The Role of Tree and Building Shades in Neighborhood Thermal Control: A Three-Dimensional Digital City Approach

Introduction

This study examines the role of urban shades created by trees and buildings in regulating the local microclimate, with special attention to the heat mitigation capacity of urban trees canopies. Devising a natural and design-based solution to combat local warming is a very important urban planning issue. Increasing temperatures are expected to strike urban communities more harshly due to the Urban Heat Island (UHI) effect, where paved and dense urban built-up structures induce much higher temperatures and extreme heat, as compared to less developed exurban and rural areas. This significant local warming poses serious threats to public health and urban energy sustainability. Extreme heat waves are already responsible for more deaths in the U.S. than any other climate-related hazard, such as hurricanes, tornadoes, and flooding, with more than 65,000 Americans suffering acute heat illness every year (USGCRP, 2016). Energy consumption for air-conditioning buildings in warmer months is one of the leading causes of greenhouse gas emissions (Norman et al., 2006). To advance our understanding of a more heat-resilient urban design, this study investigates urban land-use characteristics that could better counteract rising temperatures, with a particular focus on the effective use of shades generated by trees and buildings.

Literature Review

Earlier studies on the urban thermal environment explained local temperature variations as functions of surrounding biophysical variables: land use and land cover (LULC) compositions, in particular the spatial distribution of vegetation (grass, shrubs, trees), impervious surfaces (buildings, roads, parking lots), water bodies, and bare lands. A greater proportion of impervious construction increases local surface heat, while vegetated lands decrease it (Dai et al., 2019; Weng, 2009). The configuration and juxtaposition of these land covers were also found to influence temperature variations (Weng, 2009). In addition to these mostly planar land-cover assessment, however, recent advances in geospatial analytics and the proliferation of public geospatial big data have opened the door to a more sophisticated digital representation of complex urban geometry in the three-dimensional (3D) space. A parameterization of 3D building structure (height, volume, orientation, and spacing) and street viewshed (sky-view factor) has shown that building configuration affects localized temperatures by regulating solar irradiation absorption, air ventilation, and shadow area (Alavipanah et al., 2018; Chun & Guldmann, 2014; Yu et al., 2019). One underexamined but critical aspect, however, is the role of shades projected by trees. There is only limited research on tree shadow effects, mostly experimental and focusing on a few sites and individual trees, where all factors other than tree species are controlled (Kong et al., 2016; Zheng et al., 2018). Tree canopies are generally omnipresent, especially in suburban residential settings, and particularly relevant for controlling summertime temperature, when trees reach their full potential in evapotranspiration and shading (Rahman et al., 2018). If trees are ignored, any resulting analysis may be incomplete and biased. Also widely missing in the literature is the joint consideration of the area and location of the produced shades and the type of ground covered by them. The cooling effect of shades may vary depending on both extent and location, such as over asphalt, grass, water, or building exterior. The shadow on different building surfaces, such as rooftops and façade, may have varying effects on heat mitigation by reducing different levels of solar radiation on those surfaces. This real-life aspect can only be studied with the development of a 3D digital city model and comprehensive land-use maps. This paper develops a system of multiple land-use layers derived from 2D/3D city models consisting of buildings, trees, and different types of land cover, in order to analyze the relationship between urban structure, shade formation, and thermal fluctuations. This study is the first attempt to analyze tree shade impact on local temperature at a large geographic scale and also the effects of shade volume, extent, and sub-shadow land-use heterogeneity.

Study Area

An area in the northern part of Columbus, Franklin County, Ohio, is the study area, covering both urban and suburban areas (Figure 1). It is a very relevant case study for urban heat risk analyses, as Columbus is ranked as top 8th among sixty largest U.S. cities for UHI severity (Kenward et al., 2014).

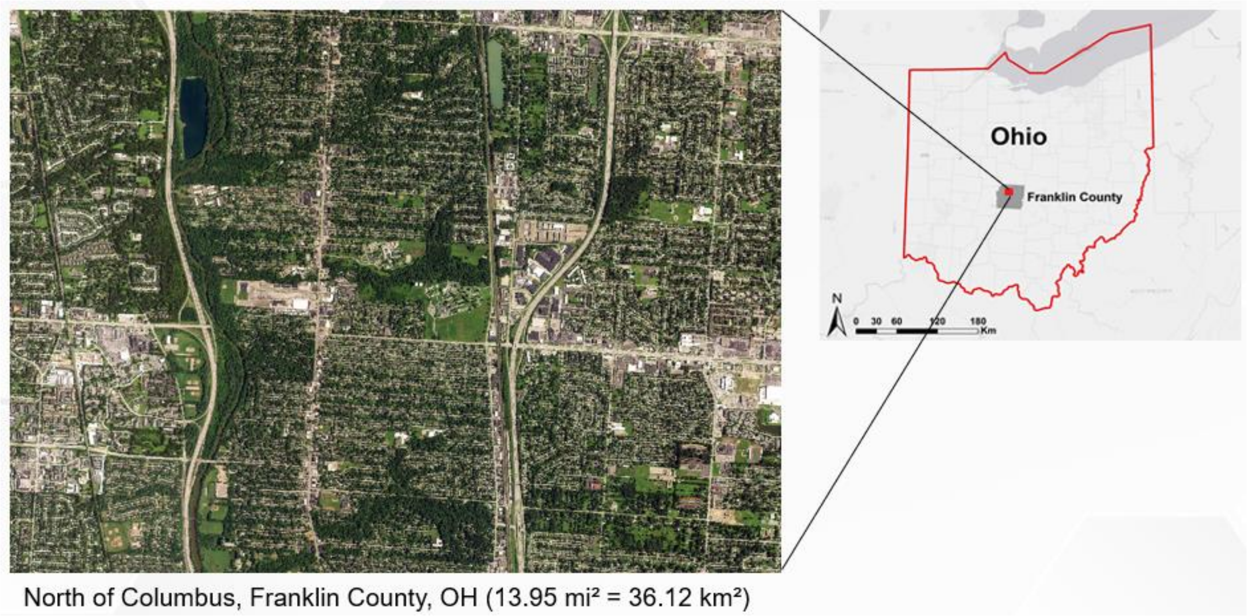

Figure 1. Study area located in the northern part of Columbus, Ohio.

Data & Methodology

The basic modeling approach is to establish a statistical relationship between local temperature variations and heterogenous urban built-up structures derived at the 2D/3D levels. The three major components of the methodology of this research are: (a) developing a system of multiple map layers representing 2D/3D land uses, derived from a 3D city model consisting of geometrically detailed buildings and trees, as well as 2D land covers; (b) computing 2D and 3D indicators (explanatory variables) quantifying the shade profile over the urban surface across the study area, as is derived from the 3D city model and shading simulation; and (c) estimating spatial statistical models that explain observed surface temperature variations. Urban thermal conditions are captured by land surface temperatures (LST) derived from thermal infrared remote-sensing imagery. Remotely-sensed LST data enables a spatially continuous analysis and is highly correlated with air temperatures, which are typically measured at only a few meteorological stations. The summertime surface temperatures in 2015 across the study area are obtained from Landsat 8 Thermal Infrared Sensors (TIRS) Analysis Ready Data (ARD), with a resampled thermal band of 30m spatial resolution.

3D Digital City Construction

First, a complete 3D city model is constructed, comprising realistic 3D buildings and trees, and 2D land cover types over the study area. Most prior studies have relied on the classification of satellite/aerial image pixels to derive the quantities of individual land cover types. As the images represent a top-down perspective, tree canopies are usually classified as vegetated cover. However, heterogenous surfaces may exist under this vegetation layer, including small houses, local street and road surfaces, lawns, and parking lots. As these ground-level structures can be occluded by tree canopies, actual land cover areas are often underestimated or misrepresented. To reveal this hidden structure, a multiple layer system stacking 2D and 3D land cover maps must be developed, leading to the computation of a suite of biophysical and urban geometric variables. As the first layer, 3D building objects are constructed, using Franklin County Auditor’s building footprint data (2015) and airborne Light Detection and Ranging (LiDAR) data

(2015) provided by the City of Columbus Data and Analytics Services. These two data are integrated using a Python-script program that utilizes machine learning algorithms to estimate building elevations. A detailed description and demonstration of this program is reported in Park and Guldmann (2019). To create 3D tree objects, Object-Based Image Analysis (OBIA) and LiDAR analysis are combined. OBIA classifies and groups image pixels based on spectral properties, object size, shape, and surface texture for object formation. It is used to delineate the extent of individual tree crown or forests, and is applied to leaf-on summer 4-band color infrared images (2015) provided by US National Agricultural Imagery Program (NAIP), with a pixel resolution of 1m. The radius, elevation, and density of individual tree crowns are estimated by further processing LiDAR point cloud data (2015). Specifically, by analyzing LiDAR point height, intensity, and number of returns, such parameters as the maximum tree crown height and radius are measured to recreate tree canopy objects in a GIS environment in terms of tree location, canopy area, and height (Zimble et al., 2003). Although there may be some variability in shade capacity and sunlight attenuation (solar permeability) across different tree species, it is very difficult to account for this variation due to data constraints. Therefore, the American Elm is selected as a representative tree species model for shade computation, as the species is one of the most common tree genus in the study area. The OBIA is also applied to leaf-off early spring false color images from OGRIP (Ohio Geographically Referenced Information Program) to capture the boundaries of other urban features, e.g. roads, water bodies, lawns, and bare plots, followed by manual and algorithmic corrections of the final image classification outcomes with additional data sources, such as OpenStreetMap network data. Finally, the 3D buildings, trees, and various land cover types are integrated using ArcGIS pro capabilities, forming a complete 3D city model (Figure 2).

Figure 2. An area of the 3D city model: single-family residential block with rich tree canopies.

Shading Simulation and 2D/3D Indicators

Based on the 3D city model, a 3D geometric shading analysis is conducted to create a realistic shadow layer (profile) over the 3D city surface, with a GIS calculation of average hourly solar radiation for a typical summer day (September 14). The sun locations and sight lines are simulated with 3D buildings and tree objects used as obstructions, in order to estimate the shade morphology projected onto the surface of the urban landscape. The hourly shading simulation is carried out with ArcGIS pro capabilities. The output of this simulation is a grid surface where each grid cell contains a value representing how long the corresponding cell is exposed to solar insolation during the specified time. To interface the simulation results with the time that the local LST values were captured by Landsat 8 satellite, the sun locations are set up to be on September 14, 2015, from 11AM to 12PM Eastern Standard Time. The simulation results are reclassified where shaded/not-shaded pixels (i.e. grid cells) are made distinct at the 2m resolution. If a given grid cell is partially or completely shaded by elevated objects for the given period, its value equals to 1, otherwise 0. This gridded surface is then quantified into a set of variables indicating the area and surface type covered by shadows or exposed to solar radiance. The novelty of this method is that the 2D and 3D objects are overlaid and simultaneously analyzed to compute shade footprints, volume, and sub-shadow land cover quantities. The computed explanatory variables include the volume and/or area of each object and the area proportions (%) of shaded/not-shaded surfaces: low vegetation cover, non-building impervious cover, water bodies, sun-facing building façade, not-illuminated building façade, building rooftop, and tree canopy volume.

Statistical Analysis and Scenario Testing

The relationship between local LSTs and 2D and 3D urban built-up characteristics is quantified using multivariate linear regression analysis. The dependent variable is the LST value of each 30m grid cell. The explanatory variables, which were initially computed at the 2m spatial resolution, are therefore aggregated into 30m grid cells to fit with the LST grid. There are 39,716 LST cells in the study area.

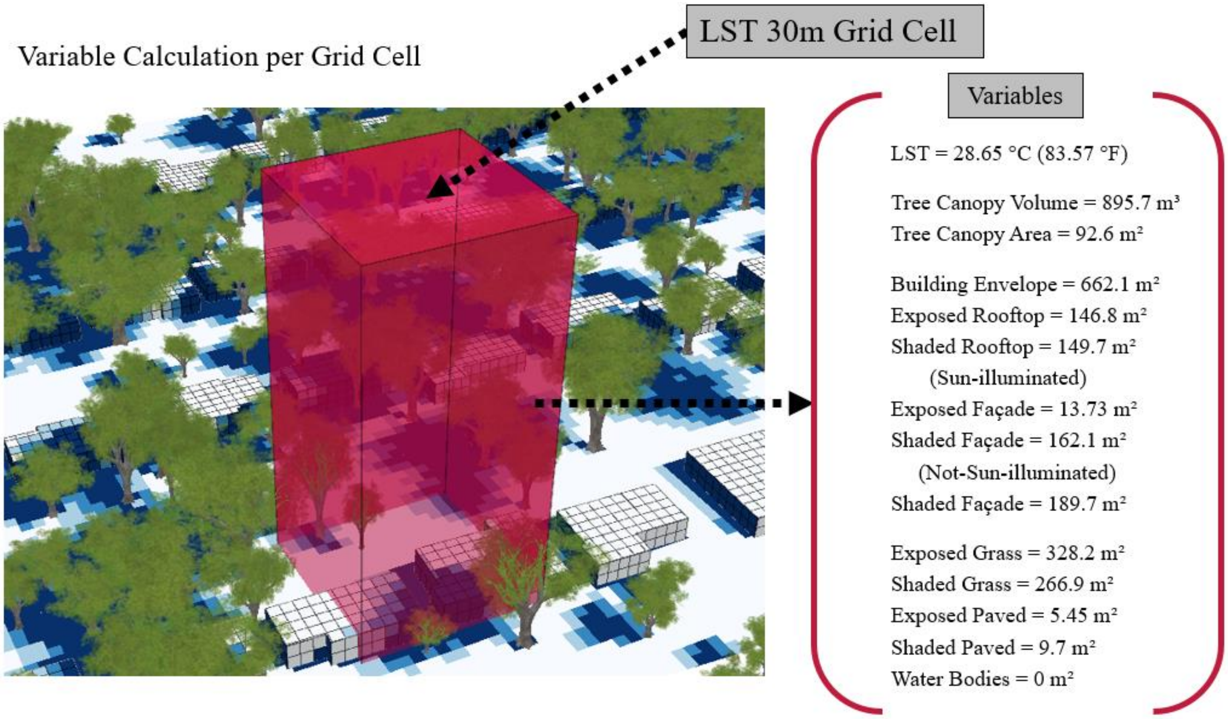

Figure 3. Aggregating explanatory variables at the 30m resolution to match the temperature grid

Results

Spatial regression modeling

The linear regression analysis results (Table 1) show that the urban shades created by trees and buildings have significant impacts of reducing local surface temperatures, and that these impacts do vary by their location over the urban surface.

First, tree canopy volume turns out to have a significant negative coefficient. This means that tree canopies can significantly reduce local temperatures. This heat-mitigation effect of tree volume is most likely due to the evapotranspiration capacity of urban trees, because the effect is statistically independent from the effects of shade cast by trees onto other urban features, such as buildings and impervious covers, that are controlled for in the regression model. It is also found that water bodies can reduce the local temperature as significantly as tree canopies. This is a rather expected result because water has a high heat capacity.

More important is that two distinctions made in terms of shade location on buildings are very meaningful in explaining LST. The distinction between rooftop, sun-facing façade, and the rest of the façade (not illuminated by the sun) turns out to be meaningful, and the distinction of shaded versus not-shaded surfaces also matters. The results show that a larger building envelope area increases LST, and it is the greatest contributor to LST, given the size of its standardized coefficient. If not shaded, the exterior area of a building has the largest impact on raising LST. However, the shaded rooftop, the shaded sun-facing façade, and the shaded not-illuminated facade areas have all negative coefficients, which means that these shaded areas reduce the local temperatures and therefore can mitigate the heat induced by building structure on surrounding LST. Among those three types of building surface, the shaded façade invisible to the sun has the largest impact on cooling LST, followed by the shaded rooftop area, and the shaded sun-facing (illuminated) façade.

Shade also modifies the effects of land covers. The sun-exposed impervious area has positive coefficient, suggesting that it increases LST. Yet, if it is shaded, the impervious area has no significant influence on LST, meaning that it may neither increase nor reduce LST. The vegetated area exposed to the sun has a negative sign, confirming that vegetation contributes to LST cooling, even when it is not shaded. If vegetation exists under shade, it has even stronger impacts in cooling down LST. In sum, shade can both mitigate heating of paved land covers and amplify the effect of natural coolants such as trees and grass.

Table 1. OLS regression model estimating the relationship between LST and urban 2D/3D built-up characteristics combined with the simulated shade profile

Explanatory Variables		Std. Coefficient	t-stat
Constant	Constant	30.82***	424.3
3D Tree	Tree Canopy Volume (m^3)	-0.225***	-38.9
3D Building	All Envelope Area (m^2)	0.344***	34.8
	Shaded Rooftop Area (m^2)	-0.072***	-15.0
	Shaded Illuminated Façade Area (m^2)	-0.035***	-5.94
	Shaded Not-Illuminated Façade Area (m^2)	-0.161***	-22.1
2D Ground Land Cover	Water Bodies (m^2)	-0.238***	-53.7
	Sun-Exposed Impervious Area (m^2)	0.195***	25.0
	Sun-Exposed Vegetated Area (m^2)	-0.149***	-24.4
	Shaded Vegetated Area (m^2)	-0.324***	-34.3
Adjusted R^2		0.550	
Std. Error of the Estimate		1.91	

***: $p<0.01$

Greening scenario simulation

The regression analysis results demonstrate that urban shade can buffer the negative impacts of urban development on the local microclimate and its impact varies by its location. With the estimated statistical parameters, it is possible to predict the LST impacts of multiple future scenarios involving changes in buildings and trees, and also land surface conversions. Based on this statistical model explaining the variations in LST, some simulation analyses are conducted to test the impacts of different urban greening scenarios at the neighborhood scale.

As an example, two common scenarios related to trees are conceived: tree growth and tree planting. As for tree growth, a change in LST is predicted when all trees in a neighborhood are allowed to grow to their full size. American Elm trees can grow up to 80 feet high and 60 feet wide on average. To simulate this situation, some parameters of individual trees are modified in the GIS environment, including the height and crown width of each tree. With regard to tree planting, an additional set of trees are planted in a neighborhood to see how much reduction in LST these new trees can bring into this neighborhood. To create as large an area of shadows as possible, these new trees are added where few trees exist. Based on these scenario-modified 3D neighborhood models, the shade simulation is carried out again, followed by variable computation, aggregation, and then application of the regression coefficients in order to predict the LST value as a function of the new set of explanatory variables.

According to the simulation results, the initial average temperature of the selected neighborhood is 31.6 degree Celsius (Figure 4). If all the existing trees in the neighborhood grow naturally to their full size, the local average LST may experience a reduction down to 29.1 degree Celsius. With twenty new trees added to the neighborhood, the average LST would go further down to 28.5 degree Celsius. The combined LST reduction effect in this case is 3.1 degree Celsius. Scenarios other than tree growth and planting, and involving changes in terms of building configuration (e.g. building footprint size, height, and location) could also be evaluated to obtain an assessment of the expected impacts of landuse change and other urban development on neighborhood thermal conditions.

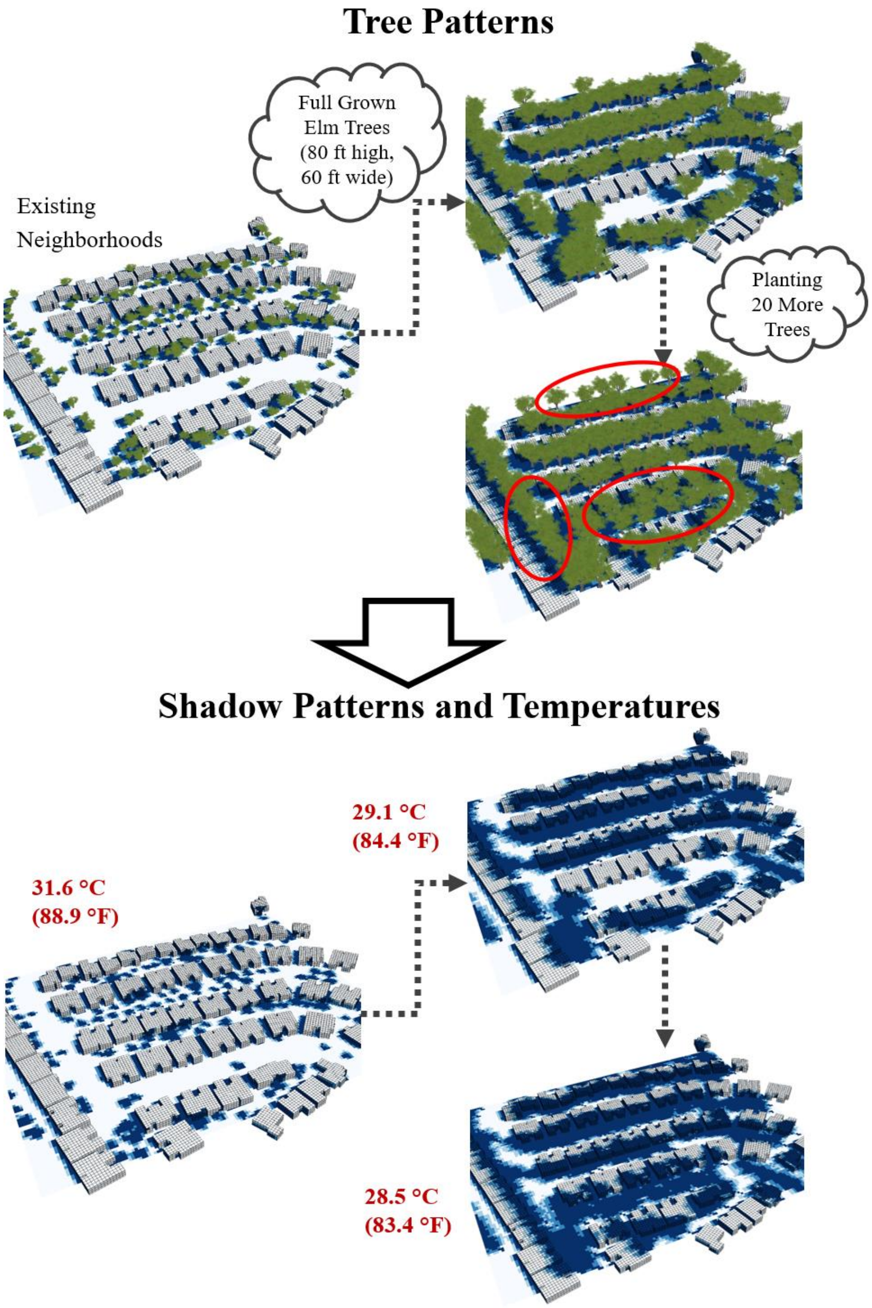

Figure 4. Predicting the LST impact of two greening scenarios: tree growth and planting

Conclusions

In pursuit of a natural, design-based urban planning solution to local warming, this study has examined effective configurations of urban shades created by 3D trees and buildings. A system of multiple map layers representing land uses at the 2D and 3D levels has been developed, including shade layers derived from an advanced geometric analysis of a 3D digital city model consisting of buildings and trees as well as 2D urban features. The variations in the observed local temperatures in Columbus, Ohio, in 2015, were analyzed by developing complex urban characteristics combining built-up structure, natural features, and shade profile, and using multivariate linear regression.

The results provide unique implications for policymakers to design climate-smart land use strategies. This study has found that urban shades, in terms of amount and location, have statistically significant effects on local LST measured at the 30m spatial resolution. Urban trees are beneficial in cooling surface temperatures of neighborhoods through two separate functions, evapotranspiration and shading of paved structures and natural lands. Larger building footprints within residential subdivisions have significant adverse effects on local warming, with greater rooftop and façade areas becoming vulnerable to solar radiation, and only limited space left for current and future tree planting efforts. Natural tree growth has a significant potential to decrease neighborhood temperatures, with a greater relief expected when combined with additional tree planting. The actual size of the drop in LST can be assessed with 3D simulation.

The quantitative modeling of the relationship between 3D land-use structure and local LSTs is critical for the development of local greening strategies and judicious decision-making on urban development and land-use change. The research outcomes could be used to formulate detailed guidelines about community greening and tree planting efforts (e.g. tree crown size and location) in relation to close-by buildings and land covers by providing empirical evidence on local heat mitigation.

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