
Urban Form and Thermal Efficiency

How the Design of Cities Influences the Urban Heat Island Effect

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This article presents findings from a study on residential development patterns and urban heat island formation in the Atlanta, Georgia, metropolitan region. High-resolution thermal imagery collected by the National Aeronautical and Space Administration (NASA) is used in conjunction with parcel-level tax records to examine the interaction between the design of single-family residential parcels and the emission of radiant heat energy. Results from a path analysis illustrate that lower density patterns of residential development contribute more radiant heat energy to surface heat island formation than higher density development patterns within the Atlanta region. Compact moderate-to-high-density new construction and area-based tree ordinances are recommended as policy strategies for mitigating the effects of urban development on regional climate change.

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Journal of the American Planning Association, Vol. 67, No. 2, Spring 2001. © American Planning Association, Chicago, IL.

In recent years, the relationship between urban land use and environmental quality has received increased attention in both planning research and practice. Evidence provided from a range of studies on the interaction between land use and air quality has illustrated that moderate to high levels of density and an intermixing of compatible land uses can reduce vehicle travel and offset pollutant emissions (Frank et al., 2000; Johnston & Ceerla, 1995). Urban intensification has the added benefit of reducing the acreage of rural land converted to suburban uses over time. In response to such findings, advocates of neotraditional design and “smart growth” management are re-embracing compact, pedestrian-scaled urban forms to achieve, in part, an environmental objective (Calthorpe, 1993). Although the precise benefits of such a reinstatement of compact forms continues to be debated, the emergence of a national dialogue on the issue of sprawl presents an opportunity to consider other ecological implications of urbanization.

In addition to the potential for urban design to reduce air pollution through the facilitation of nonmotorized travel, there may be a more direct relationship between urban development patterns and air quality. Through a climatological phenomenon known as the *urban heat island effect*, large urbanized regions have been shown to physically alter their climates in the form of elevated temperatures relative to rural areas at their peripheries. Similar to the effects of global warming, such “urban warming” can have substantial implications for air quality and human health within affected regions. Indeed, while global warming forecasts predict a rise in temperature of 3.5 to 6°F (1.9 to 3.5°C) over the next century (Intergovernmental Panel on Climate Change, 1995), large urbanized regions are already routinely measured to be 6 to 8°F (3.3 to 4.4°C) warmer than surrounding rural regions (United States Department of Energy, 1996). Increasing at a rate of

0.25 to 2°F (0.1 to 1.1°C) per decade, the heat island effect within the urban cores of rapidly growing metropolitan regions may double within 50 years (McPherson, 1994). In light of the roughly 2.9 billion new residents projected to arrive in urban regions between 1990 and 2025, there is a pressing need to ascertain the implications of urban warming for metropolitan regions and to identify potential strategies to counteract regional climate change (World Resources Institute, 1990).

This article presents findings from a case study on the interaction between urban form and surface heat island formation in the metropolitan region of Atlanta, Georgia. Specifically, the quantity of radiant heat energy emitted by approximately 116,000 single-family residential parcels within the Atlanta region is determined with the aid of remotely sensed thermal data collected by the National Aeronautical and Space Administration (NASA).¹ The basic thesis of this work is that, contrary to intuitive assumptions, lower density, sprawl patterns of development contribute more radiant heat energy to the formation of the region's surface heat island than do higher density, compact forms. What follows is a discussion of the significance of heat island formation to planning, an explanation of the research design for this study, presentation of the study's results, and policy recommendations drawing upon these results.

Defining the Urban Heat Island Effect

The physical mechanisms through which the urban heat island effect is driven are well documented. Primary constituents of urban construction, such as asphalt, cement, and roofing tile, have a much greater heat capacity than the forest vegetation and other natural features that have been increasingly displaced within metropolitan regions. As a result, urban structures absorb a large quantity of thermal energy during the daylight hours and slowly re-emit this stored heat during the late afternoon and into the night. The displacement of vegetation and soils further enhances heat retention by limiting the effectiveness of a natural cooling mechanism known as evapotranspiration. Evapotranspiration is the process through which intercepted radiation is utilized by plants, soils, and water bodies to convert water to water vapor. The use of this energy in the evapotranspiration process reduces the amount of incoming solar and terrestrial radiation available to be absorbed by surface features and re-emitted as heat energy.² The excess heat energy that is absorbed as a result of urban construction and deforestation is great enough to actually raise by several degrees the average temperature of the city over that of peripheral nonurbanized regions (Oke, 1987).³ A

generalized temperature profile for the urban heat island effect is illustrated in Figure 1.

Heat islands may be measured as either surface or atmospheric phenomena. The temperature profile depicted in Figure 1, for example, illustrates a very generalized distribution of near-surface (measured 1–2 meters from the ground) air temperatures across varying intensities of urbanized land use. An elevation in near-surface air temperatures is known as the “canopy-layer” heat island. Heat islands are also manifested through an elevation in the *surface* temperature of urban regions (the “surface” heat island; Roth et al., 1989).

This study seeks to quantify the influence of residential development on the *surface* heat island for two important reasons. The first pertains to the superiority of surface temperature as a measure of the thermal attributes of surface features. Due to the fluid properties of the atmosphere, the correspondence between surface and air temperatures is known to decrease with increasing altitude (Carlson et al., 1977). As a result, depending upon the height of measurement, air temperatures may not provide a reliable indicator of the thermal properties of distinct surface features.

Surface measurements are also preferable for an analysis of land use and urban warming in that surface temperatures may be measured through remote sensing techniques. In contrast to air temperature measurements that must be made through “in-situ” observations on the ground, radiant emissions from surfaces can be measured remotely from radiometers mounted on aircraft or satellites. An advantage of remote sensing techniques is that these methods facilitate the collection of a very large number of thermal observations. While studies of the canopy-layer heat island generally utilize a few hundred air temperature observations collected throughout an urbanized region (Oke, 1973; Saitoh et al., 1996), the dataset used for this work consists of more than 2 million surface thermal observations. This large number of observations enables the thermal properties of small surface features to be measured with a much greater precision than can be practically achieved through the collection of air temperature measurements on the ground.⁴

In light of our decision to examine the surface rather than the canopy-layer heat island, an important theoretical premise of this work is that increments in surface thermal emissions directly contribute to an elevation in atmospheric temperatures, with significant implications for air quality and human health. Evidence of a significant relationship between surface and canopy-layer heat islands is provided from a number of studies that have examined this question. In a study designed to compare remotely sensed infrared (IR) data with near-surface air

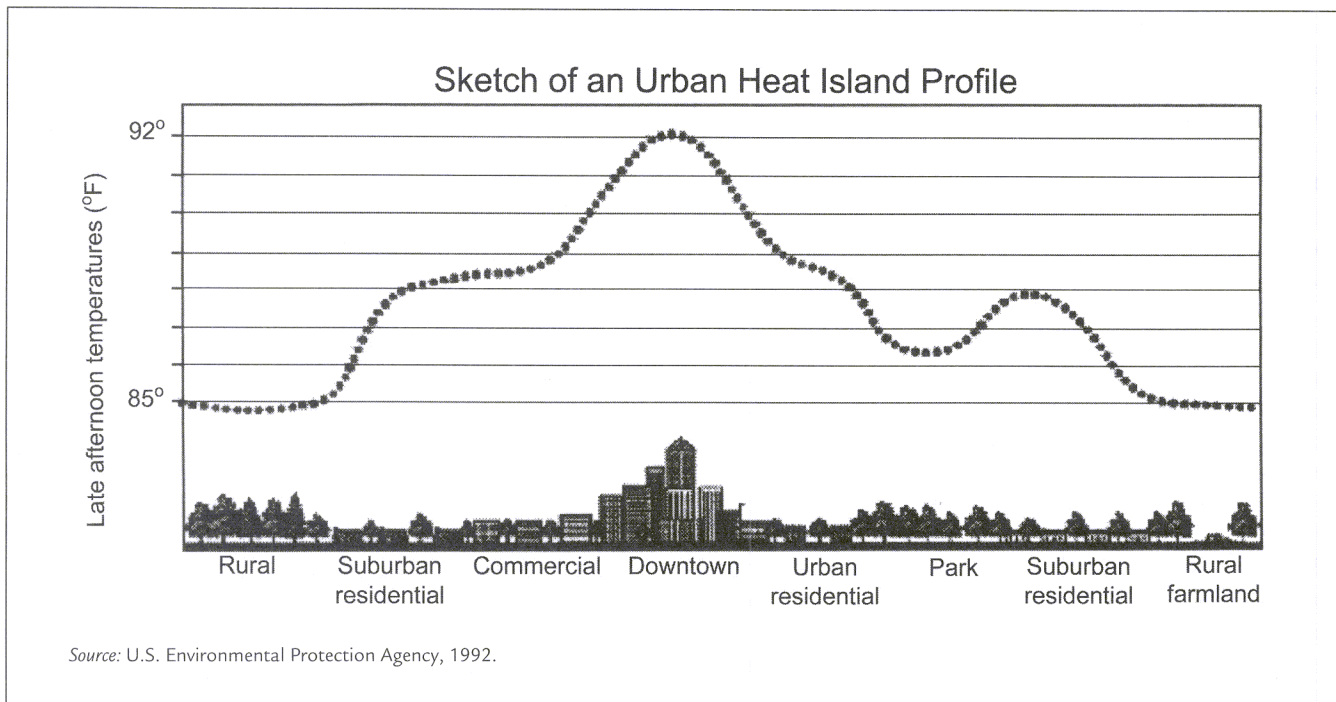


FIGURE 1. Temperature profile for the urban heat island effect.

temperature measurements, Goldreich (1985) concludes that “IR imagery is . . . a legitimate system for measuring the [canopy-layer] urban heat island structure” (p. 1243). While some studies have found the correlation between surface and air temperatures to be weak, these findings are generally an artifact of measurement techniques that do not account for the differing spatial and temporal scales upon which surface and atmospheric thermal processes occur. As concluded by perhaps the most comprehensive examination of this question, “[i]n studies where the scales match there is reasonable agreement between remotely-sensed surface temperature and that in the near-surface air” (Roth et al., 1989, p. 1718). In consideration of this finding, we believe that surface measurements provide a reliable basis for examining the interaction between urban design and elevations in both surface and near-surface air temperatures.

The Implications of Urban Warming

Heat island formation can influence air quality through a number of mechanisms. Most directly, elevated atmospheric temperatures are known to facilitate the series of chemical reactions through which ozone is formed (Cardelino & Chameides, 1990). Toxic to humans at ground level, ozone inflames lung tissue and aggravates a range of respiratory ailments such as asthma.

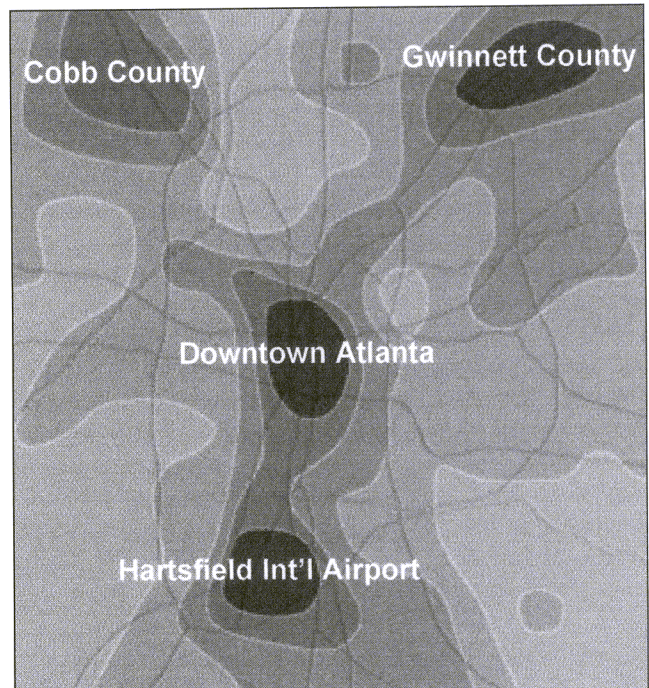
Urban warming can elevate ozone concentrations by increasing the rate at which volatile organic compounds (VOCs), a class of precursors to ozone, are emitted from vehicle engines and natural sources such as trees. Ironically, despite a 20% loss of tree cover within metropolitan Atlanta between 1974 and 1988, total emissions of VOCs from trees may have increased during this period due to the region’s rapidly growing heat island (Cardelino & Chameides, 1990). Researchers at the Lawrence Berkeley National Laboratory have estimated that each 1°F (0.6°C) rise in temperature over 70°F (21.1°C) increases the potential for ozone formation in Los Angeles, California, by approximately 3% (USDOE, 1996). A reduction in urban temperatures of approximately 3°F (1.7°C) is estimated to produce air quality benefits roughly equivalent to replacing a city’s entire fleet of gas-powered cars with electric vehicles (Adams, 1999).

In addition to its effects on ozone, heat island formation indirectly affects air quality by increasing the demand for air conditioning. It is estimated that as much as 15% of the electricity consumed for cooling within Los Angeles is utilized for the sole purpose of offsetting the effects of enhanced urban warming (Rosenfeld et al., 1996). The national cost of excess energy production necessary to compensate for heat island formation is estimated to be approximately \$10 billion annually (Rosenfeld et al., 1996). In addition, vast quantities of

carbon dioxide and other greenhouse gases that are emitted as a result of excess energy production further contribute to larger-scale climatic effects through the process of global warming. In combination with the longer-term effects of global climate change, the impact of heat island formation on human heat stress is likely to be increasingly significant.

Despite the substantial costs associated with urban warming, no cities have developed comprehensive programs to mitigate the effects of heat islands. Such inaction is attributable to the fact that little research has been conducted on the relationship between a city's design and its propensity to absorb heat. While it has been established that urbanized land uses tend to be more conducive to heat gain than nonurbanized land uses, the literature is largely silent on the issue of whether one pattern of urban development is more thermally detrimental than another. Perhaps surprising in this regard is the fact that substantial heat islands have been found to exist within both city centers and suburban communities. As Figure 2 illustrates, the metropolitan region of Atlanta, Georgia, consists of multiple surface heat islands, one within the central business district and at least three others to the north and south of downtown. Interestingly, the hotspot generated by the city's central business district is similar in size to another found in suburban Gwinnett County. It is important to note, however, that the predominant land use patterns found in each area differ dramatically in terms of population density, the distribution of commercial and residential land uses, and street network patterns. This finding provides circumstantial evidence that heat islands may be more a product of urban design than, as commonly assumed, the density of development. If a clear link can be established between the form of cities and the magnitude of their heat islands, it may be possible to identify "thermally efficient" models of development.

For the purpose of this research, *thermal efficiency* is defined as the degree to which the design of a single-family parcel (land and residential structure) minimizes the output of radiant heat energy relative to other single-family parcels of similar housing capacity (number of bedrooms), age, and tree canopy cover. Our conceptualization of an efficiency-based measure reflects our hypothesis that different forms of residential "input" are systematically associated with different levels of thermal "output." A single-family parcel is thus considered to be thermally efficient if it emits a *lower* than average quantity of radiant heat relative to all single-family parcels of similar housing capacity, age, and tree canopy cover within the study region. Those that emit a *higher* than average quantity of radiant heat relative to similarly designed parcels are considered to be thermally inefficient.



Source: American Forests, 1996

FIGURE 2. Satellite (Landsat) image of multinodal heat Island in Atlanta, GA. Darker tones denote higher temperatures.

This study seeks to determine if there are distinct design attributes related to parcel size, the proportion of a parcel occupied by impervious and vegetative materials, and the configuration of these materials that systematically distinguish parcels with high levels of radiant emissions (thermally inefficient) from those with low levels of radiant emissions (thermally efficient). The basic premise of this work is that the adoption of design attributes found to be thermally efficient will reduce the quantity of surface heat emitted by the region as a whole, and thus mitigate the negative impacts to the region of heat island formation.

Linking Land Use to Heat Island Formation

In May 1997, scientists from NASA's Global Hydrology and Climate Center (GHCC) collected high-resolution thermal data (10 meters \times 10 meters) over a major metropolitan region for the first time. Due to its exceptionally rapid rate of urban growth and deforestation over the last several decades, Atlanta, Georgia, was selected as the site for this pilot study that subsequently has been named "Project ATLANTA."⁵ At the achieved

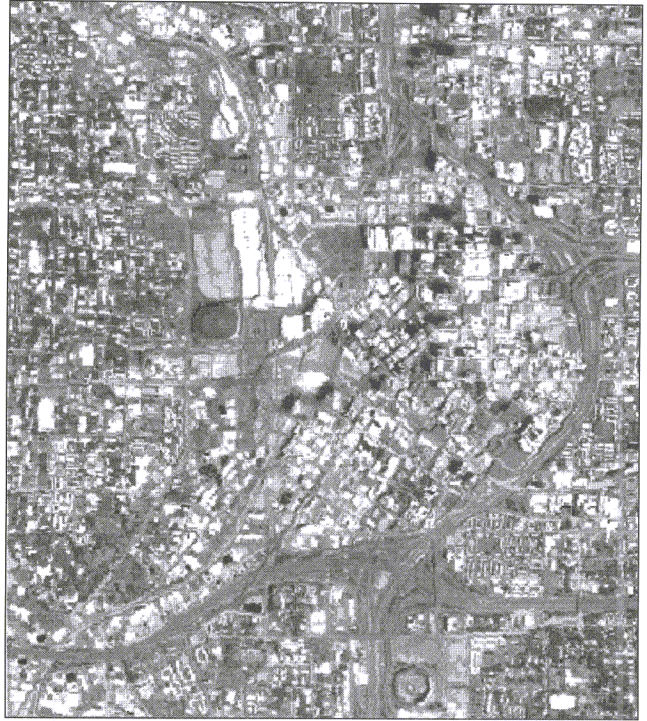
spatial resolution of 10 meters, surface temperature differentials can be identified between different categories of land use, different species of vegetation, and even adjacent buildings. Figure 3 is a panchromatic thermal-IR image of downtown Atlanta collected during the Project ATLANTA flights.

The development of a high-resolution thermal sensor permits the relationship between urban design and heat island formation to be studied with more precision than ever before.⁶ This study utilizes the Project ATLANTA thermal imagery to derive a measure of urban warming at the parcel level. For this research, boundary and attribute data for approximately 116,000 single-family parcels was obtained for the City of Atlanta and surrounding Fulton County.⁷ The single-family parcel was selected as the unit of analysis for this study for several reasons. First, residential land uses occupy over 50% of the developed land in the Atlanta region and thus capture a majority of the total urban land area. More importantly, however, we are interested in examining a class of land use within which real consumptive trade-offs exist. For example, the choice between a higher density, in-town residential lot and one within a lower density, suburban area is a realistic alternative afforded to many homebuyers. For the much larger and more diverse class of commercial land uses, regional location decisions are generally less flexible and the trade-offs less compatible for different industries. In addition, there are many non-residential land uses, such as airports and industrial districts, for which thermal impacts may not be realistically mitigated through urban design. It is for these reasons that we believe the single-family parcel to be the most appropriate unit of analysis for evaluating the link between urban design and heat island formation.

Deriving a Measure of Thermal Efficiency

The release of radiant energy from surface features is generally measured in one of two ways. One approach is to measure the quantity of radiant heat emitted per unit of area. This measure is known as the *radiant flux density* and is generally calculated in watts (joules per second) per square meter (W/m^2). Similar to other density measures, the radiant flux density provides a measure of the average intensity of a particular spatial attribute per unit of area. What is most relevant to a parcel-based analysis of urban warming, however, is not the average quantity of heat released per unit of area, but the total quantity of heat released per single-family parcel.

The total quantity of radiant heat emitted per parcel (per unit of time) is the parcel *radiant flux*. Due to the fact that single-family parcels vary in size around the study



Source: Project ATLANTA, Global Hydrology and Climate Center, NASA

FIGURE 3. Thermal-IR image of Atlanta's central business district. Lighter tones denote higher temperatures.

region, it is critical that a measure of thermal efficiency account for both the rate of radiant emissions per unit of area and the total area across which this radiant energy is being emitted. For example, if two parcels, one an acre and the other a quarter acre, are found to emit heat at the same rate per unit of area (e.g., per square meter), the acre-sized parcel is emitting four times the total quantity of heat to the atmosphere of the smaller parcel due to the fact that it is four times larger. Because every excess watt of energy emitted from a parcel theoretically contributes to the formation of a surface heat island (holding regional meteorological conditions constant), a measure of thermal efficiency must be based upon the total rather than the average quantity of energy released per parcel. The most accurate approach to quantifying the contribution of an individual parcel to surface heat island formation, therefore, is through estimation of the total parcel radiant flux.

The flux of radiant energy emitted from a parcel may be calculated by simply multiplying the radiant flux density of a parcel by its area ($W/m^2 \times m^2 = \text{radiant flux in watts}$). This study derives an estimate of the radiant flux in watts for each of approximately 116,000 single-family

parcels located in the Atlanta metropolitan region. It is important to note, however, that rather than the total quantity of heat released within urban regions, the surface urban heat island effect is more accurately defined as the *excess* quantity of heat emitted relative to adjacent rural regions. In light of this fact, the most appropriate indicator of thermal efficiency is a measure of the additional radiant energy that is emitted from a parcel once it is converted from a natural land cover, such as a forest, to a single-family dwelling. We have thus derived for this study a measure of parcel *net thermal emissions* to serve as an index of parcel thermal efficiency. The net thermal emissions of a single-family parcel is calculated by determining the radiant flux of a single-family parcel and subtracting from that quantity the radiant flux estimated to be generated by a forested parcel of equal size (radiant flux of single-family parcel – radiant flux of forested parcel of equal area = net thermal emissions).⁸ It is this resulting measure of net thermal emissions that we believe most accurately captures the contribution of any individual land parcel to urban warming.

Constructing a Thermal Database

The first step in the database construction requires that the total radiant flux be measured for each parcel in the study region. This task may be accomplished with the use of a geographic information system. Through a “geo-referencing” process, the thermal imagery and parcel boundaries may be registered to a common set of coordinates. Once registered, the thermal imagery may be overlaid with parcel boundaries and the total radiant flux per parcel calculated.

In order to calculate the net thermal emissions per parcel, it is necessary to obtain an estimate of the radiant heat energy that would be produced by a parcel were it occupied by a forested land cover. This estimate is derived by identifying a baseline flux density (W/m^2), which is representative of the radiant heat emitted by fully forested tracts of land within the study region. The forest baseline flux density may then be multiplied by each parcel’s area (in square meters) to derive an estimate of the *base radiant flux*, or the radiant flux estimated to result from the same parcel were it covered by forest vegetation. The final step in calculating net thermal emissions is to subtract the base radiant flux from the observed radiant flux for each parcel.

The second step in the database construction involves the creation of several urban design variables that we hypothesize to be significantly related to surface heat island formation. The parcel level data obtained for the study region includes a number of attribute variables that may be related to the emission of radiant heat by a

single-family parcel. The urban design variables incorporated into the database include a measure of tree canopy cover, the year of parcel development, the number of bedrooms in the residential structure, the impervious surface area, the pervious surface area, and a measure of the neighborhood street network configuration. The following bullets detail the definition, hypothesized significance, and source of each parcel design variable:

- *Tree Canopy Cover*: The tree canopy variable is a measure of the percentage of each single-family parcel overlaid by tree canopy cover. This variable is calculated by dividing the area of each parcel occupied by canopy cover by the parcel’s total area. Canopy cover is a critical control variable. As discussed above, trees directly influence thermal emissions by offsetting heat gain through the process of evapotranspiration, and thus a failure to control for this variable would confound efforts to isolate the true effects of the parcel design attributes on warming. The distribution of tree canopy may be derived from an analysis of aerial data collected by NASA in conjunction with the thermal images.⁹
- *Year of Construction*: The year of building construction is a parcel attribute recording the year in which each residential structure was built. The year of construction is utilized in the analysis as a proxy measure for the maturity of the vegetative canopy overlying the parcel. Due to the strong interaction between canopy cover and heat gain, recently developed parcels that have not had sufficient time to permit adequate tree growth will likely emit more heat energy than similar parcels of greater age. While the canopy cover variable provides a general measure of the canopy extent, it does not provide a reliable measure of canopy density. As both the extent and density of the tree canopy are known to influence heat gain, both attributes must be accounted for in the analysis. The Atlanta and Fulton County tax datasets are the source for this control measure.
- *Number of Bedrooms*: The number of bedrooms per residential structure is included in the analysis in order to control for the variability in housing capacity around the study region. In light of the fact that houses located in lower density areas are often designed to accommodate larger family sizes, housing capacity must be controlled in order to eliminate a favorable bias towards higher density regions where smaller houses tend to be located. The inclusion of this variable effectively limits the analysis to comparisons between parcels

with residential structures designed to accommodate an equal number of individuals.¹⁰ The Atlanta and Fulton County tax datasets are the source for this control measure.

- *Impervious Surface Area*: The impervious surface area of each parcel is a measure of the total area devoted to the building footprint of the residential structure and to driveway paving. Impervious surfaces are hypothesized to increase net thermal emissions by elevating the heat capacity of the parcel and reducing the quantity of water that may be absorbed and utilized to offset heat gain through evapotranspiration. The parcel surface area occupied by the building footprint was obtained from the City of Atlanta and Fulton County tax datasets. The area devoted to driveway paving was estimated from a regional sample of surveyed parcels.¹¹
- *Pervious Surface Area*: The pervious surface area of each parcel is a measure of the parcel area devoted to lawns, landscaping, and gardens. This variable is derived by subtracting an estimate of the impervious surface area from the total parcel area. It is hypothesized that, when controlling for the effects of tree canopy cover, larger yards are associated with higher levels of net thermal emissions. The basis for this hypothesis is a belief that large lawns are maintained in the study region at the expense of a more dense tree canopy. While lawn materials generally retain less heat than impervious materials, these land covers are less efficient providers of shade and evapotranspiration than trees, and thus are believed to contribute to an elevation in urban temperatures above the region's natural forested land cover. The total area of each residential parcel in square meters is recorded in the City of Atlanta and Fulton County tax datasets.
- *Street Intersection Density*: Street intersection density is a measure of the mean number of intersections found per square mile within the neighborhood of each residential parcel in the database. The number of street intersections found per unit of area provides a proxy measure of the basic residential development pattern within which a parcel is located. The reason for this is that suburban networks utilize limited access residential streets and cul-de-sacs to eliminate drive-through traffic in residential areas. The discontinuity of the suburban network form serves to reduce the intersection density of these patterns and thus provides a means of distinguishing between urban (grid-based) and suburban (based on disconnected residential streets) patterns of residential develop-

ment. Due to the general absence of street trees in suburban networks, as well as the tendency of these forms to cluster rather than more evenly distribute a canopy of trees, it is hypothesized that higher levels of intersection density will be associated with lower net thermal emissions. The intersection density variable is calculated from TIGER street network files obtained from the U.S. Census Bureau.¹²

Path Analysis

The intent of the data analysis is to model the relationship between parcel design, neighborhood configuration, and net thermal emissions. To do so, a set of regression analysis models was constructed to examine this relationship while controlling for tree canopy cover, the year of development, and housing capacity. In the first of these models, each of the three predictor and three control variables was incorporated into a regression equation in order to isolate the direct effects of the independent variables on net thermal emissions. It is important to note, however, that in addition to the direct effects of parcel design on heat production, each design variable may additionally influence net thermal emissions indirectly by affecting the distribution of trees. For example, the direct effects of parcels with large lawn areas will be predicated on the ability of the particular combination of grass and other landscaping materials to offset heat gain and re-emission. In addition to the direct relationship between grass and heat energy, parcels with large lawn areas are likely to dedicate a larger proportion of the lot to tree canopy cover due to the simple fact that more area is available for tree planting. Thus, pervious surface area has a direct (the thermal properties of lawn materials) and indirect (the potential for tree planting) effect on net thermal emissions. In order to capture the indirect effects of each design variable, a second regression equation was constructed to model the influence of parcel design on tree canopy cover.

In combination, the net thermal emissions and tree canopy regression equations can be utilized to construct a path model detailing the complete interaction between parcel design and net thermal emissions. Path models provide useful visual tools for depicting the strength and nature of the effects of predictor variables that act directly, as well as indirectly through an intermediary variable, to influence a dependent phenomenon. In the path model presented in Figure 4, arrows of varying size are utilized to depict the direct and indirect influence of each parcel design attribute on net thermal emissions. The width of each arrow is proportionate to the strength of the effect as captured by the standardized regression

coefficients derived in the regression analysis. The use of standardized as opposed to the natural coefficients permits comparisons to be made between predictor variables measured in different units. All of the variable interactions presented in the diagram were found to be significant at the .001 level. The complete results of the regression analysis are detailed in Table 1.

The results of the path analysis provide statistical evidence that parcel design as captured by the independent variables is significantly related to residential surface heat emissions. The right hand side of the diagram depicts the direct effects of each predictor variable on net thermal emissions. Pervious surface area was found to have the greatest direct effect on excess parcel heat production with a regression coefficient of .498. The positive sign on this coefficient indicates that as the pervious surface area expands, net thermal emissions increase as well.

It should be noted, however, that pervious surface area was also found to have a positive influence on tree canopy (.269). Due to the fact that tree canopy is known to have a strong negative relationship with net thermal emissions (-.300), any variable that serves to promote canopy cover indirectly mitigates heat production. The actual indirect effect of pervious surface area on net thermal emissions may be calculated by multiplying the coefficients on the pervious surface-to-tree canopy and the tree canopy-to-net thermal emissions paths (.269 × -.300). The result of this calculation, -.081, confirms the fact that pervious surface area has a negative indirect relationship with net thermal emissions through its positive effects on tree canopy. The total effects of pervious surface area on excess heat production may thus be derived by summing the direct and indirect effects (.498 + -.081 = .417). The resulting total effect of .417 indicates that the pervious surface area variable has a strong positive

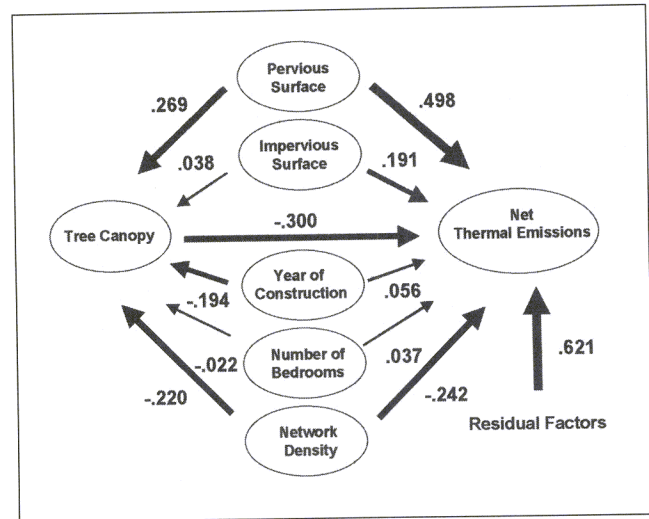


FIGURE 4. Path model of direct and indirect influences (via tree canopy) on net thermal emissions.

itive influence on net thermal emissions when accounting for both direct and indirect interactions. The total effects for each of the variables included in the path model are presented in the far right column of Table 1.

Similar to pervious surface area, impervious surface area was found to have a significant positive effect on both net thermal emissions (.191) and tree canopy cover (.038). The total effect of this variable on excess heat gain was calculated to be .180, indicating that increases in impervious surface area are associated with increases in net thermal emissions. In combination, the pervious and impervious surface area measures capture the effects of total lot size on net thermal emissions. The positive total effects of each of these measures supports the hypothe-

TABLE 1. Total effects and summary statistics from path analysis.

| Variable | Net thermal emissions* | Tree canopy cover | Significance | Total effects |
|-------------------------------------|------------------------|-------------------|----------------|---------------|
| Tree canopy cover (%) | -.300 | N/A | .000 / N/A | -.300 |
| Number of bedrooms | .037 | -.022 | .000 / .000 | .044 |
| Year of parcel development | .056 | -.194 | .000 / .000 | .114 |
| Pervious surface area (sq. feet) | .498 | .269 | .000 / .000 | .417 |
| Impervious surface area (sq. feet) | .191 | .038 | .000 / .000 | .180 |
| Intersection density (per sq. mile) | -.242 | -.220 | .000 / .000 | -.176 |
| Summary statistics | Adj. R-Square | F Statistic | F Significance | |
| Net thermal emissions | 0.61 | 30390.27 | .000 | |
| Tree canopy cover | 0.16 | 4229.22 | .000 | |

*Natural log of variable used as a variance stabilizing transformation.

sis that, holding other factors constant, larger lot sizes tend to exhibit a higher level of net thermal emissions than smaller lot sizes.¹³ On average, each 1/4-acre increase in parcel area was found to be associated with an increase in net thermal emissions of 33%. This finding directly challenges the common assumption that higher residential densities are less thermally efficient than lower residential densities. To the contrary, the smaller parcel sizes of higher-density neighborhoods were found to emit less excess radiant heat energy per single-family household than households situated on larger lots. This relationship holds true even when accounting for the tendency of higher-density parcels to exhibit a less extensive tree canopy cover.

Street network densities were found to have a significant negative effect on net thermal emissions (-.242) and tree canopy cover (-.220). In contrast to the pervious and impervious surface measures, high intersection densities are associated with lower levels of heat production and reduced tree canopy per parcel. Despite the association between grid networks and a reduced tree canopy, the total effect of intersection densities on net thermal emissions was found to be negative (-.176). This finding supports the hypothesis that the configuration of trees throughout a neighborhood may be more significant to heat production than the total number of trees. It should be noted, however, that the effects of the intersection density variable cannot be precisely determined from this analysis. As a mechanism for distinguishing between urban and suburban development models, the intersection density measure captures the effects of all factors related to these development patterns not already included in the model. Identification of the exact mechanism through which grid networks reduce net thermal emissions will thus require further study.

Discussion and Conclusions

The analysis results lend support to the theory that an expansive form of urban residential development emits more excess radiant heat energy per parcel than one of urban densification. Evidence for this conclusion is provided by the strong positive relationship found between the pervious and impervious areas of single-family residential parcels and net thermal emissions. It is important to note, however, that large parcels are not inherently thermally inefficient. As discussed above, a fully forested parcel of land, no matter how large, contributes no excess radiant emissions to surface heat island formation. Rather than the total parcel area, it is the quantity of *exposed* surface area that likely underlies the positive relationship found between parcel size and net thermal emissions. Although larger parcels tend to ded-

icate a greater *proportion* of the lot to tree canopy cover, these lots tend to have a greater uncanopied *area* as well. For example, if both an acre- and a 1/4-acre-sized lot exhibit a 50% tree canopy cover, the larger lot is exposing four times as much surface area (1/2 acre vs. 1/8 acre) to incoming radiation. This relationship is confirmed by a positive and significant correlation found between total parcel area and the area of the parcel not covered by tree canopy ($r=0.70$, $p<.000$).

As Figure 5 illustrates, there are exceptions to the general relationship between parcel size and thermal efficiency. While the quantity of net thermal emissions within a typical low-density neighborhood is high, there are a few parcels greater than 1/2 acre with low to moderate levels of net thermal emissions. Likewise, a handful of high-density parcels, depicted in the thematic map on the right, exhibit moderate to high levels of net thermal emissions. This variability in net thermal emissions illustrates that parcel thermal efficiency is sensitive to both the area and design of single-family parcels.

The finding of a significant relationship between parcel size and net thermal emissions provides empirical support for two general design strategies: (1) the imposition of restrictions on the zone of urban development (e.g., an urban growth boundary) and (2) the introduction of area-based tree canopy requirements. The promotion of infill development and higher-density new construction as strategies for accommodating new growth would improve the study region's thermal efficiency by reducing the area of urban development and deforestation. As illustrated by the analysis, smaller parcel sizes are associated with lower net thermal emissions per single-family household. By reducing the total quantity of land allotted to residential uses, infill and higher-density new development preserve a greater quantity of undeveloped land at the region's periphery, offsetting the additional thermal emissions that would result from continued urban expansion.

A second design strategy for mitigating the thermal effects of large parcels might involve the creation of an area-based requirement for tree planting. Similar to tree ordinances recently enacted in portions of the Atlanta region, design guidelines specifying that a particular number of trees be set aside or replanted in proportion to the area of the parcel being developed recognize the interaction between parcel area and heat production. In addition to the number of trees planted, the placement of trees is critical as well. A thin but well distributed canopy of trees is likely to be more thermally efficient than a dense cluster that leaves a large proportion of the property completely unshaded. Street trees should be required to provide shading over hot street surfaces, sidewalks, and houses set back only a short distance from

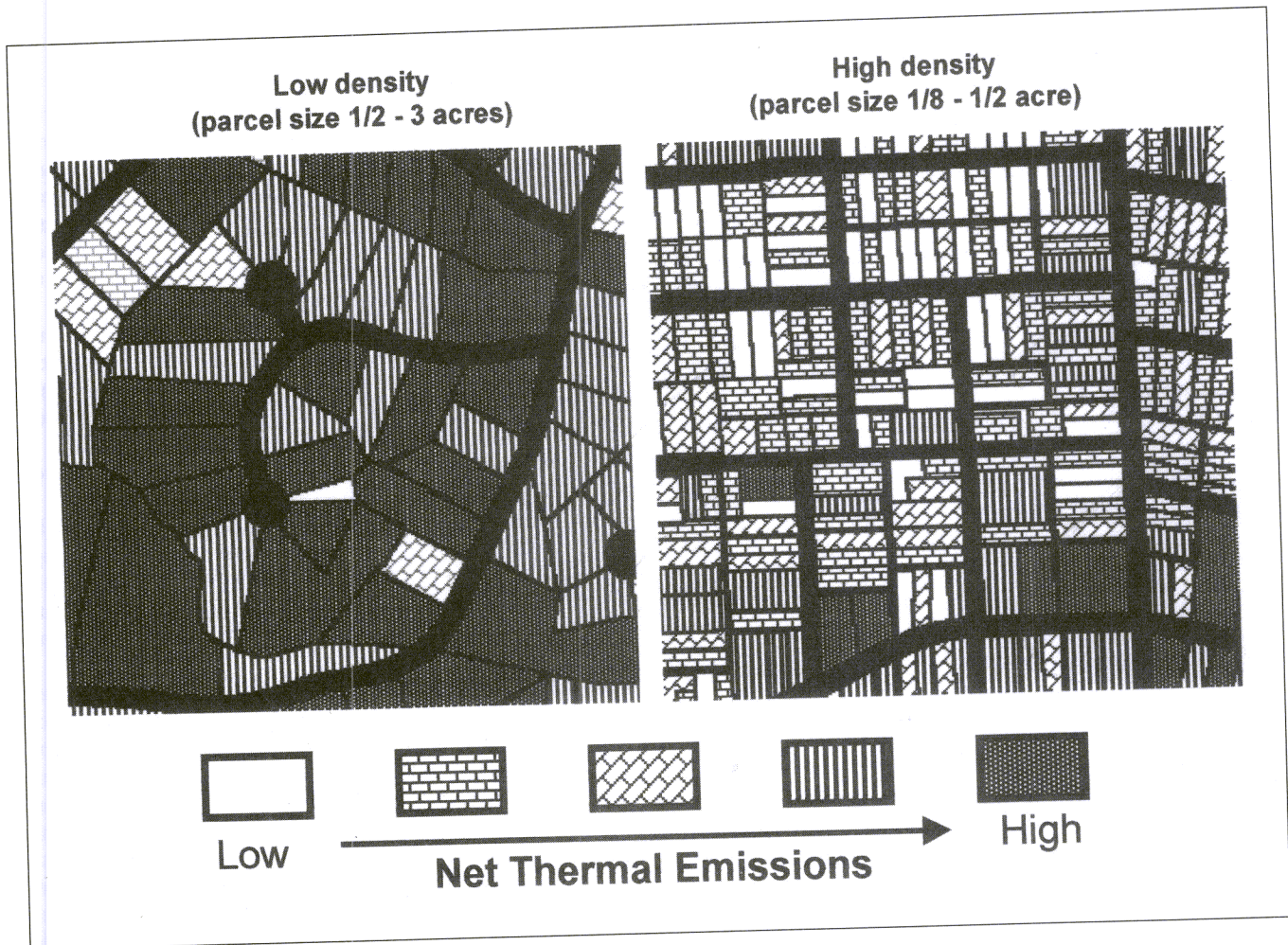


FIGURE 5. Net thermal emissions by development pattern.

the street. A graduated tree canopy standard has the advantage of improving the thermal efficiency of both new and existing residential development.

In general, we believe the findings from this analysis indicate the need for a two-part strategy to combat urban warming. Currently, the range of mitigation strategies advocated by organizations such as the Cool Communities program and the Heat Island Group of the Lawrence Berkeley National Laboratory rely upon the use of reflective roofing and paving materials to enhance urban albedo¹⁴ and offset heat absorption. In our view, this strategy embodies a technological approach to heat island mitigation that serves as a moderately effective short-term strategy. As with most problems related to urban sustainability, it is the predominant patterns of land use that fuel an overconsumption of scarce natural resources such as forests and elevate the per capita demand for infrastructure and energy. The results from

our analysis indicate that, rather than the area of paved and shingled impervious surfaces, it is the quantity of land devoted to residential lawns and landscaping that is most strongly related to excess heat production from single-family development in Atlanta. In light of this finding, we believe that fundamental changes in the patterns of residential development must be adopted in concert with albedo enhancements to effectively mitigate urban warming over the long term.

Prior to adopting design policy based upon the results of this work, it is important to note that the findings presented herein are climate specific. The intensity of heat island formation is driven largely by climatic attributes concerning annual temperatures, rainfall, and wind regimes. In the absence of data from cities within a range of diverse climates, the results of this analysis are most appropriately applied to the Atlanta region alone. It is likely, however, that similar patterns of development

found in any mid-latitude, temperate setting would exhibit a relationship with thermal emissions similar to that found herein.

Future work on this topic is needed to establish the significance of urban design to heat island formation within additional climatic regions. As noted above, the predominance of heavily forested land covers in proximity to the Atlanta region contributes to a strong urban-rural temperature gradient that is not characteristic of many large metropolitan areas. An analysis of high-resolution thermal data obtained by NASA over other metropolitan areas such as Baton Rouge, Louisiana; Sacramento, California; and Salt Lake City, Utah, will aid in better establishing the interaction between urban design and heat island formation across a more diverse set climatic regions and development patterns. In addition, the precision of this type of analysis could be improved with detailed information on the species of canopy vegetation and the types of paving and roofing materials found per parcel, and the contribution of street paving to thermal emissions on the neighborhood level. Future analysis of the Atlanta data will also examine the role of commercial and industrial patterns of development on surface heat island formation.

The purpose of this research has been to develop and test a methodology for measuring the interaction between urban residential land use and surface heat island formation. The results of the analysis challenge the notion that heat islands are predominantly a product of high-density development found within traditional downtown cores. Rather, the mechanisms that drive urban warming are regional in scale and highly sensitive to the total area occupied by the city and its suburbs. While it is important to note that all urban regions will alter their local climates in some fashion, the findings from this analysis provide evidence that the intensity of these changes and their ultimate harm to the environment can be significantly reduced through informed and efficient uses of land.

ACKNOWLEDGEMENTS

This project was made possible through the provision of data and technical support from the Project ATLANTA group of NASA's Global Hydrology and Climate Center. The authors would like to acknowledge the efforts of Maury Estes, in particular, without whose continual assistance and interest a project of this nature could not have been undertaken.

This research was supported through the STAR Graduate Fellowship Program. This article represents the views of the authors. It was not edited in any way by the U.S. Environmental Protection Agency, nor subjected to the agency's peer review process. Mention of trade names or specific applications of research or technologies does not imply endorsement or acceptance by U.S. EPA.

NOTES

1. "Radiant heat" refers to the flux (rate of flow) of energy that is transported from the earth's surface in the form of longwave radiation. This study utilizes remotely sensed thermal data to derive an estimate of the radiant flux from single-family residential parcels within the Atlanta metropolitan region. It is important to note that accurate determination of the total quantity of heat released by surface features requires information on the range of particular materials found per parcel of land and the emissivity of those materials. Consistent with previous remote sensing analyses of the surface heat island, this study is interested in the relative quantity of heat emitted per parcel rather than the absolute quantity (Roth et al., 1989).
2. Radiation intercepted by the earth's surface is received from both the sun and the atmosphere.
3. Although the displacement of vegetative land covers by urban construction materials is the most widely recognized influence of urbanization on heat island formation, other factors such as air pollution and the release of anthropogenic heat are also known to enhance urban temperatures (Oke, 1987).
4. One important limitation of remotely sensed thermal imagery is that it presents a "birds-eye" or planimetric view of the urban surface. As a result, radiant emissions from the horizontal surfaces of streets, rooftops, and lawns tend to be overemphasized relative to those from the vertical surfaces of building walls. This limitation of remote sensing complicates the process of deriving an accurate surface temperature for all surfaces. It is important to note, however, that this study is interested not in the absolute but rather the relative thermal emissions from single-family parcels. Because the contribution of vertical surfaces to net thermal emissions is underestimated to some degree for all parcels, this limitation is not expected to significantly influence the results.
5. It should be noted that this work is not being conducted as a formal component of the Project ATLANTA study. The Global Hydrology and Climate Center of the National Aeronautic and Space Administration is utilizing an advanced multispectral sensor (the Advanced Thermal Land Applications Sensor, or ATLAS) to obtain high-resolution thermal data over four cities in different regions of the country. The Project ATLANTA team is conducting a land cover and thermal analysis within the Atlanta region to develop a comprehensive climatic model for estimating the impacts of various changes in urban form on future warming. This work differs from the Project ATLANTA study primarily in its unit of analysis, the parcel as opposed to the planning district, and its specific focus on residential parcel design.
6. Prior to Project ATLANTA, surface thermal data obtained through remote sensing was too low in spatial resolution to measure the thermal effects of distinct urban features. Weather satellites, for example, generally measure surface temperature at a resolution of one square kilometer, indicating that one measurement is made for each square

kilometer of surface area. At this low resolution, it is not possible to gauge the thermal impacts of features smaller than 1 kilometer in area.

7. Although NASA's thermal images cover a region of about 900 square miles centered on Atlanta's downtown district, full attribute data on the region's parcels in digital form is currently available only for the roughly 300 square miles situated in the City of Atlanta and Fulton County. As a result, the study region for this research includes all parcels located in the City of Atlanta and approximately 75% of those located outside of the city limits within Fulton County.
8. A forested land cover is utilized in deriving a baseline surface flux density due to the fact that a mixed forest of deciduous and pine trees is the natural land cover for the study region. In addition, the prevalence of highly erodible soils in the Atlanta region has prevented large-scale agriculture from persisting in this area of the state. A land cover analysis conducted as part of the Project ATLANTA study indicates that approximately 70% of all new development in the metropolitan region over the last 20 years has involved the conversion of forested tracts of land to residential land uses. It is important to note, however, that in regions where agriculture has a greater presence, the urban-to-rural temperature gradient can be expected to be somewhat lower than that produced by forested land covers.
9. Specifically, a Normalized Difference Vegetation Index (NDVI) was created with the use of the visible red and near infrared bands. The NDVI equation is as follows: $(\text{Near IR} - \text{Visible Red}) / (\text{Near IR} + \text{Visible Red})$.
10. A second approach to controlling housing capacity would be to control for the number of residents found per parcel. A decision was made to control for the number of bedrooms rather than family size due to the more direct link that exists between this measure of housing capacity and thermal emissions. A three bedroom house occupied by three individuals, for example, is not expected to emit significantly less heat than the same house occupied by five individuals. Were we to control for family size, it is likely that two identical houses and parcels would be found to have different levels of thermal efficiency due to the number of residents found in each house at the time of the analysis. Such a finding would complicate the process of isolating the influence of parcel design on net thermal emissions.
11. The area of each lot occupied by driveway paving is not included in the tax datasets. As a result, a sample of residential parcels stratified by age and size was selected to derive an estimate of paved surface area. The driveways of selected parcels were then physically measured to determine how driveway areas scale with parcel size and age throughout the region. The resulting driveway area estimate per parcel was then combined with the building footprint area to derive an estimate of the total lot area occupied by impervious surfaces.
12. Intersections may be identified from street network files in a geographic information system. To calculate inter-

section density, all discontinuous streets (dangling nodes) are removed from the street intersection file. A density "surface" may then be created that tabulates all the intersections found within a specified radius (1/2 mile) of all points in the survey region. This surface can be used to determine the number of intersections found per unit of area. The density surface may then be overlaid with parcel boundaries to estimate the average node density found in proximity to each parcel.

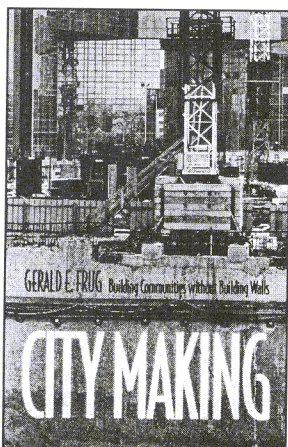
13. Total parcel area was not directly incorporated into the path analysis as an independent variable due to the strong covariance found between this measure and the pervious surface variable. A partial correlation between parcel area and net thermal emissions was found to be positive and significant when controlling for tree canopy cover, housing capacity, the year of development, and street network density ($r = 0.68, p < .000$).
14. Albedo is the ratio of the amount of solar radiation reflected by a surface feature to the amount incident upon it.

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