band, under conditions present at the time of data collection. It is this excess surface flux that most directly captures the contribution of an individual land parcel to regional surface heat island formation. The large range and standard deviation for this variable suggests a wide distribution of parcel surface warming throughout the Atlanta study region.

To evaluate the graphic correlation between parcel area, material composition, and surface warming, values of increasing lot size are plotted against impervious area, lawn area, and the net black body flux in Fig. 1. As illustrated in this figure, the magnitude of surface warming scales closely with lot size, with the mean net black body flux increasing by a factor of almost six between the highest and lowest density classes. While this descriptive evidence supports our hypothesis of a negative relationship between the density of single-family residential development and surface warming, it is important to note that this simple covariation does not account for the distribution of residential capacity or tree canopy cover throughout the region. If larger lot sizes are also associated with greater residential capacities (e.g., four and five bedroom houses) and a less mature tree canopy cover, then the relationship between the density of development and thermal performance may be attributable to incompatible design objectives or to the age of development in different areas of the city. In order to control for these important influences, a multivariate statistical model is developed and evaluated in the following section.

4.1. Explanatory analysis

In order to quantify the potential thermal benefits of specific design-based strategies, ordinary least squares was employed to develop a predictive model linking parcel design to the net black body flux. The resulting model included the following dependent and independent variables:

Y = net black body flux (W),
X_1 = area of impervious cover (m^2),

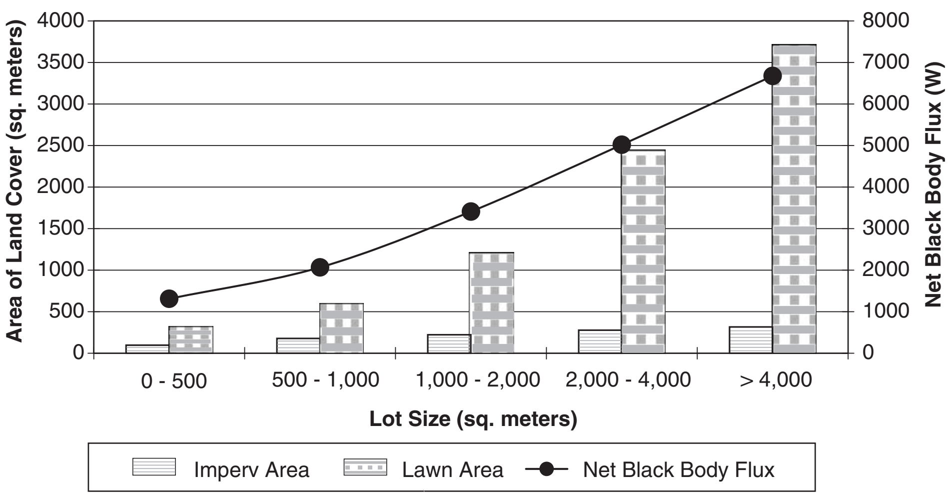

Fig. 1. Mean area of land cover and net black body flux by lot size.

$X_2 =$ area of lawn and landscaping (m^2),
$X_3 =$ tree canopy cover (%),
$X_4 =$ number of bedrooms.

With the aid of SPSS, a set of parameter estimates and model summary statistics was generated for the approximately 104,000 single-family residential parcels located in the Atlanta study region. The results of this modeling process are presented in Table 4.[1]

The results of the regression analysis indicate that the various parcel design attributes are significantly related to the parcel net black body flux. As expected, the area of impervious cover exhibits a significant positive relationship with parcel warming when controlling for other parcel design attributes believed to be associated with the dependent variable, as indicated by the positive sign on the *B*-coefficient. While the use of a transformed-dependent variable complicates the interpretation of model coefficients, the standardized regression coefficients provide an indication of the relative strength of the relationship between the parcel design attributes and parcel warming. The standardized regression coefficient for the area of impervious cover indicates that, with each one standard deviation increase in impervious area, the level of the transformed net black body flux variable increases by approximately 0.29 standard deviations. Significantly, this relationship was found to hold when controlling for the number of bedrooms in the residential structure, suggesting that the elevated surface warming is not solely attributable to variation in residential capacity.

Perhaps surprisingly, impervious cover was not found to be the strongest determinant of parcel warming. With a standardized regression coefficient of 0.51, variation in the area of lawn and landscaping was found to have the strongest association with the net black body flux. Specifically, an increase of one standard deviation in pervious surfaces is associated with an increase in the transformed net black body flux of approximately 0.51 standard deviations. This standardized effect on the dependent variable is significantly greater than that of the other independent variables and is believed to be attributable to two mechanisms.

[1]A residual analysis conducted to evaluate the reliability of the OLS model showed evidence of heteroscedasticity, suggesting non-normal variance of model residuals. The performance of a square root transformation of the dependent variable was found to correct for this potential source of error. The results reported in Table 4 reflect this variance stabilization transformation.

Table 4
Linear regression results for parcel net black body flux (W)

Variable	*B*-coefficient	Standardized coefficient	Significance
Impervious area (m^2)	0.083	0.290	< 0.001
Lawn area (m^2)	0.012	0.512	< 0.001
Tree canopy cover (%)	−24.42	−0.432	< 0.001
Number of bedrooms	0.440	0.020	< 0.001
Summary statistics	Adj. R^2	*F*-statistic	*F* significance
	0.55	31,866	< 0.001

Note: the square root of the net black body flux was used in this model as a variance stabilization transformation.

First, although not as great as the impervious flux density, the flux density of grass and other landscaping materials is greater than that of the predevelopment land cover of forest canopy. As a result, the displacement of tree canopy by residential lawn areas increases the flux of energy per unit of area. Second, the area of lawn and landscaping accounts for a larger proportion of the average residential parcel than impervious materials. Thus, while the flux density of energy from lawn materials is less than that of impervious materials in watts per square meter, the number of square meters of coverage is greater—resulting, in many cases, in a greater total flux of energy from pervious materials per parcel. As discussed in the following section, this finding holds important implications for design-based approaches to heat island management.

With a standardized regression coefficient of −0.43, the proportion of tree canopy cover was also found to be a strong predictor of parcel warming. As discussed in the following section, this finding confirms the value of tree planting programs as a strategy to mitigate surface warming in cities.

Overall, a regression model incorporating the four parcel design attributes was found to explain approximately 55% of the variation in the square root of the net black body flux within the Atlanta study region (Adj. $R^2 = 0.55$). As such, this model provides a reasonable basis for assessing the thermal impacts of various planning policies governing the design of residential parcels in the Atlanta, Georgia study area. However, given the complexity of interpreting the model coefficients with a transformed dependent variable, there is a need to assess what magnitude of benefits may be realized from targeted design modifications to residential parcels. To address this limitation of the analysis, the following discussion quantifies the potential benefits of three specific planning strategies for reducing surface heat island formation in residential zones.

5. Discussion

The results of this analysis provide compelling evidence that the size and material composition of single-family residential parcels is significantly related to the magnitude of surface warming in the Atlanta study region. Specifically, smaller, higher density parcels were found to be associated with a lower net black body flux than larger, lower density parcels when controlling for the class of land use and the number of bedrooms in the residential structure. While both the area of impervious materials and lawn and landscaping were found to be positively related to the parcel net black body flux, the area of lawn and landscaping—a strong correlate of parcel size—was found to be the strongest predictor of excess surface warming.

In contrast to previous work on the urban heat island (e.g., Hoyano, 1984), the results of this study support the hypothesis that lower density, dispersed patterns of urban residential development contribute more surface energy to regional heat island formation than do higher density, compact forms. While specific to the Atlanta metropolitan region, due to the uniformity of building materials and development patterns found throughout North American cities, we believe these findings are generalizable to a number of large, mid-latitude cities characterized by a similar climatological and physiographic characteristics. For such cities, this work illuminates at least three specific planning strategies that may be employed to offset the excess surface heat energy emitted from both existing and future residential development.

5.1. Reducing lawn areas

The results of our analysis suggest that the most effective design-oriented strategy for mitigating the thermal impacts of new housing development is a reduction in the area of the residential lawn. For the average parcel, a reduction in the lawn area of 25%, holding other design attributes constant, would be associated with a 13% reduction in the parcel net black body flux. By serving to increase the density of land use, a reduction in the lawn area of new residential development would offset enhanced surface warming through at least two mechanisms. First, by reducing the average lot size of development at the urban periphery, the area of rural land converted from forest to urban land uses is reduced, constraining the zone of enhanced warming. Second, by limiting the total zone of urban expansion, higher density development limits the extension of roadways and other thermally intensive infrastructure, also serving to preserve rural landscapes.

A reduction in the area of residential lawns may be achieved through a number of planning policy tools. The most straightforward approach entails the inclusion of maximum lot size restrictions in municipal zoning codes. Consistent with many large cities, Atlanta's zoning code imposes a minimum standard for residential lot sizes by land use class but no maximum, and thus fails to effectively control the area of land conversions at the urban periphery. Alternatively, cities may adopt a large minimum lot size (e.g., greater than 40 acres) or restrictions on land uses in future development zones beyond the periphery of present day development, a policy known as an "urban growth boundary." By limiting parcel subdivision and restricting residential classes of development in the rural hinterland, municipalities and regional governments can create clearly demarcated boundary between urban and rural zones, serving to promote higher densities in the established urban core. A final policy employed to encourage smaller lot sizes is the scaling of development impact fees with lot size. If sufficiently graduated, impact fees for larger lot sizes can provide an effective deterrent to developing expansive residential lawn areas.

5.2. Decreasing impervious cover through reconfiguring the parcel

The finding of a positive relationship between the area of impervious cover and the parcel net black body flux confirms the well-established role of mineral-based building and paving materials in urban heat island formation. The most widely advocated approach to mitigating the thermal impacts of impervious materials is through the application of high albedo surface treatments to increase surface reflectivity—an approach that is cost-effective and applicable to both new and existing development. For new construction, a reduction in the total area of impervious cover provides an additional tool for offsetting an increase in surface warming. Our findings suggest that a 25% reduction in the impervious cover of an average single-family parcel is associated with a 16% reduction in the net black body flux. When combined with an equivalent reduction in lawn area, parcel warming was found to be 28% lower.

The area of parcel impervious cover may be reduced in a number of ways with no net loss in the living space of residential structures. For new development, the use of multistory construction provides a straightforward approach to minimizing building footprint areas.[2] Likewise, a revision of zoning and subdivision regulations to shorten front yard setbacks and narrow lot frontages can significantly reduce driveway areas and the area of street paving required to service the parcel. For both new and existing development, the replacement of driveway paving at the time of routine resurfacing with driveway runners (narrow strips of paving for vehicle tires) can reduce the area of parking surfaces by as much as one-third. Research has demonstrated that modest revisions to zoning and subdivision regulations, with no change in the size or design of residential structures, can achieve a 30% reduction in the impervious cover of residential lots (Stone 2004).

5.3. Shading existing development through tree planting

While the potential to reduce the thermal impacts of new growth is significant, it is important to note that changes to a city's land development regulations will have only a limited influence on existing development. As the vast majority of the Atlanta region's 2025 built area is already in place, changes in future peripheral development will serve to offset continued growth rather than abate present day heat island formation. In light of this observation, the most effective design-oriented strategies for reducing total regional warming must address both new and existing development. As noted above, one strategy for doing so would entail the replacement of traditional driveways with driveway runners at the time of routine resurfacing. A second critical strategy for existing development entails the planting of trees. As indicated by our analysis, for the average single-family parcel, an increase in tree canopy cover from 45% to 60% reduces the parcel net black body flux by 14%. For trees strategically planted along roadways and in proximity to houses, the thermal benefits are likely to be greater.

Cities can promote residential tree planting through the development and enforcement of municipal tree ordinances. Such ordinances can regulate the number, size, species, and placement of trees along streets and within private parcels. While most cities have incorporated some type of tree protection ordinance into their municipal codes, the enforcement of these policies is often lax due to the inadequate funding of city arborists. However, in light of the substantial costs of energy consumption and air pollution associated with heat island formation, the cost effectiveness of urban tree planting is likely to enhance the appeal of these strategies for growing metropolitan regions over time.

6. Conclusions

The results of this study indicate that, when measured as an enhanced flux of surface energy and adjusted for residential capacity, the magnitude of surface warming associated with single-family residential development in the Atlanta, Georgia, metropolitan region is greatest in low density areas and is sensitive to the size and material composition of residential development. We believe the results of this study make two important contributions to the heat island literature. First, the development of a parcel-based measure of surface heat island magnitude permits the thermal impacts of development activities to be measured at a spatial dimension compatible with legal land use controls. As a policy-relevant measure of heat island formation, variation in the parcel net black body flux provides a much needed quantitative basis for evaluating the influence of specific municipal land development regulations such as zoning regulations, subdivision regulations, and building codes, which control parcel design. As a result, in addition to enhancing the surface albedo of existing development, planners can modify the land development regulations governing the underlying structure of cities to enhance the thermal performance of new development at the urban periphery and redevelopment in the established core. In this sense, policy-relevant

[2]It should be noted that, while reducing the area of the impervious footprint, multistory construction can increase the potential for radiative warming through increasing urban canyon geometries. As our analysis is limited to single-family residential zones, we assume any enhanced warming through increased canyon geometries to be minimal.

measures of environmental performance enable policy makers to be both reactive and proactive in planning for urban growth and environmental change.

Second, this study assesses the magnitude of benefits associated with parcel design changes in a major metropolitan area of the United States. Based on our findings, a 25% reduction in the area of impervious and residential lawn space for the average single-family parcel, combined with an increase in average tree canopy cover from 45% to 60%, would reduce the parcel net black body flux by approximately 40%. It is important to note that these benefits may be achieved with no changes to the size, capacity, or material design of the residential structure. When combined with strategies to increase the surface reflectivity of paving and roofing materials, additional cooling benefits may be realized. Future work will focus on the full range of benefits that may be derived from integrated land use, tree planting, and albedo enhancement strategies across an expanded array of land use types.

Before concluding, it is important to highlight a few limitations of our analysis. First and most importantly, this analysis considers only a single class of land use, residential, which, while significant to urban growth for the reasons noted above, is not fully representative of the urban landscape. By focusing on single-family residential development, we have made no attempt to assess the impacts of dense canyon geometries that can intensify warming in zones characterized by tightly clustered medium to high rise buildings. Furthermore, the results of our analysis are highly responsive to the natural land cover of the Atlanta study region, which is that of a mixed deciduous forest canopy. For more arid regions characterized by non-forested pre-development land covers, the divergence between pre- and post development fluxes of energy are likely to be much less pronounced. And, finally, while we assume a reasonably close correspondence between the surface and near surface canopy heat islands in Atlanta, averaged over time, we have made no attempt to link parcel based development patterns to air temperatures directly, and thus our results may be presumed to apply to the surface heat island only. A more complete coupling of the surface and near-surface canopy heat islands will require extensive data on regional air circulation patterns and waste heat emissions. Given our limited focus on the role of residential land use patterns in the enhancement of surface radiant heat fluxes, we have not attempted to model these more complex interactions herein.

In closing, we believe heat island abatement will prove to be one of the most effective means for cities to adapt to the process of climate change over time. While the drivers of the greenhouse effect are global in nature, and are largely insensitive to the policy actions of individual cities or regions, regional scale climate change in the form of heat island formation can be abated over the near to medium term through comprehensive land use controls, building design, and energy conservation at the metropolitan scale. As a result, municipal decision makers concerned about the implications of climate change on human and environmental health can take steps in the near term to mitigate the thermal impacts of urban land use on surface temperatures, ambient temperatures, and air quality. In formulating such local scale strategies, it is imperative that land use planners have a more complete understanding of the role of land use policies in heat island formation. To this end, this work is intended to inform a more comprehensive approach to climate change management in cities.

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