Investigating the Impact of Urban Tree Planting Strategies for Shade and Residential Energy Conservation

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Geospatial and Environmental Analysis

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August 11, 2015
Blacksburg, VA

Keywords: arboriculture, cooling and heating energy, energy savings, simulation modeling, urban forestry, urban heat island, urban tree canopy

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ABSTRACT

Expanding urbanization, characterized by increased impervious surfaces and decreased tree canopy, is contributing to rising urban temperatures. This trend has implications for energy consumption, which strategically placed trees can modify by casting shade upon building and ground surfaces. However, urban densification, a paradigm of modern residential land development, often constrains space for planting shade trees. Thus, the overall objective of this dissertation was to investigate shade tree planting strategies and their effects on residential cooling and heating energy conservation for dense urban neighborhoods in U.S. cities on a latitudinal gradient. The first study used a computer program called Shadow Pattern Simulator to examine the effects of tree form, tree placement, and sunlight exposure on shade provision for a residential structure model. Simulation results affirmed the conventional strategy in northern latitudes that recommends planting shade trees on the east or west aspect for maximizing beneficial shade while avoiding tree plantings on the south aspect to minimize any heating penalty of undesirable shade. However, in southern latitudes, planting trees on southerly aspect should not be discounted because the shorter heating season lessens the detrimental heating penalty while providing beneficial season shade. The second study, using an energy simulation program called EnergyPlus, evaluated the effect of a single shade tree upon the energy consumption of the structure model. This study affirmed that energy conservation benefits are influenced by the quantity as well as the quality of tree shade upon building surfaces. In addition, interactions between sun angle, tree form, and tree placement were observed to influence tree shade effects on annual energy consumption. In the third study, based on the first two studies, an alternative tree placement strategy, which reconfigured tree placement around the residential structure, was developed to maximize cooling and heating energy savings while attenuating space conflicts. The alternative strategy was found to be as effective as the conventional strategy while being more responsive to parcel or building orientations in dense urban neighborhoods. Overall, understanding the fundamental interactions between tree form, tree placement, and geographic settings is critical for improving energy conservation benefits of shade trees in dense urban settings.

Acknowledgements

First of all, I would like to express my greatest appreciation to my co-advisors, Dr. Eric Wiseman and Dr. Valerie Thomas. Without their endless advice, guidance, and support, I could not have achieved my goal here at Virginia Tech. Especially, Dr. Wiseman, I was greatly encouraged by your enthusiasm for mentoring and research.

I would like to thank my committee members, Dr. James Campbell and Dr. Randolph Wynne, for your time and valuable advice. Meeting with you guided me in the right direction for academic and research accomplishments. Dr. Campbell, you showed me what a teacher really is.

I would like to thank VT faculties for their generous support. Dr. Susan Day (FREC), Dr. Steve Prisley (FREC), and Dr. Inyoung Kim (Statistics). Special appreciation goes to Dr. Harold Buckhart (FREC) for his interest in and advice on my research.

I would like to thank Dr. Hongman Kim, Dr. Byoung-Do Kim, Dr. Gwibo Byun, Dr. Sungwon Kim, Pastor Dongjin Lim and other friends in the Korean communities for the advice and encouragement.

I would like to thank Tammy Parece and other fellows in the RS/GIS group as well as the Urban Forest/Urban Horticulture group.

I would like to thank Jason Yoon and Carla Edward for their valuable perspectives while preparing the dissertation.

I would like to thank my parents and parents-in-laws for their love, prayers, and support with their best wishes.

I would like to thank my lovely wife Sujeong Kim and my two daughters Woosul (Kristine) and Naum (Kaylee) for their love, encouragement, and patience.

Last but not least, I would like to thank God for his love and guidance me in my life.

Table of Contents

List of Figures

List of Tables

Chapter 2 Tree planting configuration influences shade on residential structures in four U.S. cities

Chapter 3 Simulation of Shade Tree Effects on Residential Energy Consumption in Four U.S. Cities

Chapter 4 Enhancing the energy conservation benefits of shade trees in dense residential developments using an alternative tree placement strategy

Chapter 1 Introduction

Research Context and Justification

Major U.S. cities have experienced an increase in temperatures at a higher average rate per decade as compared to suburban and rural areas (Stone 2007). Urban trees play an important role in altering heat fluxes, which, in turn, contributes to moderating urban temperatures (Gill et al. 2007; Loughner et al. 2012). As urbanization progresses, tree canopy is displaced by impervious surfaces, such as roads, sidewalks, and parking lots. Impervious surfaces store and re-radiate heat more so than natural land cover, contributing to increased urban temperatures, known as the Urban Heat Island (UHI) effect (Rizwan et al. 2008). As well, due to higher temperatures, urban areas often experienced Extreme Heat Events (EHEs) – oppressive conditions due to a combination of hot and humid summertime weather, which leads to heat-related illnesses (Luber and McGeehin 2008; Patz et al. 2009). When considering that each 1 °C rise in urban temperature typically increases electricity demands by 2-4% (Akbari et al. 2001), the UHI effect could have significant detrimental implications for human health and for building energy consumption for regulating indoor temperatures.

Trees can modify urban temperatures and consequently help to reduce residential cooling and heating energy consumption through three distinct processes: (1) by casting shade that cools surface temperatures of ground covers and buildings; (2) by providing evapotranspiration cooling, and (3) by reducing wind speeds (Huang et al. 1987; Akbari 2002). By intercepting solar radiation, tree canopies can help keep residences cool and minimize cooling energy consumption. This is especially true when trees are located on the west aspect and cast shade on building surfaces in the afternoon when cooling demands have peaked, thereby providing the highest conservation benefits (Simpson and McPherson 1998; Akbari et al. 2001; Simpson 2002; Donovan and Butry 2009; Nikoofard et al. 2011). Also, in summer months, moisture released from trees (transpiration) and the surrounding ground (evaporation), known collectively as evapotranspiration, lowers ambient temperatures, thus reducing cooling energy demands. As tree canopy increases, the evapotranspiration cooling effect increases (Huang et al. 1987; Jensen et al. 2003). As well, windbreak effects decrease cooling and heating demands through reducing the infiltration of cold (winter) or hot (summer) air into a house (DeWalle and Heisler 1983; Heisler 1986a).

With the notion that areas with more trees are cooler and residents in those areas tend to spend less energy for space conditioning, numerous planting programs have been implemented to offset the UHI effects and thereby mitigate its impacts on energy consumption (Hildebrandt and Sarkovich 1998; Pincetl et al; 2013; Sawka et al. 2013). Lower-density urban residential areas contain not only more existing tree canopy but also more potential tree planting sites. Old neighborhoods typically have more established trees (with more canopy) than new residential developments (Carver et al. 2004; Donovan and Butry 2009). As well, these new developments typically have fewer mature trees many of which are not optimally located for energy conservation. Therefore, recent developments would be considered as important potential areas for strategic tree planting for energy conservation. The recent trend of reduced parcel size and increased home size (Sarka 2011), often limits the possibility of multiple tree plantings. For this reason, when considering that shade benefits per tree could be greater with a strategically placed single tree than with some multiple tree landscapes (McPherson and Dougherty 1989; Souch and Souch 1993), strategic tree planting becomes more significant.

The quantity, quality, and timing (daily and seasonal patterns) of tree shade cast upon building surfaces impacts the magnitude of shading benefits with regard to energy conservation (Heisler 1986b). The important interactions between tree form (shape, size, and type) and placement influence shade quantity and timing. As well, the quality of tree shade would be determined by the time of day and season that a tree casts shade on building surfaces. Therefore, comprehensive knowledge of the relationship between these variables is critical for developing appropriate shade tree planting strategies for dense urban neighborhoods.

Research Scope and Aim

This dissertation, using computer simulations, analyzes tree shade effects on residential energy consumption across a U.S. latitudinal gradient. Quantifying and qualifying tree shade upon a residential structure model help to explicate the effects of tree planting configuration and interactions with sun movements and local climate.

Dissertation Components and Attribution

This dissertation is composed of three interrelated manuscripts prepared for submission to peer-reviewed academic journals. Combining the three manuscripts reflects a study of how tree shade contributes to temperature mitigation that results in residential energy conservation. The first manuscript (Chapter 2) characterizes daily and seasonal patterns of tree shade cast by a single tree (quantitative focus on a residential structure) situated across a broad latitudinal gradient in the U.S. The research findings were then used to ascertain whether regional planting guidelines provide adequate recommendations for maximizing tree shade given the local solar conditions. This first manuscript, co-authored with Dr. P. Eric Wiseman (co-chair) and Dr. Valerie A. Thomas (co-chair), was published in *Arboriculture & Urban Forestry* (Hwang et al. 2015). The second manuscript (Chapter 3) evaluates tree shade cast by various single tree planting configurations (qualitative focus) in diverse geographic locations in order to improve residential cooling and heating energy conservation by the use of a single shade tree. This second manuscript, co-authored with Dr. P. Eric Wiseman and Dr. Valerie A. Thomas, is under review by *Cities And The Environment (CATE)*. Based on the findings from the first two manuscripts, the third manuscript (Chapter 4) proposed tree placement strategies that would correspond to conditions of recent residential developments as a means to enhance energy conservation benefits as urban neighborhoods densified. As an intermediate step for developing optional tree placement strategies, this chapter began with characterizing the urban landscape conditions in new residential developments and evaluating how much the current residential trees could save on annual energy consumption. Then, this chapter proceeded to delineate tree placement strategies for improving on current conditions. This third manuscript, co-authored with Dr. P. Eric Wiseman (co-chair) and Dr. Valerie A. Thomas (co-chair), is being prepared for submission to *Landscape and Urban Planning*.

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Chapter 2 Tree planting configuration influences shade on residential structures in four U.S. cities

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Published in *Arboriculture & Urban Forestry* 2015, 41 (4): 208-222, available via

http://auf.isa-arbor.com/request.asp?JournalID=1&ArticleID=3363&Type=2

Abstract

Expanding urbanization, characterized by increased impervious surfaces and decreased tree canopy, is contributing to rising urban temperatures. This trend has implications for energy consumption and human health, which urban trees may help mitigate by casting shade upon building surfaces. This study looks at how tree form and placement can improve on current shade tree planting guidelines to more effectively use shade trees to offset this trend. Shade provision is not only a function of tree characteristics but also daily, seasonal, and latitudinal variability in sunlight exposure. In order to understand how these variables influence shade provision and to evaluate existing tree planting guidelines, a computer program called Shadow Pattern Simulator was employed to quantify shade cast by a single tree upon a prototypical residential structure in four U.S. cities. A total of 576 shade simulations showed large trees situated within five meters on the east or west aspect of the structure provided the greatest amount of shade during the cooling season. The simulation results affirm existing tree planting guidelines in northern latitudes that recommend planting shade trees on the east or west aspect while avoiding tree plantings on the south to minimize the heating penalty of unwanted shade in northern latitudes. However, planting trees on southerly aspect should not be discounted in southern latitudes because the shorter heating season lessens the detrimental heating penalty of unwanted shade while providing much-needed cooling season shade.

Keywords: Climate change; Cooling; Energy Conservation; Heat Stress; Urban Heat Island; Urban Tree Canopy

Introduction

Trees situated in urban environments can significantly influence ambient air temperatures through evapotranspiration and shading (Akbari 2002). Urbanization displaces tree canopy cover with buildings and pavement, which absorb, retain, and reradiate heat at greater rates than vegetation. As a result, urban areas tend to have higher air temperatures than outlying rural areas where vegetation is more abundant – this phenomenon is known as the urban heat island (UHI) effect. The trend of increasing impervious surfaces and decreasing tree canopy cover in major U.S. cities (Nowak and Greenfield 2012) has been implicated as a key driver of rising urban temperatures nationwide. Stone (2007) reported that, from 1951 to 2000, the temperature of 50 large U.S. cities increased at a higher average rate per decade than comparable rural areas. Given current trends in land use and demographics, the UHI effect will likely impact an ever-expanding land area and population base in the future, which could have significant implications for human health and building energy consumed to cool buildings.

In urban areas, the UHI effect increases the incidence of Extreme Heat Events (EHEs) – oppressive conditions due to a combination of hot and humid weather – leading to heat-related morbidity and mortality of people (Luber and McGeehin 2008). Exacerbating EHEs in urban areas is the lack of shade trees and other vegetation, increasing exposure of urban residents to more heat stress compared to their rural counterparts (Patz et al. 2009). Even in the absence of EHEs, urbanites must still endure the physical discomfort and stress of the UHI effect during hot summer months. The Human Thermal Comfort Index (HTCI) is an indicator used to identify the level at which increased temperatures cause heat-related illness. Research has shown that neighborhoods with sparse vegetation have higher temperatures and HTCIs (Harlan et al. 2006). Heat-related health disorders not only diminish quality of life for urbanites, but also have significant economic impacts. From 2002 to 2009, health care costs for heat-related diseases in the U.S. were about $5.3 billion (Knowlton et al. 2011).

The UHI effects also impact energy consumption for cooling buildings. During EHEs, increased use of air conditioning puts a strain on electric utility grids, often leading to infrastructure failures and brownouts (Kurita and Sakurai 1988; Walsh 2013). Each 1 °C rise in urban temperature typically increases electricity demand by 2% to 4% (Akbari et al. 2001). As well, because electricity generation relies heavily on extraction and combustion of fossil fuels in many parts of the U.S., increased energy demand for cooling also impacts air and water quality. Electricity generation emits an average of 0.45 kg of carbon dioxide and requires 157 liters of water for each kWh generated (US Government Accountability Office 2012; Wilson et al. 2012). With the average U.S. residence consuming about 900 kWh (about 6% of which is air conditioning) per month in 2012 (US Energy Information Administration 2014), the annual carbon and water footprint of electricity consumption per U.S. residence is nearly 400 kg and 142,000 L, respectively. Moreover, costs of electricity for air conditioning may create financial hardships for both businesses and residences, particularly in economically disadvantaged urban neighborhoods (Harlan et al. 2007). Compounding the UHI effect on cooling energy consumption is climate change. Given predictions of a warmer planet in the future (US Global Change Research Program 2009), demand for cooling energy will likely increase in some regions of the U.S.

Numerous strategies have been proposed to counteract the UHI effect and thereby mitigate its impacts on human health and energy consumption. Increasing tree canopy cover through the strategic planting of trees in the built environments is increasingly seen as a key strategy for mitigating the UHI effect. Because areas with shade trees are typically cooler, occupants of shaded buildings tend to consume less energy for air conditioning during the summer months. According to the Arbor Day Foundation, its Energy-Saving Trees program has distributed more than 140,000 trees in six U.S. cities, and these trees are expected to save up to 264 million kWh of energy by 2025 (US Administration 2014). Planting more trees for energy conservation is clearly important, yet residential parcels are increasingly constrained for space and resources for planting shade trees. Average yard sizes in the U.S. are decreasing due both to an increase in home sizes and a decrease in lot sizes (Sarkar 2011), which limits spaces for planting multiple shade trees. Moreover, community tree distribution programs are often limited to providing one tree per parcel in order to distribute trees equitably. Therefore, to maximize the health and energy benefits of trees, it is crucial that we understand how the selection and placement of a single tree on a residential parcel influences shading (and therefore energy consumption) for nearby buildings.

Shade provision by a single tree onto a building is a function of two factors: tree form and tree placement. Tree form describes the physical attributes of a tree whereas tree placement describes its location relative to a building targeted for shading. Each of these two factors comprises a suite of variables (Figure 1) that – in combination – constitute a unique tree planting configuration, hereafter referred to as TPC (see Methodology for a full description of how TPCs are configured). The interaction between a particular TPC and the diurnal and seasonal patterns of sunlight in a particular geographic location dictate the subsequent shade cast upon a building. Of all the variables that constitute a TPC, Rudie and Dewers (1984) found that tree height and distance from a building were significant variables in shade provision. Numerous other studies have shown that the cardinal direction of a tree from a building is also important: large, dense-canopied trees positioned on the west aspect of a building are commonly reported to provide the greatest cooling benefits (Hildebrandt and Sarkovich 1998; Simpson 2002; Donovan and Butry 2009; Ko and Radke 2014). A study conducted in Sacramento, CA found that trees on the west aspect of buildings saved the most cooling energy – as much as 400 kWh annually – followed by trees on the east and south aspects (Simpson 2002). Similarly, Nikoofard et al. (2011) found that a structure with a tree on the west aspect consumed the least annual cooling energy (as much as 554 kWh less) in four Canadian cities, followed by trees on the east and south aspects.

Because tree form and placement are crucial factors in shade provision, authoritative sources throughout the U.S. have published regional guidelines on tree planting for energy conservation (Table 1). These guidelines tend to affirm the general recommendation of placing a large tree in close proximity to the west aspect of a building. However, it is unclear whether these recommendations take into account the interaction of the physical form and placement of a shade tree with the diurnal and seasonal patterns of sun exposure in a given geographic location, all of which influences shade coverage and duration. The study reported here was undertaken to quantify, using computer simulations, the shade cast by a single tree onto a prototypical residential structure in four U.S. cities situated across a broad latitudinal gradient. The goal of the study was to characterize daily and seasonal patterns of tree shade in order to ascertain whether regional tree planting guidelines provide appropriate recommendations for maximizing tree shade given the local solar conditions.

Methodology

Study Areas

Four U.S. cities were chosen for tree shade simulations: Minneapolis, MN; Indianapolis, IN; Charlotte, NC; and Orlando, FL (Figure 2). Their locations span a broad latitudinal gradient of the conterminous U.S. and represent diverse climate zones based on a 30-year average of annual cooling and heating degree-days (Baechler et al. 2010) (Table 2). These cities have also been used as reference cities for i-Tree Streets (an urban forest assessment software), which models a range of tree benefits, including energy conservation (McPherson 2010).

In order to better understand the implications of annual patterns of shade provision for these four cities, cooling and heating seasons were defined based on the climate data obtained from the National Oceanic and Atmospheric Administration (2011). During the cooling season (shaded blue in Table 2), when monthly mean temperatures exceed 18.3 °C, there is increased air-conditioning demand as well as heat stress risk for people, thereby emphasizing the need for tree shade. The heating season (shaded red in Table 2), when monthly mean temperatures are less than 18.3 °C, however, defines a period when tree shade may be undesirable because it diminishes passive solar heating of buildings and thus potentially increases heating costs.

Prototypical Residential Structure

Computer simulations of shade provision were performed using a prototypical residential structure. The structure was defined as a single-level residence with a north-south orientation and south-facing gable end (Figure 3). The floor area was approximately 200 m^2 (11 m x 18.2 m) and the building had a total surface area of 410.6 m^2 (four walls and two roof halves). Although the average floor area of a new single-family house built since 2000 is approximately 211 m^2 (Sarkar 2011; US Census Bureau 2012), a 200 m^2 floor area was chosen for computational convenience.

Tree Planting Configurations (TPCs)

For the tree shade simulations, 144 unique single-tree TPCs were permutated using combinations of tree form and tree placement variables (Figure 3). Tree form (TF) consisted of five variables: tree height, bole height, crown diameter, crown opacity, and crown shape. Three coniferous and three deciduous trees ranging in height from 7.3 m (small) to 15.2 m (large) were simulated using the TF variables (Simpson and McPherson 1998; Simpson 2002). In order to avoid space conflicts between the structure and the tree's crown, tree distance from the structure was set at a minimum 5 m with two additional 5-m intervals (10 and 15 m). Tree distances were permutated with eight directions from the structure (four cardinal and four intercardinal). The simulated values for all TPC variables used in this study were based upon data from previous studies, typifying many urban landscape trees found in the U.S. (Simpson and McPherson 1998; Simpson 2002; Troxel et al, 2013).

Shade Simulation Framework

Tree shade simulations were processed with a computer program called Shadow Pattern Simulator (SPS, Windows Version 2.0), which was developed by scientists with the U.S. Forest Service (Simpson and McPherson 1998). Based on specifications for both a tree and a structure, the SPS program precisely estimated hourly shaded areas on each building surface as a percent of total exposed area (accuracy has been reported at 95%; see McPherson et al. [1985] for more details about the SPS program). The SPS program had several limitations: it could only simulate basic geometric crown shapes, a static crown opacity factor, and a rectangular-shaped building. Nonetheless, it has tremendous computational capability for understanding daily and seasonal trends in shade provision and has been used in previous studies to quantify shaded areas on building surfaces as an intermediate step for energy consumption simulations (Simpson and McPherson 1998; Simpson 2002; Sawka et al. 2013).

Tree Shade Simulations

Each simulation using the SPS program calculated tree shade coverage on building surfaces using the following inputs: a TPC permutation, building specifications, study area, and simulation time frame. Simulations were run at diurnal half-hour intervals (beginning of hour, middle of hour, and end of hour), and then the three half-hour shade coverage estimates were averaged for each hourly estimate. Monthly simulations were run one day per month (each at the middle of the month) over a year and then quantified as daily shade surface area (hereafter referred to as shade provision), which represented the accumulated daily value of shade coverage on building surfaces from sunrise to sunset:

$$Shade\ Provision\ (S) = \sum Ksunrise + \cdots + Ksunset$$

where K is an hourly shade estimate. Two measures of shade provision are reported here based on the simulations: average shade provision and maximum shade provision. Average shade provision is the value calculated by summing shade provisions divided by the number of months during either the cooling or heating season. Maximum shade provision constitutes the greatest value (of single day shade provision) over the duration of each season. Across the four study areas, a total of 6,912 shade provision estimates were acquired through a total of 576 tree shade simulations (144 TPC permutations × 4 study areas × 12 months). Average and maximum shade provision values were then evaluated in the context of annual cooling and heating degree-days data for each of the four study areas (Table 2).

Results and Discussion

Overall Trends in Shade Provision

Within the calendar-year simulation time frame, maximum daily shade cast upon the exterior surface area of the prototypical residential structure ranged from 0 m^2 (no shade) to 580 m^2 (deciduous tree) or 706 m^2 (coniferous tree), depending on the particular study area and simulated TPC. Figure 4 shows data for the large, nearby trees at the latitudinal extremes (Minneapolis and Orlando), which best exemplify the differential influence of TPC and latitude. In all simulations, compared to a deciduous tree, a coniferous tree provided more shade because of its higher crown opacity and year-round foliation. In addition, the larger the tree placed adjacent to the structure, the greater the shade provided. In contrast, smaller trees placed at further distances provided low levels of shade. Small trees placed ≥ 10 m away or medium trees ≥ 15 m away typically produced shade coverage less than 112 m^2, the 75th percentile of all shade estimates over the entire year (Figure 5). Among small and medium trees, only a few trees on the east or west aspect of the building provided shade greater than 112 m^2, during the yearlong simulation time frame.

Differences in shading amongst study areas were due to latitudinal differences in sun angle above the horizons during the course of the day and year. In the same TPC permutation, trees placed on the southern aspects of the structure in northern cities cast more shade than those in southern cities (Figure 4). Because the sun was relatively lower above the horizon throughout the day and year in northern cities, the tree crowns intercepted more sunlight. Shade provision by the south-positioned tree decreased when moving from northern to southern cities because of the higher sun angles in southern cities; in particular, shade decreased substantially in May through July when sun angles were highest. Conversely, shade provision by a tree on the north increased when moving to southern cities. However, trees on northern aspects produced very limited overall shade because of the short intervals that they cast shade each day during the summer (at certain times of the year they never cast shade due to seasonal changes in sunrise and sunset). As well, when moving from northern to southern cities, shade provision from trees on east or west aspects increased in winter months due to lower sun angles while it decreased in summer months because sunlight passed over the tree crown. The latitudinal differences in shade from east to west aspect trees, among the various locations, were subtle because sun angles in the early morning and the late afternoon are less influenced by latitude. Because smaller trees and trees placed on the north aspects of a structure provided negligible levels of shade, discussion in the following sections primarily focuses on the latitudinal nuances of large trees placed on east, south, and west aspects.

Shade Provision in the Cooling Season

Across study sites, the cooling season ranges from three months (Minneapolis) to nine months (Orlando) (Table 2). During these time periods, maximizing tree shade on building surfaces is critical for energy conservation and human health. A more practical measure of sustained shade benefit is the average shade provision, which is the value calculated by summing shade provision (coverage) divided by the number of months over the duration of the cooling season. The shade simulations revealed some notable trends in tree shade (only data for large, nearby trees is shown in Table 3 to best exemplify the influence of aspect and latitude on shade). First, when considering tree types, coniferous trees provided greater average shade provision (averaged values over the duration of the cooling season) than the deciduous trees – these differences were most pronounced in Orlando where the cooling season is considerably longer and therefore dense, persistent foliage is more advantageous. Second, tree placement on the east or west aspect of the structure provided greater average tree shade over the course of the season, regardless of latitude. In contrast, shade was consistently lowest for trees on the south or southwest aspect because the sun angle is very high and therefore sunlight passes over the top of the tree during the cooling season. All of these trends in shade provision also held for the peak of the cooling season in July or August. Average daily shade provision by either tree types during the cooling season (and its peak) diminished when moving from northern to southern cities, due to progressively higher sun angles as moving toward more southerly locations.

The measure of maximum shade provision (single-day coverage value) gives an indication of how tree shade could be maximized on a single day. During the cooling season, the maximum daily shade provision of all TPC permutations on building surfaces ranged from 445 m^2 (in Charlotte) to 564 m^2 (in Orlando) (Figure 5). Large, nearby trees consistently provided the most shade, with the majority of these TPCs exceeding the 90th percentile of all TPC permutations. In three of the four localities, tree placement on the south aspect maximized daily shade in the cooling season. Minneapolis was the exception, where shade was maximized by an east-positioned tree. Due to the longer cooling season in southern localities extending well into fall when the sun angle is low, south-positioned trees maximized sunlight interception by tree crowns. Across all localities, although coniferous trees provided greater average shade provision, deciduous trees tended to provide the maximum shade (of any single-day values) (Figure 5). The differences in shade provision between coniferous and deciduous trees were primarily due to the elliptical crown shape simulated for deciduous trees, which have their widest diameter positioned at a greater vertical height above the ground than do parabolic coniferous trees. In general, differences in shade provision between tree types diminished when moving from northern to southern localities as duration of the cooling season increased.

Shade Provision during Peak Cooling Demand

Historical weather data shows that both monthly average temperatures and cooling degree-days (CDDs) peak in the month of July or August, depending on the study area (Table 2). The most severe EHEs in the U.S. since 1980 have typically occurred during July in locations such as Chicago, IL (1980; 1983; 1986; and 1995), Kansas City, MO (1980), Memphis, TN (1980), Philadelphia, PA (1993), and Phoenix, AZ (2005) (Whitman et al. 1997; US Environmental Protection Agency 2006; Centers for Disease Control and Prevention 2013). Our simulation results showed that, during the peak of the cooling season, both coniferous and deciduous trees placed on the east aspect of the structure cast the most shade on building surfaces, followed by trees placed on the west. Orlando was a notable exception, with trees on the west aspects providing more shade (Table 3). Compared to trees on other aspects, south-positioned trees provided lower levels of shade across all study areas due to the high sun angles that occur at mid-day during peak cooling demand. However, differences in shade provision between trees on the south and on other aspects decreased when moving toward northern latitudes. Using this understanding of the benefits of tree shade, it is asserted that, during the peak cooling season, shade cast by a strategically placed tree could decrease temperatures of both building surfaces and interior surfaces, subsequently helping to reduce heat-related health incidents and deaths that are prevalent during EHEs.

Shade Provision in the Heating Season

Past studies have shown that tree canopy blocking sunlight during the heating season can adversely diminish the passive solar heating of structures, resulting in a heating penalty in terms of year-round energy consumption for climate control (Simpson and McPherson 1996, 1998; Simpson 1998). In our tree shade simulations during the heating season, a large tree placed on the south aspect of the structure produced a large amount of shade. Due to crown opacity and year-round foliation, coniferous trees on the south aspect cast twice as much shade as deciduous trees, depending on the study area (Table 3 and Figure 4). These high shade levels became most pronounced in early fall, usually in September, at the same time that heating energy demands typically start increasing. These conditions persisted in all localities except Orlando, FL, where the heating season does not begin until mid-November, by which time, the sun angle has substantially dropped so that sunlight passes both under and through the crown of deciduous trees that have recently shed their leaves. Therefore, the impact of shade cast by a south-positioned deciduous tree on heating energy demand would be less significant in southern cities such as Orlando.

Regional Tree Planting Guidelines

Aimed at energy conservation, authoritative sources throughout the U.S. have published regional guidelines for shade tree planting (Table 1). While Community Tree Guides, published by US Forest Service, cover multiple states in specific climate zones (McPherson et al., 2005, 2006; Peper et al., 2009, 2010), regional guidelines published by university extension programs focus solely on the associated state. Therefore, university extension guidelines tend to be more specific. For example, the Minnesota guidelines recommend a specific tree direction (either east or west), distance (6 m away), as well as tree form (large canopied tree at least 3 m higher than window), with which our simulations agree. Even though all guidelines affirm that trees on the west aspect are the best option for shade tree planting, they often do not fully address the interaction between tree form, tree placement, and geographic latitude.

Our simulations show that regional tree planting guidelines that recommend planting a shade tree on the east or west aspect of a dwelling for energy conservation is appropriate. Trees on these aspects have been found to provide abundant shade during the cooling season while simultaneously minimizing unwanted shade during the heating season. In contrast, shade trees placed on the southern aspects are shown to do the opposite. Southerly-placed trees cast a lot of undesirable shade in the heating season, yet provide minimal shade during the cooling season. Therefore, planting guidelines are correct in restricting or attaching conditions for planting a tree on the south aspect. For example, a common recommendation to minimize the heating penalty of tree shade (especially in northern latitudes) is to plant a "solar-friendly tree" – a deciduous, high-crowned tree, which allows sunlight to pass under the tree and reach the structure during the heating season (McPherson et al., 2005, 2006; Peper et al., 2009, 2010).

While planting guidelines tend to correctly recommended cardinal tree orientation around a dwelling, they often do not stress the important interaction between tree form and tree distance, which were found through our simulations to have significant impacts that should be addressed for optimal tree planting strategies. For example, the Community Tree Guides (Table 1) recommend planting a tree at a distance between 9 and 15 m in order to provide effective shade on windows and walls as well as to avoid tree conflicts to the structure (McPherson et al., 2005, 2006; Peper et al., 2009, 2010). Avoiding conflicts between a tree and a structure is an important aspect of a sustainable landscape; however, our simulation results indicated that shade provision on building surfaces noticeably decreased when placed more than 5 m away from the structure. Our simulations also showed that, at all latitudes, shade provision was reduced even more drastically with distance as the tree size decreased. This effect was evident particularly in northern latitudes when considering the average shade provision during the cooling season (Table 4). For example, in Minneapolis, when a large deciduous tree (15.2-m tall) situated at 5 m on the west aspect, average shade provision as valued 419 m^2, but reduced to 303 m^2 at 10 m, and 210 m^2 at 15 m. Likewise, a small deciduous tree (7.3-m tall) placed at 5 m on the west provided average shade provision of 114 m^2, but reduced 46 m^2 at 10 m, and 18 m^2 at 15 m.

Shade simulations showed recommendations for distance associated with tree sizes. Large trees (15.2-m tall) were less influenced by an increase in distance from the structure than medium (11-m tall) and small (7.3-m tall) trees. Large trees were shown to provide increased tree shade (exceeding the 75th percentile of all estimates over the entire year) at distances from 5 to 15 m. On the other hand, it is recommended to plant a medium tree within 10 m or a small tree within 5 m away in order to acquire tree shade greater than 112 m^2 (the 75th percentile) during the cooling season. In comparison to trees on either east or west aspects, due to higher sun angles, south-positioned trees are more sensitive to an increase in distance from the structure; regardless of tree size these trees should be placed close to the structure for tree shade to ensure adequate shade during peak cooling season while also minimizing the winter season heating penalty.

Across the study areas, our simulations support that planting a shade tree on either the east or west aspect would be the best option for energy conservation. However, when planting on the east or west aspect is not an option, the recommendation for shade tree selection and placement will depend on the latitude and climate. In northern latitudes (Minneapolis and Indianapolis) with longer heating seasons, trees on the southeast or southwest aspect would be the second-best option. Trees on these aspects provide constant tree shade throughout the year, casting more shade in the cooling season and less in the heating season than a south-positioned tree. In these northern latitudes, the south-positioned tree, especially a coniferous tree, should be avoided to minimize heating penalties. However, if this tree were necessary, proper pruning may help manage unwanted shade during the heating season. An increase in bole height (by pruning lower branches) would allow sunlight to better reach a dwelling, thus increase passive solar heating. In southern latitudes (Orlando) with their longer cooling season, differences in shade between deciduous trees on the southern aspects (southeast, south, and southwest) would be subtle and the heating penalty less dire, and would therefore be considered as a second option for a shade tree if the east or west aspects are not available.

Plant the Right Tree in the Right Place

The phrase “plant the right tree in the right place” has become a widespread philosophy for maximizing tree benefits and minimizing costs in urban areas. Results of our tree shade simulations have shown the importance of strategic tree selection and placement for optimizing shade, which has positive benefits for energy conservation and human comfort. Even though larger trees provide high levels of shade, they can also create possible hazards or conflicts when placed too close to a structure. The resulting problems, such as structural damage, could possibly negate the benefits of energy conservation (McPherson et al., 2005, 2006; Peper et al., 2009, 2010). Therefore, the compromise between tree size and distance should be carefully considered when selecting and planting shade trees.

The use of a strategically placed single tree is amplified when considering that shade trees can contribute to “spill-over” shade benefits to neighboring structures especially in dense urban developments (Nikoofard et al. 2011). These trees may also contribute to energy conservation by shading low albedo ground covers (e.g., streets and driveways) and by evapotranspiration cooling (Huang et al. 1986) and windbreak effects (Heisler 1986a). In addition, tree selection and placement must also be considered in the full context of the landscape situation and across the full range of potential benefits. For example, a greater environmental benefit may occur from placing a tree on a low-shade north aspect if its canopy projects over an impervious surface, thereby intercepting rainfall and delaying stormwater runoff. The key is to understand how tree form and tree placement interact with the built environment to derive a multitude of environmental benefits and then select the planting configuration that puts the tree to its highest use.

Conclusion

This study has demonstrated a simulation method to assess the impact of a single-tree planting configuration on shade provision for a prototypical residential structure in various geographic locations. To isolate some of the key variables, the simulations considered a contrived situation that simplified the geometry of the structure and placement of specific trees in selected geographic settings. As a result, it demonstrated that shade provision is influenced by not only tree form and placement, but also daily, seasonal, and latitudinal variability in sunlight exposure. These simulations support the general recommendation that large trees placed adjacent to buildings on their east or west aspects provide high levels of shade during the cooling season while minimizing unwanted shade during the heating season. However, our simulations indicate that, in addition to the tree direction relative to the structure, tree distance should be considered in conjunction with tree size.

Quantity, quality, as well as timing of shade cast upon building surface areas impact the magnitude of shading benefits with regard to energy conservation and human health (Heisler 1986b). However, because this study only quantified shade provision, we cannot draw conclusions about how the quality of shade (e.g. shade of similar magnitude cast by an east versus a west aspect tree) impacts energy conservation. Through simulating shade effects specifically on building energy consumption, further studies could address this limitation. As well, shade provision is not the only factor that influences building energy performance; for example, weather, building characteristics, and occupant behavior have notable impacts (Livingston and Cort 2011). Despite these limitations, this study has demonstrated the nuanced relationship between TPC variables, geographic latitudes, and shade provision across a broad spectrum of urban settings in the US. With these findings, we can move closer towards providing recommendations for optimal tree selection and placement based on geographic location in order to maximize shade benefits for both energy conservation and human health. Our ability to make precise tree planting recommendations takes on even greater significance for urban neighborhoods where UHI effects are more acute and potential tree planting space is more limited.

Acknowledgements

We would like to thank Dr. James R. Simpson for providing the Shadow Pattern Simulator (SPS) program and technical support, and Dr. Susan D. Day, Dr. James B. Campbell, and Tammy E. Parece at Virginia Tech for their valuable perspective for preparing the manuscript. We also acknowledge anonymous reviewers and the editors for their constructive comments.

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Figures

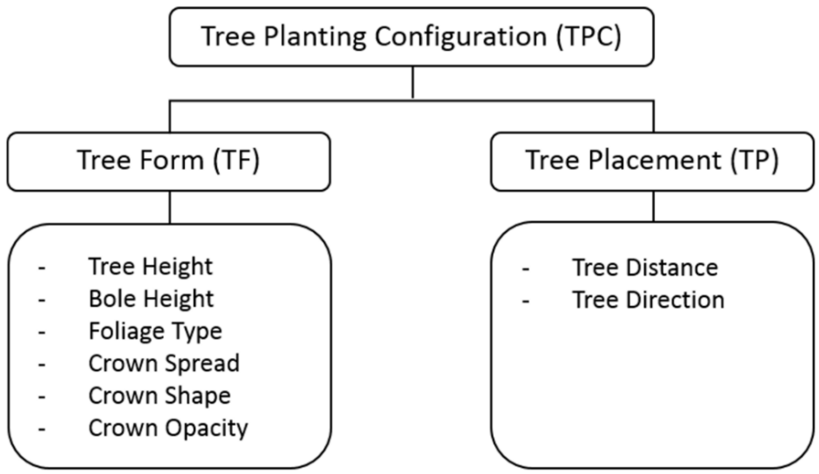

Figure 1 Integral factors and component variables in a tree planting configuration (TPC) that influence shade provision. These factors and variables were used in computer simulations of shade provision by a single tree onto a prototypical residential structure in four U.S. cities.

City	Latitude	Climate Zone[1]	Min. Temp.[2] (°C)	Mean Temp.[2] (°C)	Max. Temp.[2] (°C)	Normal CDD[3]	Normal HDD[3]
Minneapolis, MN	45° 07' N	1	2.1	7.4	12.6	699	7,876
Indianapolis, IN	39° 73' N	2	5.7	11.4	16.8	1,042	5,521
Charlotte, NC	35° 22' N	4	10.6	16.3	22.1	1,681	3,162
Orlando, FL	28° 55' N	5	16.9	22.7	28.4	3,248	580

[1] Climate zone defined by the U.S. Energy Information Administration (http://www.eia.gov/consumption/residential/maps.cfm)
[2] Min./Mean/Max. Temp.: annual average minimum/mean/maximum normal temperature
[3] CDD / HDD: Cooling / Heating Degree-Days. Degree-day is a unit used to relate the day's temperature to the space cooling / heating energy demands.

Figure 2 Location and climatic information for four U.S. cities where computer simulations of shade cast by a single tree onto a prototypical residential structure were performed.

Tree Form (TF)

		small	medium	large
Deciduous tree	Tree height (m)	7.3	11	15.2
	Bole height (m)	1	2	3
	Crown diameter (m)	7.6	9.1	10.6
	Crown opacity[1]	75% (Apr. - Oct.) & 25% (Jan. - Mar. / Nov. - Dec.)		
	Crown shape	ellipse	ellipse	ellipse
Coniferous tree	Tree height (m)	7.3	11	15.2
	Bole height (m)	1	2	3
	Crown diameter (m)	7.6	9.1	10.6
	Crown opacity[1]		80%	
	Crown shape	ellipse	parabola	parabola

[1] Crown opacity (shade coefficient): the percent of available solar radiation blocked by the tree crown (McPherson et al., 1985)

Tree Placement (TP)

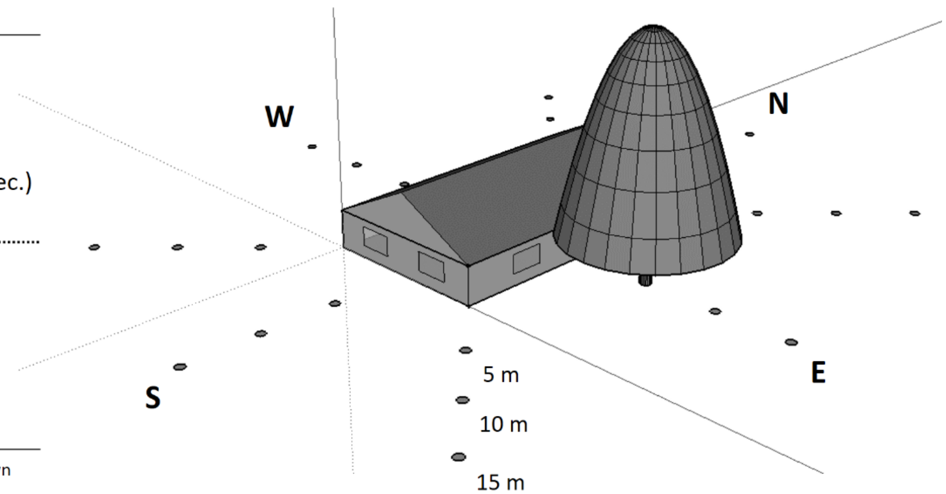

Figure 3 Tree Form (TF) and Tree Placement (TP) variables used in the computer simulation of tree shade cast upon a prototypical residential structure in four U.S. cities. A single coniferous tree or deciduous tree of specified physical dimensions was simulated at three distances on eight azimuths to generate 144 unique tree planting configurations (TPCs).

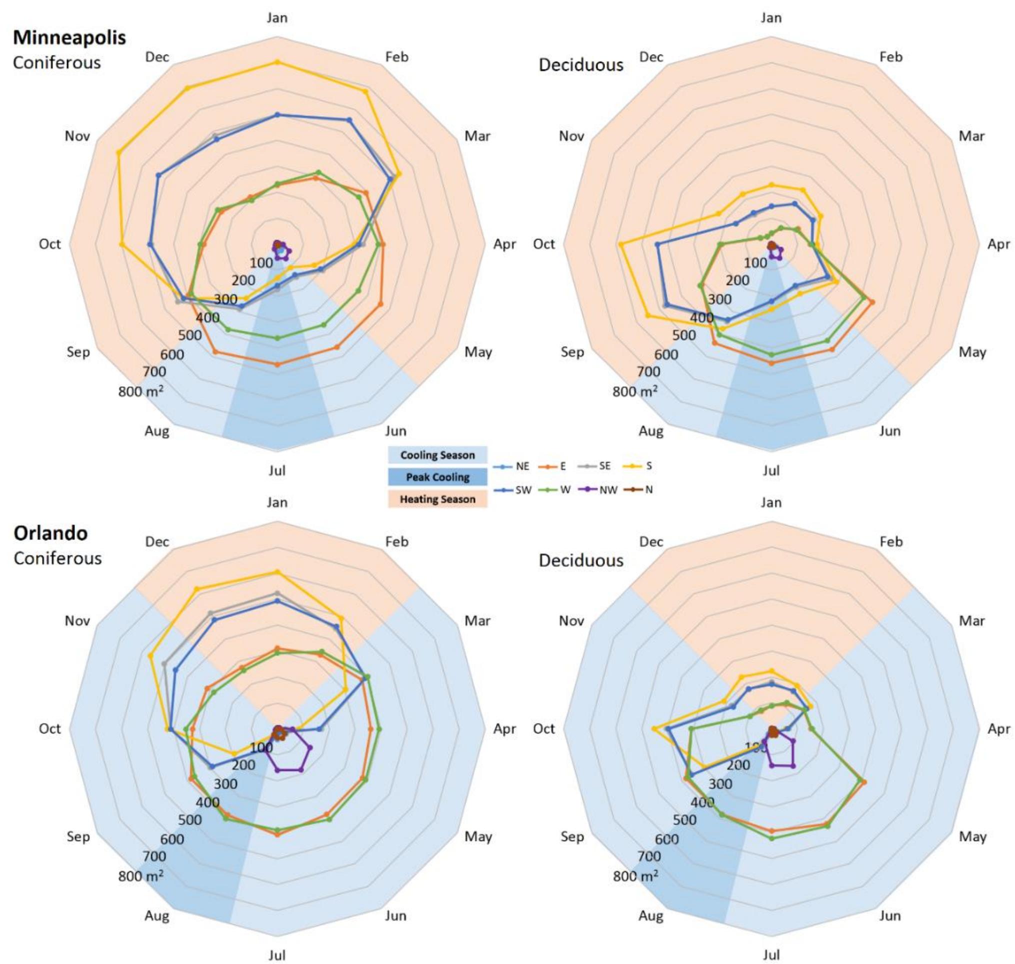

Figure 4 Annual patterns of maximum shade provision produced by a large coniferous tree and a large deciduous tree placed 5 m away from a prototypical residential structure in Minneapolis, MN (top) and Orlando, FL (bottom). Each node represents the building surface area (m^2) shaded over the course of a single day during the middle of each month. (Note: Due to the scale of the graphs, shade provisions by northerly-placed trees may be imperceptible at the center of the graphs.)

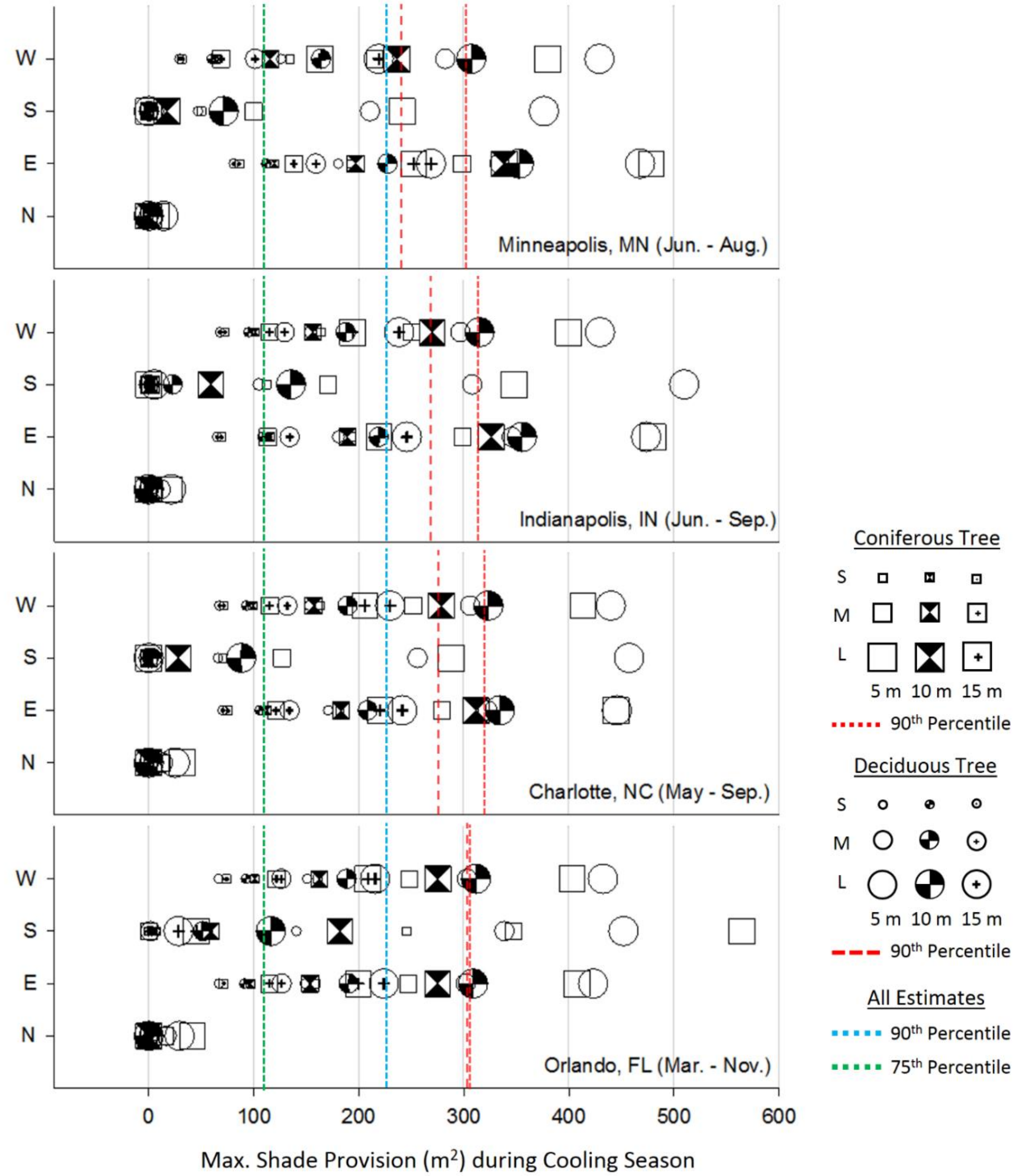

Figure 5 Maximum shade provision produced by coniferous trees (squares) and deciduous trees (circles) during the cooling seasons in four U.S. cities. Each data point depicts the maximum building surface area (m^2) shaded by different tree sizes (S: small, M: medium, and L: large) over the course of a single day during the entire cooling season (the duration is listed next to the city name in each graph. Red lines denote the 90th percentile of maximum shade provision for coniferous or deciduous tree planting configurations in a specific city. Blue and green lines denote the 90th percentile (222 m^2) and the 75th percentile (112 m^2) of maximum shade provision for all tree planting configurations across four U.S. cities.

Tables

Table 1 Regional tree planting guidelines for energy conservation published by authoritative sources

Area	Tree Placement* Direction (Distance)	Tree Form	Sources
General	W	Trees with crown lower to the ground;	U.S. Department of Energy
	S	Deciduous trees with high, spreading crowns	
Minnesota	W, E (6 m)	At least 3 m higher than window with large canopy	University of Minnesota Extension
North Carolina	W, E, S (3 - 9 m)	Not specified	North Carolina Cooperative Extension Service; TreesCharlotte
Florida	W, E, S, SE	deciduous trees on the S and SE	Florida Solar Energy Center; University of Florida IFAS Extension
Midwest	W, E (9 - 15 m; min. 3 m)	Not specified	Center for Urban Forest Research, USDA Forest Service
(Minneapolis)	S (3 - 6 m)	Solar-friendly trees**	
Lower Midwest	W, E (9 - 15 m; min. 3 m)	Not specified	Center for Urban Forest Research, USDA Forest Service
(Indianapolis)	S (3 - 6 m)	Solar-friendly trees**	
Piedmont	W, E (9 - 15 m; min. 3 m)	Not specified	Center for Urban Forest Research, USDA Forest Service
(Charlotte)	S (3 - 6 m)	Solar-friendly trees**	
Central Florida	W, E (9 - 15 m; min. 3 m)	Not specified	Center for Urban Forest Research, USDA Forest Service
(Orlando)	S (3 - 6 m)	Solar-friendly trees**	

* Direction and distance from a building to be shaded.
** Solar-friendly trees are deciduous trees that allow sunlight to pass through or under the crown in winter for passive solar heating of buildings (McPherson et al., 2005)

Table 2 Cooling and heating seasons in four U.S. cities where computer simulations of shade cast by a single tree onto a prototypical residential structure were performed. Cooling season (values in bold text) is when monthly mean temperature is above 18.3°C, while heating season is when monthly mean temperature is below 18.3°C. Peaks of the cooling season (values denoted with *) are when monthly mean temperatures are the highest.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MN[1]	T_{Mean}[2] (°C)	-9.1	-6.2	0.4	8.6	15.1	**20.4**	**23.2***	**21.8**	16.7	9.4	0.9	-6.8
IN[1]		-2.2	0.1	5.7	11.7	17.1	**22.2**	**24.1***	**23.4**	**19.4**	12.8	6.4	-0.2
NC[1]		4.5	6.6	10.7	15.2	**19.7**	**24.1**	**25.8***	**25.2**	**21.6**	15.7	10.4	5.8
FL[1]		15.7	17.2	**19.4**	**21.8**	**25.2**	**27.4**	**28.2**	**28.2***	**27.3**	**24.2**	**20.3**	17.0
MN	CDD[2]	0	0	0	5	37	**158**	**276***	**205**	66	6	0	0
IN		0	0	2	13	69	**226**	**323***	**288**	**128**	16	1	0
NC		0	0	0	6	**45**	**173**	**266***	**231**	**90**	9	1	0
FL		45	59	**118**	**199**	**380**	**490**	**549**	**553***	**483**	**331**	**147**	70
MN	HDD[2]	1531	1236	998	530	218	**44**	**5**	**14**	154	507	939	1404
IN		990	783	558	248	65	**4**	**0**	**0**	**29**	206	495	879
NC		770	592	433	200	**53**	**3**	**0**	**0**	**23**	183	430	701
FL		193	115	**59**	**12**	**1**	**0**	**0**	**0**	**0**	**5**	**42**	144

[1] Study location: Minneapolis, MN; Indianapolis, IN; Charlotte, NC; and Orlando, FL

[2] T_{Mean}: 1981-2010 monthly normal of mean temperature; CDD: Cooling Degree-Days; and HDD: Heating Degree-Days (Degree-day is a unit used to relate the day's temperature to the space cooling/heating energy demands).

Table 3 Average shade provision cast by a large coniferous and a large deciduous tree placed 5 m from a prototypical residential structure in four U.S. cities during the cooling season, peak of the cooling season, and the heating season. Only east to west aspects are shown. Each value is the average of daily cumulative shade coverage over the duration of the season. Minimum and maximum shade provision values for each season are denoted with bold text.

		Deciduous Tree Shade (m^2)			Coniferous Tree Shade (m^2)		
		Cooling Season	Peak Cooling	Heating Season	Cooling Season	Peak Cooling	Heating Season
Minneapolis, MN	E	**455.1**	**458.3**	156.5	**466.8**	**463.9**	324.5
	SE	252.4	221.7	237.3	202.9	174.9	449.3
	S	282.7	251.6	304.4	158.3	130.3	533.1
	SW	246.4	219.4	235.2	190.2	159.1	440.1
	W	419.4	426.6	**154.5**	367.3	363.0	**311.7**
Indianapolis, IN	E	**415.4**	**431.9**	**145.6**	**422.7**	**414.8**	**312.1**
	SE	246.8	149.0	202.6	205.2	111.8	424.6
	S	277.6	168.8	259.2	156.8	65.2	499.7
	SW	244.6	144.6	202.0	197.6	105.4	420.6
	W	403.0	423.4	148.9	384.6	372.7	317.7
Charlotte, NC	E	**417.0**	**445.8**	**119.3**	**418.6**	**444.8**	**316.2**
	SE	187.0	98.1	205.8	148.2	60.2	456.6
	S	195.9	91.6	255.1	95.2	21.7	514.0
	SW	188.5	93.7	199.7	143.4	57.0	439.9
	W	411.0	434.1	121.3	403.8	406.9	317.0
Orlando, FL	E	298.9	381.0	**91.7**	367.9	383.2	304.7
	SE	143.6	85.4	173.5	214.8	89.6	495.1
	S	144.7	65.3	215.3	180.4	27.8	573.0
	SW	140.7	80.7	172.9	205.4	88.0	477.6
	W	**301.0**	**382.1**	96.2	**375.7**	**399.3**	**298.7**

Table 4 Average shade provision produced by different sizes of a coniferous and a deciduous tree placed on the west aspect of a prototypical residential structure in four U.S. cities during the cooling season, the peak of the cooling season, and the heating season. Minimum and maximum shade provision values for each season are denoted with bold text.

Area	Size	Distance	Deciduous Tree Shade (m^2) Cooling Season	Deciduous Peak Cooling	Deciduous Heating Season	Coniferous Tree Shade (m^2) Cooling Season	Coniferous Peak Cooling	Coniferous Heating Season
Minneapolis, MN	L	5	**419**	**427**	154	**367**	**363**	312
		10	303	305	99	225	220	163
		15	210	207	67	146	138	101
	M	5	281	280	133	202	198	209
		10	156	153	75	103	97	106
		15	82	74	46	53	45	62
	S	5	114	109	83	122	116	147
		10	46	39	43	49	42	73
		15	18	13	**24**	19	14	**39**
Indianapolis, IN	L	5	**403**	**423**	149	**385**	**373**	318
		10	296	311	96	252	241	171
		15	215	222	63	177	163	106
	M	5	288	287	125	229	216	215
		10	176	168	72	133	116	112
		15	113	100	44	87	71	67
	S	5	138	129	79	148	137	153
		10	75	62	43	79	66	79
		15	45	32	**25**	48	34	**45**
Charlotte, NC	L	5	**411**	**434**	121	**404**	**407**	317
		10	303	322	73	268	268	168
		15	220	230	46	188	184	103
	M	5	292	301	108	242	244	216
		10	184	189	60	148	145	113
		15	120	115	36	98	91	66
	S	5	146	144	70	156	154	152
		10	85	81	38	91	87	80
		15	56	50	**23**	59	53	**46**
Orlando, FL	L	5	**301**	**382**	96	**376**	**399**	299
		10	214	279	52	243	271	138
		15	151	207	26	170	200	69
	M	5	220	278	84	233	246	212
		10	137	176	42	142	154	102
		15	89	126	20	95	115	50
	S	5	114	149	56	152	159	150
		10	68	91	28	90	97	76
		15	45	67	**14**	60	71	**38**

Chapter 3 Simulation of Shade Tree Effects on Residential Energy Consumption in Four U.S. Cities

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In review: *Cities And The Environment (CATE)*.

Abstract

Strategically placed trees can modify urban temperatures by casting shade and thus affect energy consumption for residential cooling and heating. Energy conservation benefits are influenced by the quantity as well as the quality of tree shade upon building surfaces. In this study, we employed an energy simulation program called EnergyPlus as a means to evaluate the effect of a single shade tree upon a structure model having a floor area of 200 m^2 in four U.S. cities. Results of EnergyPlus simulations with various single tree planting configurations showed that a large tree on the west aspect of a structure could decrease annual energy costs by up to $18.38 in southern cities with longer cooling seasons. Whereas, the same tree on the south aspect could increase annual energy costs by up to $14.17 in northern cities with longer heating seasons. In addition to tree placement around the structure, interactions between sun angle, tree form, and tree distance were observed to influence the effects on energy consumption. Understanding the fundamental interactions between tree form, tree placement, and geographic settings, which influence both the quantity and quality of shade provision, is critical for improving energy conservation benefits of trees in urban settings.

Keywords: arboriculture, cooling and heating energy, energy conservation, tree planting, tree shade, urban forestry

Introduction

Landscape trees modify urban temperatures by casting shade onto man-made ground covers and buildings (Akbari 2002; Pandit and Laband 2010; Chagolla et al. 2012). By intercepting sunlight that would otherwise penetrate windows, walls, and roofs, strategically placed shade trees help reduce cooling energy consumption of buildings (Simpson and McPherson 1998). In contrast, during winter months, shade from misplaced trees may disrupt passive solar heating of buildings, leading to additional energy costs for space heating, which is often referred to as a shade tree heating penalty (Simpson and McPherson 1996; Simpson and McPherson 1998; Simpson 1998). Cooling and heating indoor spaces account for approximately 40 percent of the total energy consumed by residential structures in the U.S. (US Energy Information Administration 2012). Therefore, it would be prudent to maximize the cooling energy savings from desirable tree shade while concurrently minimizing the heating penalties from undesirable tree shade. To bring attention to the effective use of tree shade for this purpose, we employed computer simulations to examine the impact of individual tree planting scenarios on the annual energy consumption of a nearby prototypical residential structure.

Given that dwellings with shade trees tend to consume less energy for space cooling during summer months (Heisler 1986; Huang et al. 1987; Akbari and Taha 1992; Souch and Souch 1993; Simpson and McPherson 1996; Akbari et al. 1997), many civic tree planting programs have emphasized tree shade for energy conservation (Hildebrandt and Sarkovich 1998; Sawka et al. 2013). For example, in 1990, the Sacramento Municipal Utility District initiated a well-known program that planted more than 200,000 shade trees aimed at energy conservation (Hildebrandt and Sarkovich 1998). They found that planting an average of 3.1 program trees per residential parcel resulted in an annual energy savings of up to $10.00 per tree (Simpson and McPherson 1998). As well, a tree planting program in Toronto, Canada planted 577 trees in residential areas between 1997 and 2000, which led to an annual electricity savings of 77,140 kWh (167 kWh per tree) as of 2009 (Sawka et al. 2013). And, currently, the Energy-Saving Trees program organized by the Arbor Day Foundation has provided more than 140,000 trees to six U.S. cities, expecting to save as much as 264 million kWh of energy by 2025 (US Administration 2014).

Past research has shown that energy conservation benefits of shade are highly dependent on tree characteristics such as size, canopy type, and placement relative to the structure (Meier 1990/91; Simpson and McPherson 1998; Simpson 2002; Donovan and Butry 2009; Nikoofard et al. 2011). In general, the larger the tree placed adjacent to the structure, the greater the shade provided (Donovan and Butry 2009; Ko and Radke 2014). Additionally, tree canopy density determines the intensity of solar radiation reaching the structure, with a denser canopy providing more significant shading effects (Heisler, 1986; Pandit and Laband 2010). Finally, the most beneficial shading effects come from shade trees placed in close proximity (9-15 m) to the structure (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010), with the influence of tree height varying depending on distance from the structure (Rudie and Dewer 1984); only tall trees provide substantial shade when situated far from the structure.

Directional location of a tree relative to the structure is another important aspect of tree placement that influences shading effects. During a summer day, trees on the east side provide shade in the morning, while trees placed on the west side cast shade in the late afternoon. Because ambient air temperatures and air conditioning usage are highest in late afternoon (Donovan and Butry 2009), west positioned trees are considered top priority for maximizing cooling effects, followed by trees on the east aspect (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010). Trees placed on the south aspect cast minimal shade onto a building in summer because the sun reaches its maximum midday zenith at this time of year and most of the shade is cast straight down (Heisler 1986; Hildebrandt and Sarkovich 1998). Thus, south aspect trees provide minimal direct cooling effects in summer unless they are placed very close to the structure (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010). Furthermore, trees on the north aspect rarely intercept sunlight destined for the structure and thus provide minimal cooling effects from shading (Donovan and Butry 2009).

During the winter months, trees prevent solar radiation from reaching building surfaces, deterring passive solar heating and necessitating additional energy use for space heating. This heating penalty can be particularly acute when a coniferous tree with dense evergreen foliage is located on the south aspect of a building (Nikoofard et al. 2011). The heating penalty impact of a south-positioned tree, placed in close a proximity to a building, can be approximately twice as large compared to a tree on either an east or west aspect (Hildebrandt and Sarkovich 1998).

These well-known biophysical effects of trees have been used by authoritative sources across the U.S. to develop regional guidelines for shade tree planting aimed at energy conservation (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009;

Peper et al. 2010). However, there are still gaps in information about these biophysical effects on optimal shade tree planting in urban environments (Bowler et al. 2010). Examples of fundamental concepts that are often overlooked in tree planting guidelines include local climate effects and daily/seasonal sun movements that interact with tree placement and tree form. When considering that 'per tree' shade benefits could be greater with a properly placed single tree than with some multi-tree plantings (McPherson and Dougherty 1989; Souch and Souch 1993), the strategic selection and placement of a single tree becomes more important, especially when tree planting resources are limited. As well, an increase in the utilization of shade trees in this manner would not only improve energy conservation but also magnify the benefits of canopy cover across a community, including air quality improvement, carbon sequestration, and stormwater reduction (Roy et al. 2012). With this in mind, we built upon a previous study that focused on quantifying shade cast by a single tree onto a simulated residential structure in several U.S. cities (Hwang et al. 2015). Other studies that were examined in support of our research indicate that, along with the quantity of shade, the quality and timing of tree shade are also important factors that influence building energy conservation (Heisler 1986). Therefore, the goal of the current study was twofold: (1) to evaluate how shade provision by a single landscape tree influences cooling and heating energy consumption of a residential structure and (2) to critique regional tree planting guidelines for energy conservation based on the findings of our simulations.

Methodology

Study Areas

In order to examine the diverse effects of climate and daily/seasonal sun movements on building energy conservations, four cities were chosen for our tree shade-energy simulations: Minneapolis, MN; Indianapolis, IN; Charlotte, NC; and Orlando, FL (Table 1). These cities are located in different American Institute of Architects climate zones, which are determined based on cooling and heating degree-days (Baechler et al. 2010). Degree-days are based on the number of degrees that the daily average temperature is above 18.3 °C (65 °F in the U.S.) and are used to estimate energy requirements for maintaining the standard indoor temperature, which is also 18.3 °C (US Energy Information Administration 2013). Because local climate is an important factor that influences energy consumption (Livingston and Cort 2011), cooling and heating seasons for each study area were defined in order to examine geographic variability within the energy simulations. The cooling and heating seasons were determined based on the 30-year (1981-2010) normal climate data reported by the National Oceanic and Atmospheric Administration (2012) for each city. During the cooling season, when monthly mean temperatures exceed 18.3 °C, air-conditioning demands increase; whereas, during the heating season, when monthly mean temperatures are below 18.3 °C, heating demands increase. The most significant climatic contrast in this study was between Orlando and Minneapolis. The cooling season in Orlando is markedly longer (nine months from March to November) than locations in northern cities. In contrast, the heating season in Minneapolis is comparatively longer (nine months from September to May) than locations in southern cities.

Building Energy Simulations

This study used a suite of computer simulation programs to quantify tree shade impacts on annual residential energy consumption. EnergyPlus (version 8.0, US Department of Energy, Washington, DC) was used to calculate the estimated annual energy consumption of a prototypical residential structure model. In addition, two supplemental programs were employed, as an interface to EnergyPlus, to support the simulation processes. SketchUp Pro 2013 (Trimble, Sunnyvale, CA) was used to draw the three-dimensional residential structure and tree models. OpenStudio 1.2.0 (National Renewable Energy Laboratory [NREL], Golden, CO) supported EnergyPlus by converting the geometry and envelope features of these models into text-based inputs for energy simulations.

EnergyPlus calculated, based on weather data, the cooling and heating loads of the structure model that were required to maintain thermal setpoints of 23.9 °C for cooling and 21.1 °C for heating. These weather data were downloaded from the EnergyPlus website and comprised hourly values of solar radiation and meteorological data (e.g., temperature, precipitation, and wind speed) for a one-year period (US Department of Energy 2014). Trees in the energy simulations were considered to be an adjacent object, which influenced heat gain by casting shade upon the building surfaces and altering airflow around the structure. EnergyPlus computed the impacts of trees on heat gains and airflow and applied the values to calculate the annual cooling and heating energy consumption (US Department of Energy 2014).

Across the four study areas, EnergyPlus was used to perform a total of 576 annual energy consumption simulations (January through December) using a single tree model (144 tree models × 4 study areas). Simulations were first run in the absence of a tree and then with a tree present on the landscape in order to determine, by comparison, the impact of a single tree on annual energy consumption. Both the cooling and heating energy consumption values (in kWh) reported through OpenStudio were then monetized into a dollar value using the monthly average residential electricity prices in 2012 for each state (US Energy Information Administration 2014).

Residential Structure Models

Energy simulations were conducted on a residential structure model. The single-level structure had a floor area of approximately 200 m^2 (11 m × 18.2 m) and a total surface area (four walls and two roof halves) of 410.6 m^2 (Table 2). The model was oriented north to south with a south-facing gable end and had two windows (1.2 m × 2.1 m) on each wall (Figure 1). These dimensions approximate an average single-family house built since 2000, which is about 211 m^2 of floor area (Sarkar 2011; US Census Bureau 2012). With a fixed size specification, thermal specifications for the structure were determined based on standard 189.1 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Long et al. 2010).

Shade Tree Models

Shade tree models for the energy simulations were derived through a combination of tree form and tree placement variables, resulting in 144 unique single-tree planting scenarios for the energy simulations (Figure 1). Three deciduous and coniferous tree models were developed using combinations of five tree form variables: tree height, bole height, crown diameter, crown opacity, and crown shape. Because tree canopy has a fluctuating density dependent upon variations in tree type and season, crown opacity was set at 75% (leaf-on) and 75% (leaf-off) for deciduous trees and 80% for coniferous trees. In the energy simulations, each of the six tree models was placed at 24 pre-defined locations around the structure: three distances (5, 10, 15m) by eight directions (four cardinal and four inter-cardinal).

Our previous shade simulation study found that small tree models (either parabolic coniferous or elliptical deciduous trees) placed at long distances from the structure provided minimal shade coverage (Hwang et al. 2015) and would therefore provide minimal energy conservation benefits. For this reason, the results and discussion presented in the following sections primarily focus on large tree models placed close to the structure.

Results and Discussion

Overall Trends in Energy Simulations

Energy simulations were first performed on the residential structure model in the absence of a shade tree. Within a single-year simulation time frame (January through December), the structure consumed from 8,846 kWh in Orlando (valued at $1,019) to 13,216 kWh in Minneapolis ($1,482). It was evident that the amount of cooling and heating energy consumed varied depending on the study areas and their associated local climates. The structure in Orlando required more annual energy for space cooling (1,774 kWh; valued at $204) than for heating (578 kWh; $67), whereas the structure in Minneapolis required less cooling energy (792 kWh; $89) but more heating energy (5,930 kWh; $655).

Using the same time frame, a second series of energy simulations were performed with a single shade tree model adjacent to the structure model. As expected, a larger tree, placed close to the structure, most often produced a greater effect on energy consumption. As well, compared to deciduous trees, coniferous trees with dense crowns year-round brought greater impacts on energy consumption. However, the intensity of the effects on both cooling and heating energy consumption varied depending on tree form, tree placement, and study area. Differences in cooling energy savings versus heating penalties from tree shade were most evident when comparing the southernmost (Orlando) and northernmost (Minneapolis) cities. For example, during the cooling season, when comparing two simulated structures in Orlando (one with and one without a tree), the structure with a large coniferous tree on the west had reduced energy consumption by up to 142 kWh (maximum savings valued at $16). In contrast, during the heating season, a structure in Minneapolis with the same tree model, but on the south, had increased heating energy consumption by up to 190 kWh (maximum cost valued at $21).

Impacts of the Shade Tree Model on Cooling Energy Consumption

Energy simulations indicated that differences in the lengths of cooling seasons impacted annual cooling energy consumption. During the cooling season, tree shade impacts on annual energy consumption ranged from $0 (no effect) to $16.26, depending upon tree form, tree placement, and study area (Figure 2). In Orlando, where the cooling season is markedly longer, cooling energy consumption was reduced by more than three times compared to the other study areas using the same tree models. When moving toward the north, the length of the cooling season became shorter and the amount of energy savings from tree shade diminished. For example, the large deciduous tree model placed on the west aspect (5 m away) had an annual cooling energy savings of $10.19 in Orlando, $3.41 in Charlotte, $2.42 in Indianapolis, and $2.45 in Minneapolis.

Due to the mechanics of seasonal sun angles interacting with tree form, tree placement, and structure orientation (Figure 3), the prevailing notion that large trees provide the most energy-conserving shade was not always borne out by the simulations; when considering tree distance, a smaller tree closer to the structure was sometimes more effective than a larger tree at a further distance. For example, in Minneapolis, the small coniferous tree on the east at 5 m from the structure saved $0.52 more than the large coniferous tree at 15 m away. The differences between small and large deciduous trees became greater when comparing them placed on the south aspect (a small tree at 5 m versus a large tree at 15 m); due to a higher sun angle, tree impacts on cooling energy consumption remarkably decreased (from $2.44 to $0.59) when this south-positioned tree was placed further away from the structure.

Likewise, our simulations did not show that the west-positioned large tree close to the structure (5 m in this study) always produce the most substantial reduction in cooling energy consumption, particularly where the cooling season is shorter. For example, in Indianapolis, large deciduous trees on the south aspect at 5 m away saved the most annual cooling energy ($3.34) for a north-south oriented structure model because of the interaction between tree form (elliptical canopy with tall height) and higher sun angle; the tree shade covered the narrow north-south oriented roof. However, when planting the same tree at 10 m or further, a west-positioned tree produced the most significant reduction in cooling energy consumption.

Impacts of the Shade Tree Model on Heating Energy Consumption

During the heating season, ranging from three months (Orlando) to nine months (Minneapolis), energy simulations showed that a few of the tree models, particularly those on the west and northwest aspects, produced heating energy savings, which were primarily driven by windbreak effects. This heating savings was also shown in southern latitudes with a shorter heating season; however, the savings were mostly less than a dollar per year (Figure 4). In northern cities, heating penalties were more common in the simulations than were heating savings. Coniferous trees (with retained foliage year round) caused greater heating penalties than deciduous trees through the blocking of passive solar heating. This heating penalty was magnified in northern latitudes with their longer heating seasons. In Indianapolis and Minneapolis, both coniferous and deciduous tree models showed some level of adverse effects on heating energy consumption. The simulations estimated annual heating penalties to be as much as $18.41 depending on tree form, tree placement, and study area. Especially in Minneapolis, where lower sun angles result in undesirable shade being cast onto the structure (Figure 3), a coniferous tree is detrimental on the south aspect in close proximity to the structure. Increasing the distance of a south aspect tree from the structure would be effective for reducing heating penalties. For example, in Indianapolis, the difference in heating penalty between a large and a small tree was only $1.80 at 5 m away, while an increase in tree distance to 10 m reduced the heating penalty as much as $3.54. In southern latitudes where the heating penalty is less dire, planting a coniferous tree should not be discounted. In Orlando, only a few coniferous tree models increased heating expenditure, yet often provided substantial cooling savings.

Impacts of the Shade Tree Model on Annual Energy Consumption

The simulations quantified the combined cooling and heating effects of shade tree models on annual energy consumption, depending on tree form, tree placement, and geographic latitudes, and local climates. Net annual energy consumption (the difference between energy savings in summer and energy costs in winter) by the residential structure model in the presence of a shade tree ranged from a net energy saving of $18.38 to a net energy cost of $14.17 (Figure 5). Across the study areas, most tree models on the west aspect reduced annual energy consumption. In contrast, southerly placed (south, southeast, and southwest) coniferous trees typically increased annual energy consumption, particularly in Minneapolis and Indianapolis.

Annual energy consumption was closely related to geographic latitude, which reflects variations in lengths of cooling and heating seasons as well as daily/seasonal sun movements. In Orlando, with the longest cooling season, more than 95% of tree models provided cooling savings large enough to compensate for any heating penalty accrued during the heating season. Trees in Orlando reduced annual energy consumption maximally $18.38 (the west-positioned coniferous tree at 5 m away) and minimally $0.00 (no impact with deciduous trees placed on the north at 10 to 15 m away) (Figure 5). In comparison to trees in Orlando, trees in cities with shorter cooling seasons showed different trends in net energy consumption. First, certain tree models that had been beneficial in Orlando started producing additional energy costs, depending on tree form and tree placement, and their extra costs were magnified at northern latitudes. Second, depending on the study area, a south-positioned large deciduous trees at 5 m away reduced annual energy consumption (up to $4.61) more than a tree on either the west (up to $3.05) or east (up to $3.12). When sun angle was higher during the cooling season, the elliptical deciduous tree on the south aspect could cast shade covering the north-south oriented roof of the structure model, thus reduce cooling demands (Figure 3).

In contrast to deciduous trees, coniferous trees, particularly in northern locations, adversely impacted annual net energy consumption due to acute heating penalties. In Minneapolis, in particular, the south-positioned coniferous tree caused the most notable additional energy consumption: as much as $14.17. When the sun angle is lower in the heating season, the parabolic coniferous tree would block passive solar heating (Figure 3), resulting in heating penalties. Unlike the cooling effects provided by most south-positioned deciduous trees, which showed diminishing energy impacts moving further away from the structure, the heating penalty of a coniferous tree prevailed even at 15 m away, due to lower sun angles and longer heating seasons. Lastly, compared to the east-positioned trees that typically saved annual energy consumption in southern cities, some tree models on the east in Indianapolis and Minneapolis also caused additional energy consumption up to $1.69 because trees on this placement blocked passive solar heating in early morning.

Is Planting a Large Shade Tree on the West Aspect Always Best?

Many U.S. cities have implemented tree planting programs aimed at moderating urban temperatures and consequently saving residential energy consumption (Pincetl et al. 2013). Community-based tree planting programs have successfully mobilized shade tree planting projects that have resulted in noteworthy residential energy savings (Simpson and McPherson 1998; Simpson 2002; Sawka et al. 2013). However, tree planting programs may overlook providing guidance tailored to local conditions for strategic tree planting for energy conservation (Pincetl et al. 2013; Sawka et al. 2013).

A previous study (Hwang et al. 2015), using the same shade tree and residential structure models evaluated in the current study, quantified shade provision of various single-tree planting configurations. The previous and current studies both found evidence (in terms of shade provision and energy conservation) to further support the prevailing recommendation for shade tree placement on the west aspect of buildings (Figures 5). A tree on the west aspect typically provided greater cooling effects in our simulation because late afternoon shade coincides with peak cooling demand (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010). However, our simulations showed that both east- and west-positioned trees were effective for reducing net energy consumption in northern latitudes. The differences in energy savings between the two became smaller (from $7.33 down to $0.20) moving from Orlando to Minneapolis because a lower quality of shade (less solar intensity) is experienced in northern latitudes due to lower daily/seasonal sun angles.

In northern study areas, large trees at a close distance (5 m away in this study) on the west did not always provide substantial annual energy savings. Due to a lower sun angle in the northern latitudes, a large elliptical deciduous tree with a greater bole height (distance between ground and canopy base) allowed solar penetration, thus leading to more cooling demands than smaller trees. When considering that heat gains through windows is the major cause of increased cooling energy demands (Farrar-Nagy et al. 2000), a smaller deciduous tree with a lower bole height or a coniferous tree with a broad-based crown, which blocks solar penetration, might be a better option for cooling energy savings. This would be a useful strategy in urban neighborhoods where potential tree planting sites for large shade trees are often limited.

Is Planting a Shade Tree on the North Aspect Useless?

Our simulations showed that trees on north aspects provide limited shade on building surfaces due to daily/seasonal sun movements and therefore would be expected to have limited effects on annual energy consumption (Akbari et al. 1997; McPherson and Simpson 2003). However, these trees may cast shade on low albedo ground covers within their surroundings (Huang et al., 1987; Akbari and Konopacki, 2004) as well as provide windbreak effects depending on proximity to the structure (Liu and Harris 2008). Our simulations substantiated some of these effects and showed, for example, that northerly placed tree models reduced annual energy consumption as much as $6.63 (coniferous) and $5.38 (deciduous) driven by shading heat-reflective ground cover, especially in southern latitudes during the summer months. Those same trees in northern latitudes saved heating energy consumption through windbreak effects in winter. However, the heating savings by northerly-placed trees in our simulations were minimal because windbreaks are most effective with a dense multi-tree planting rather than a single tree standing alone. Even though the microclimate factors of shading ground covers and windbreak effects were not the primary focus of our study, it is certainly noteworthy to mention their impact on energy conservation. With this in mind, if a tree's other ecosystem benefits are taken into consideration, planting a single tree, even on northern aspects (particularly in southern locations) could bring overall energy conservation benefits to communities that may outweigh any possible shortcomings.

Is Strategically Planting a Single Shade Tree Worth It?

Energy impacts of shade trees (from savings of $18.38 to additional costs of $14.17 annually) estimated in our study may not be enough incentive for individual homeowners to plant a shade tree strategically on their properties. However, these small influences by single trees could have a substantial impact on annual energy consumption in the aggregate. For example, in California, for 15 years after planting 50 million trees on the east or west aspect of urban private properties, the annual cooling reduction was expected to be over 46,000 GWh (valued at $3.6 billion) (McPherson and Simpson 2003). And, when considering further spill-over benefits, such as stormwater reduction, air quality improvement, and carbon sequestration, along with energy conservation benefits, planting even a single shade tree strategically on individual properties could bring significant benefits across communities.

The monetary values of energy impacts reported in our study appear to be underestimated in comparison to other previous studies. Due to differences in tree and structure models, it was difficult to compare our results to other studies directly; however, there are three potential factors that distinguish our study from others: (1)

improved house energy efficiency; (2) omission of evapotranspiration cooling effects; and (3) contrived simulation environments. Since 1975, the stringency of U.S. residential energy code has strengthened, leading to more efficient structures and a decrease in energy consumption by approximately 14% (US Department of Energy 2008). Our simulation used the recent specification (ASHRAE Standard 189.1), which is highly energy efficient. Well-insulated structures are less sensitive to temperature change from solar heat gain and therefore the benefits of tree shade are attenuated. Also, our study didn't consider the effect of evapotranspiration cooling, which would be a part of the aggregate effects of multiple trees (McPherson and Rowntree 1993). When considering that individual trees on residential properties can add up to significant canopy cover across a community, the indirect evapotranspiration cooling effects from neighboring trees would also promote wide-scale energy savings that could not be captured in our simulations. Finally, in order to reduce simulation complexity, we examined an isolated residential structure with a single tree, which would be uncommon circumstances, especially in dense urban neighborhoods. In particular, trees in dense residential areas could cast shade not only on the target building, but also neighboring buildings (Sawka et al. 2013); therefore, the impact of planting a single tree could have greater impacts (good or bad), depending on tree form and placement. Despite these differences in simulation frameworks, our study lends further evidence to a key principle of urban landscape design: tree form, tree placement, and geographical context influence tree shade impacts on energy consumption of residential structures and merit the attention of both homeowners and tree planting programs.

Conclusion

This study has demonstrated a method using EnergyPlus simulation to evaluate the impacts of single shade tree planting on annual energy consumption of a residential structure model in diverse geographic locations. In order to isolate some of the key variables, the simulations considered a contrived situation that simplified the geometry of the structure and placement of a specific tree in selected geographic settings. Along with the expectation that a large tree placed adjacent to the structure resulted in more significant influences on residential energy consumption, this study demonstrated that the magnitude of these effects were dependent upon not only tree form and tree placement, but also seasonal and geographic variability in sun path and solar heat gains.

In order to enhance energy conservation benefits of a shade tree, it is necessary to consider, simultaneously, the potential for cooling savings and heating penalties. Therefore, fundamentally, the main objective for planting a shade tree is to target a planting scenario that will maximize the cooling effects in southern latitudes with their longer cooling season while concurrently minimize the heating penalties from shade in northern latitudes, where the heating season is longer and passive solar heating is important. With this in mind, and as a result of our simulation findings, the general recommendation for planting a deciduous tree on the west seems to be the most reliable approach to energy conservation. However, the shading nuances of single tree scenarios in this study revealed that this will not always be the optimal tree planting guideline. When moving toward the northern latitudes with shorter cooling seasons, our simulations showed that it is not necessary to persist with planting a shade tree on the west; both east- and west-positioned trees help to reduce annual energy consumption. These findings about optimal tree placement and variances between northern and southern locations, are evidence that our simulation method could be useful for designing more specific planting guidelines that would provide shade tree benefits more fitting to specific geographic locations.

Although we are confident in the simulation calculations, we recognize that there were several limitations to the study: 1) simulations were not equipped for adequately describing the effects of seasonal foliage changes during the simulation time frame, which would influence shade quality (Heisler 1986); (2) the effect of evapotranspiration cooling was not considered because this would be a part of the aggregate effects of neighborhood trees (Huang et al. 1987; McPherson and Rowntree 1993); and (3) because additional validation data was not available, this study solely relied on the computations of EnergyPlus. Despite these limitations, we expect that, by refining our simulation process, researchers could use our findings to develop updated models for estimating the energy conservation benefits of trees in planned residential developments. As well, the findings could be adopted for developing tree planting guidelines and used to create supportive policies that would benefit a broad spectrum of urban settings.

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Figures

Tree Form

		Small	Medium	Large
Deciduous tree	Tree height (m)	7.3	11	15.2
	Bole height[1] (m)	1	2	3
	Crown diameter (m)	7.6	9.1	10.6
	Crown opacity[2]	75% (Apr. – Oct.) & 25% (Jan. – Mar. / Nov. – Dec.)		
	Crown shape	Ellipse	ellipse	ellipse
Coniferous tree	Tree height (m)	7.3	11	15.2
	Bole height[1] (m)	1	2	3
	Crown diameter (m)	7.6	9.1	10.6
	Crown opacity[2]	80%	80%	80%
	Crown shape	ellipse	parabola	parabola

[1] Bole height: the distance between the ground level and crown base.
[2] Crown opacity (shade coefficient): the percent of available solar radiation blocked by the tree crown (McPherson et al. 1985).

Tree Placement

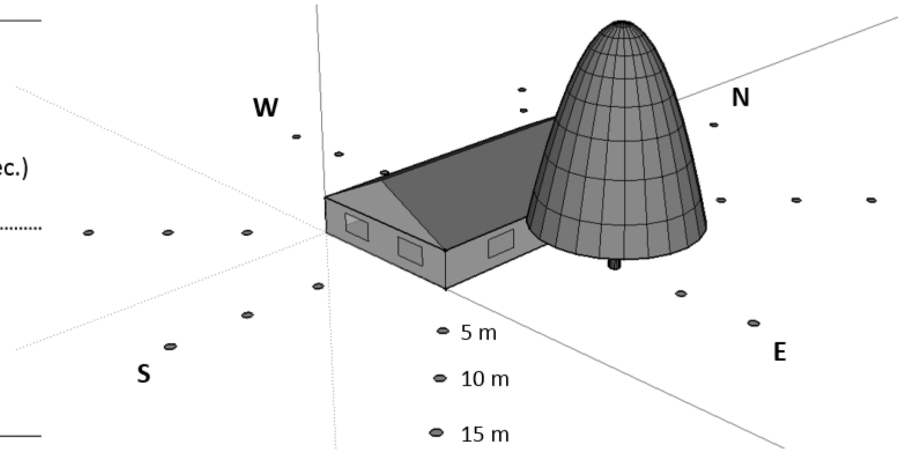

Figure 1 Tree form and tree placement variables used in simulations of tree shade effects on energy consumption of a residential structure model in four U.S. cities. In this depiction, a large coniferous tree is drawn to scale at 5 m east of the structure.

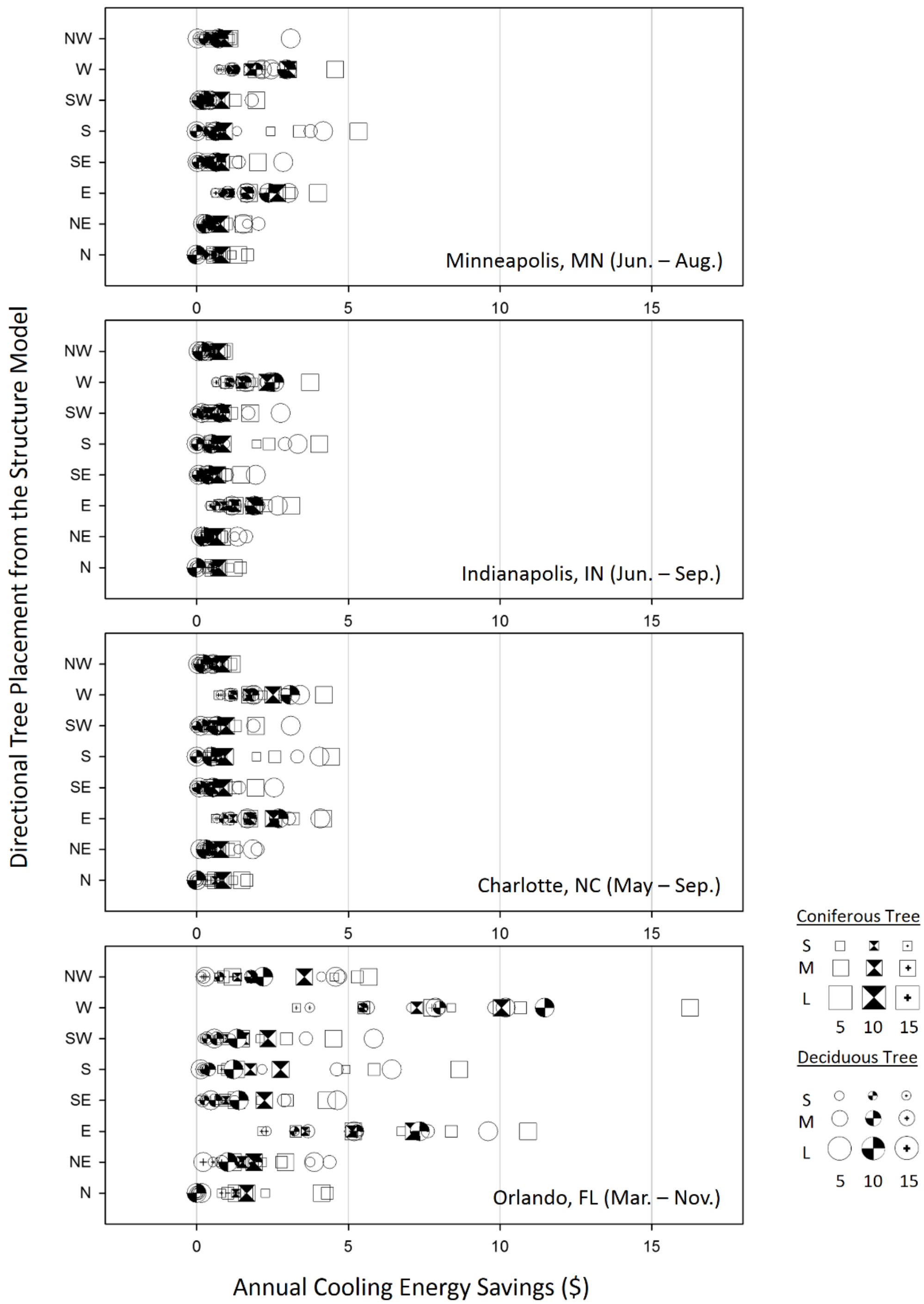

Figure 2 The impact of various single-tree planting configurations on annual cooling energy consumption for a residential structure model simulated in four U.S. cities. The duration of the cooling season is listed next to the city name in each graph. Six tree forms (two leaf types × three stature classes: S [small], M [medium], and L[large]) were placed at three distances (5, 10, and 15 m) from the structure model on eight azimuth directions.

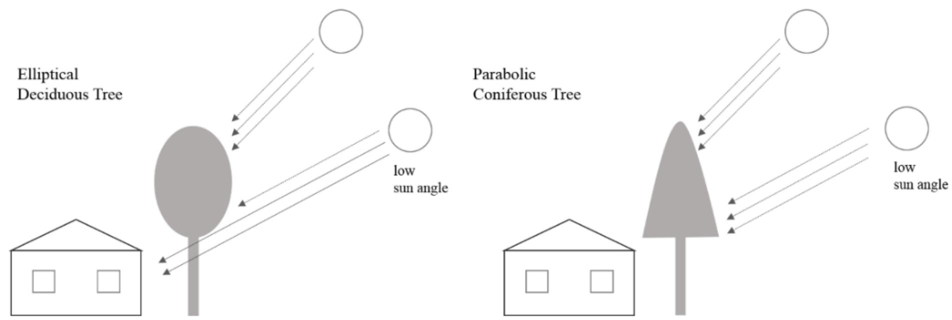

Figure 3 Mechanics of sun angle interacting with tree form and tree placement to influence solar heating of a structure. A large deciduous tree with an elliptical crown (left) allows solar penetration when sun angle is low. In contrast, a parabolic coniferous tree would block solar penetration when the sun angle is low. Sun angle is lower: (1) in northern latitudes, (2) during the winter heating season, and (3) after sunrise on the east aspect and before sunset on the west aspect.

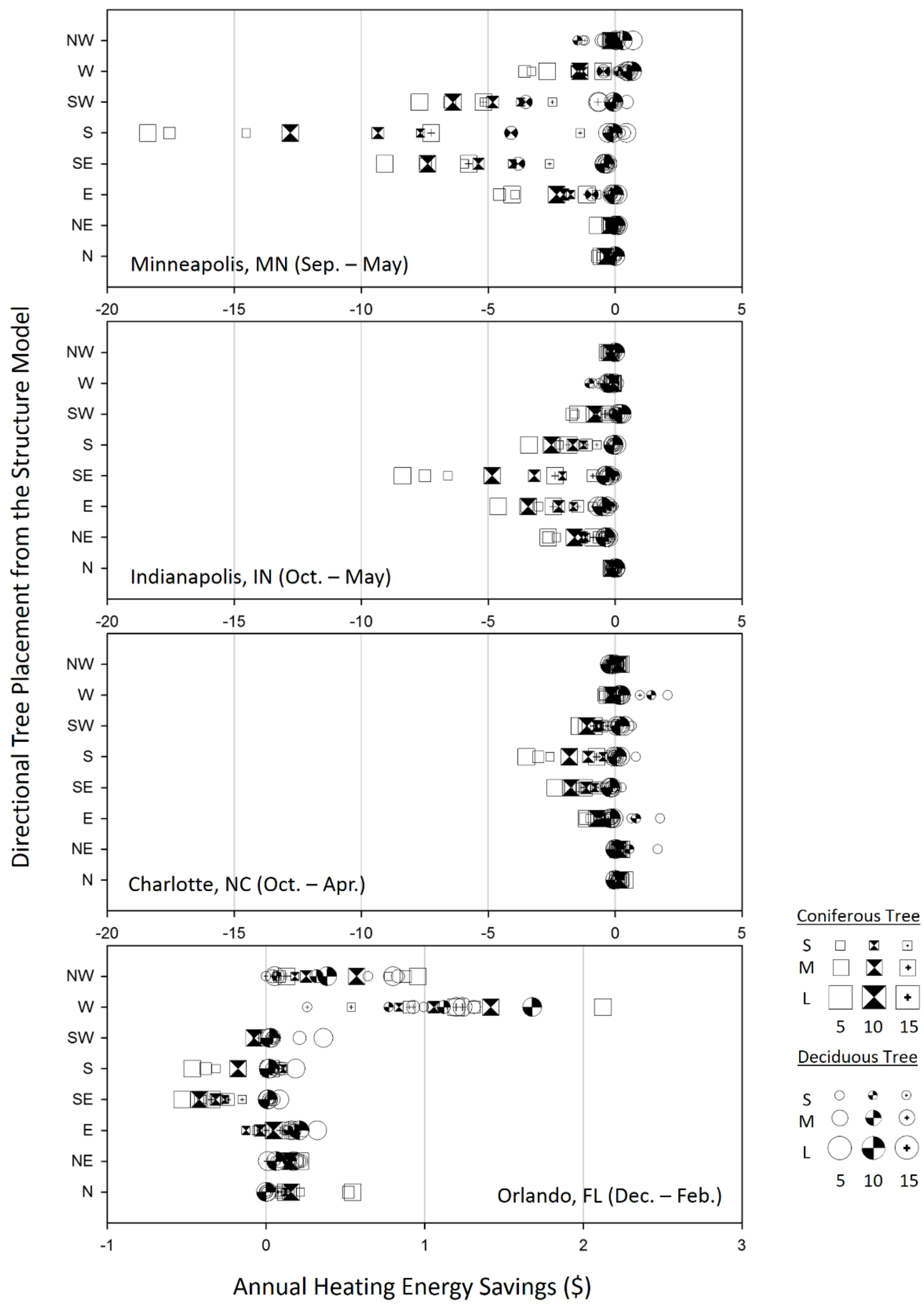

Figure 4 The impact of various single-tree planting configurations on annual heating energy consumption for a residential structure model simulated in four U.S. cities. The duration of heating season is listed next to the city name in each graph. Six tree forms (two leaf types × three stature classes: S [small], M [medium], and L[large]) were placed at three distances (5, 10, and 15 m) from the structure model on eight azimuth directions.

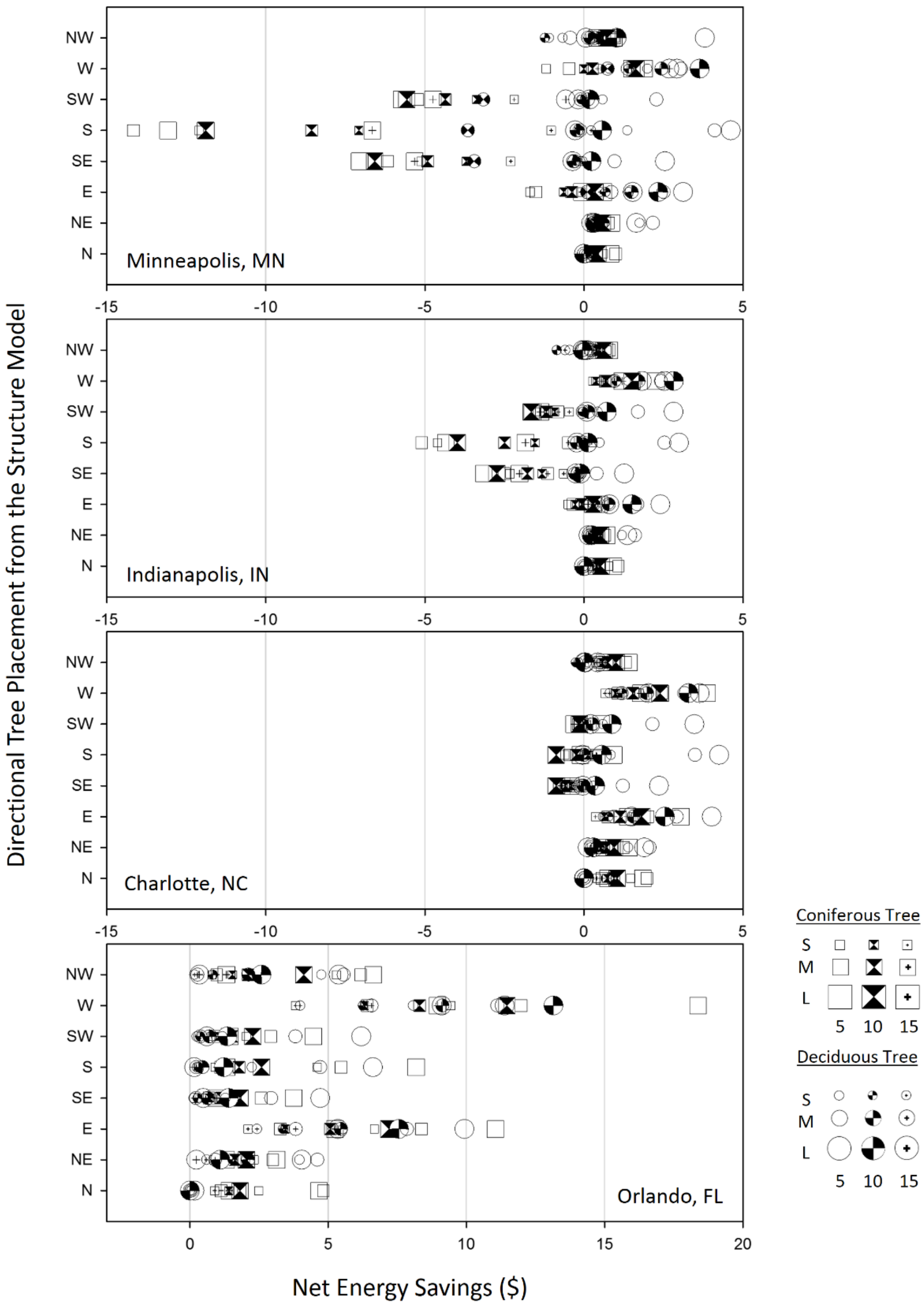

Figure 5 The impact of various single-tree planting configurations on net energy consumption for a residential structure model simulated in four U.S. cities. The duration of heating season is listed next to the city name in each graph. Six tree forms (two leaf types × three stature classes: S [small], M [medium], and L[large]) were placed at three distances (5, 10, and 15 m) from the structure model on eight azimuth directions.

Tables

Table 1 Average monthly temperatures and cooling and heating seasons in four U.S. cities where simulations of tree shade effects on energy consumption of a residential structure model were performed. The 30 year normal climate data (1981-2010) were obtained from the National Oceanic and Atmospheric Administration (2012). Cooling season (values in bold text) is when monthly mean temperatures are above 18.3 °C, while heating season (values in italic text) is when monthly mean temperatures are below 18.3 °C.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MN[1]	T_{Mean} (°C)[2]	-9.1	-6.2	0.4	8.6	15.1	20.4	23.2	21.8	16.7	9.4	0.9	-6.8
IN		-2.2	0.1	5.7	11.7	17.1	22.2	24.1	23.4	19.4	12.8	6.4	-0.2
NC		4.5	6.6	10.7	15.2	19.7	24.1	25.8	25.2	21.6	15.7	10.4	5.8
FL		15.7	17.2	19.4	21.8	25.2	27.4	28.2	28.2	27.3	24.2	20.3	17.0
MN	CDD[2]	0	0	0	5	37	**158**	**276**	**205**	66	6	0	0
IN		0	0	0	6	45	**173**	**266**	**231**	**90**	9	1	0
NC		0	0	2	13	**69**	**226**	**323**	**288**	**128**	16	1	0
FL		45	59	**118**	**199**	**380**	**490**	**549**	**553**	**483**	**331**	**147**	70
MN	HDD[2]	*1531*	*1236*	*998*	*530*	*218*	44	5	14	*154*	*507*	*939*	*1404*
IN		*990*	*783*	*558*	*248*	*65*	4	0	0	29	*206*	*495*	*879*
NC		*770*	*592*	*433*	*200*	53	3	0	0	23	*183*	*430*	*701*
FL		*193*	*115*	59	12	1	0	0	0	0	5	42	*144*

[1] Study areas where simulations were performed: Minneapolis, MN; Indianapolis, IN; Charlotte, NC; and Orlando, FL.
[2] T_{Mean}: 1981-2010 monthly normal mean temperature; CDD: Cooling Degree-Days; and HDD: Heating Degree-Days (Degree-day is a unit used to relate the day's temperature to the space cooling/heating energy demands).

Table 2 Characteristics of the residential structure model used in simulations of single-tree shade effects on building energy consumption in four U.S. cities.

Variables	Orlando, FL	Charlotte, NC	Indianapolis, IN	Minneapolis, MN
Physical dimensions of the structure	11 m x 18.2 m x 2.4 m (floor height) / 5.2 m (roof peak)			
Climate Zone[1, 2]	2A	3A	5B	6B
Effective R-value[2]				
External wall (m^2K/W)	2.624	3.073	3.689	3.689
Roof (m^2K/W)	8.104	8.104	8.104	8.104
Window (U-factor, W/m^2K)	2.56	4.26	1.42	1.42
Insulation Min. R-value[2]				
External wall	R-13 + R3.8 ci	R-13 + R3.8 ci	R-10 + R10 ci	R-10 + R10 ci
Roof	R-49	R-49	R-49	R-49
Internal loads[2]				
Light	Climate Zone 1-3 Mid-Rise Apt Light		Climate Zone 4-8 Mid-Rise Apt Light	
Electric Installation	Climate Zone 1-3 Mid-Rise Apt Electric		Climate Zone 4-8 Mid-Rise Apt Electric	
No. of Occupants	3			
HVAC system	Electric Heat Pump			
Thermostat setting				
Cooling season (°C)	23.9			
Heating season (°C)	21.1			
Annual Energy Consumption of Unshaded Structure[3]				
Cooling (kWh / percent of total energy consumption)	1,012 / 11%	567 / 6%	466 / 4%	376 / 3%
Heating (kWh / percent of total energy consumption)	329 / 4%	1,535 / 16%	2,348 / 22%	4,698 / 36%
Annual Average Electric Price ($/kWh)[4]	0.1152	0.1082	0.1053	0.1137

[1] International Energy Conservation Code (IECC) Climate Regions (US Department of Energy 2013).

[2] Physical characteristics of the structure models were downloaded and employed from the U.S. Department of Energy's online library (Fleming et al. 2012) and their specifications met ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 189.1 for Mid-Rise Apartments.

[3] Annual energy consumption of unshaded structure was estimated using a north-south oriented model structure.

[4] 2012 Annual Average Electric Price from US Energy Information Administration (US Energy Information Administration 2014).

Chapter 4 Enhancing the energy conservation benefits of shade trees in dense residential developments using an alternative tree placement strategy

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This chapter is formatted for submission to Landscape and Urban Planning.

Abstract

The paradigm of modern residential land development is densification, resulting in relatively limited greenspace on individual parcels. As a result, land developers and homeowners are often constrained for space to plant shade trees. In the long run, suboptimal placement of shade trees diminishes their building energy conservation benefits. The conventional strategy for maximizing tree benefits for residential heating and cooling is to plant a large-maturing tree close to the west aspect of the house. However, this strategy is often not feasible due to space constraints from parcel orientation or building orientation on the parcel. In this study, we examined the effect of tree placement, along with parcel and building orientation, on the energy conservation benefits of trees in three U.S. cities with distinct climates. We used a program called EnergyPlus to simulate building energy consumption of recently constructed homes under existing landscape conditions. We then developed an alternative tree placement strategy that reconfigured tree placement around the homes to both minimize space conflicts and maximize cooling and heating energy savings. Our results showed that, assuming that the existing trees are large-stature deciduous trees, the average annual energy conservation benefits per parcel are $1.54 in Metro Minneapolis, MN, $2.68 Charlotte, NC, and $15.12 in Metro Orlando, FL. With our alternative tree placement strategy, annual energy savings per parcel could be improved by up to 320%, 88%, and 132%, respectively. We conclude that our alternative tree placement strategy was as effective as the conventional strategy, however, unlike the conventional strategy, our alternative strategy is more responsive to parcel or building orientations in dense urban neighborhoods.

Introduction

Residential areas account for more than 20% of the total energy consumed in the U. S. (Pitt et al., 2012; US Energy Information Administration 2012). About 40% of the energy consumed in residential structures is used for space cooling and heating (US Energy Information Administration 2012). Growing concerns about the increase in energy consumption for both cooling and heating have spurred research across multiple disciplines. Architects are increasingly recognizing the potential of low-energy buildings, such as passive solar homes (Satori and Hestnes 2007). Urban planners are paying more attention to aspects of urban form in order to reduce residential energy consumption (Ewing and Rong 2008; Ko 2013). And researchers in other related disciplines, such as urban forestry, horticulture, and landscape architecture have been increasingly examining how trees and other vegetation reduce residential energy consumption for cooling and heating (Akbari et al. 1997; Donovan and Butry 2009; Simpson and McPherson 1998). In the current study, we examine how shade tree placement is impacting residential energy consumption in recently developed single-family neighborhoods in several U.S. cities.

Energy demand for maintaining interior thermal comfort is influenced by various factors, including not only the building itself but also its local setting. Building variables, such as vintage, style, and size, have been shown to influence residential energy consumption (Kahn 2000; Norman et al. 2006; Kaza 2010; Pandit and Laband 2010). Passive solar design is one approach that has been found to increase building energy efficiency. Careful selection of building layout and materials appropriate for local climates reduces energy consumption while retaining thermal comfort (Aksoy and Inalli 2006; Morrissey et al. 2011; Pacheco et al. 2012). Beyond individual building design and construction, variables of urban form, such as density, community layout, and street networks, can impact residential energy consumption too (Ewing and Rong 2008; Kaza 2010; Ko 2013). In our study, the variable that interests us is how urban residents can utilize shade trees to modify daily and seasonal solar energy loads of their homes and thereby conserve energy (Simpson and McPherson 1998; Akbari 2002; Rosenzweig et al. 2006).

While it is well documented that urban trees provide multiple ecosystem benefits such as carbon sequestration, air quality improvement, and stormwater reduction (Roy et al. 2012), the main focus of the current study is how trees can be used for energy conservation. Urban trees can reduce residential cooling and heating energy consumption in three ways: (1) casting shade onto building surfaces and manmade ground covers, (2) modifying air flow around buildings, and (3) lowering ambient air temperature through evapotranspiration (Akbari 2002). Research has established that (1) properly selected and placed trees around a structure can provide heat-attenuating shade in summer by intercepting direct sunlight, yet allow passive solar heating of the structure during winter (Hwang et al. 2015); (2) windbreak effects decrease cooling and heating demands by reducing the infiltration of hot (summer) or cold (winter) air into a structure (Akbari 2002; Heisler 1986); and, (3) evapotranspiration during summer months, influenced by the amount of tree canopy cover, decrease ambient air temperatures and thereby cooling energy demand (Huang et al. 1987; Jensen et al. 2003). To maximize energy conservation benefits of these aforementioned processes, it is necessary to identify the relevant characteristics of the local setting and then select an appropriate tree form and tree placement around a structure (McPherson and Rowntree 1993).

Many U.S. cities have implemented tree planting programs to increase tree shade and canopy cover and decrease urban heat island effects. A well-known Sacramento shade tree planting initiative of more than 200,000 shade trees, aimed at reducing summer cooling energy demand, was implemented between 1990 and 1995 (Hildebrandt and Sarkovich 1998). Simpson and McPherson (1998) examined the residential properties that participated in this planting program and estimated that an average of 3.1 program trees per parcel saved up to $10.00 per tree on annual energy expenditure. In Illinois, the Chicago Urban Forest Climate Project expected to save up to $90 per dwelling on annual cooling and heating energy following a 10% increase in tree cover (McPherson et al. 1997). And currently, a shade tree program called Energy-Saving Tree, organized by the Arbor Day Foundation, expects to save as much as 264 million kWh of energy consumption by 2025 by planting more than 140,000 trees in six U.S. cities (Austin, TX; Chicago, IL; Hartford, CT; Miami, OH; Oakland, CA; and Washington, DC) (US Administration 2014). Although these initiatives are impressive, the reality is that thousands of trees are planted across the U.S. each year by land developers and homeowners without consideration for how the energy conservation benefits of these trees could be optimized.

New residential developments are important settings for strategically planting shade trees. Due to extensive urbanization, millions of acres of green spaces have been displaced in the U.S. by construction of residential and commercial developments (Maguire et al. 1997; Theobald 2005). In the U.S., residential construction has trended toward decreased lot sizes and larger house sizes (Sarkar 2011). Within these smaller lots, there are typically fewer mature trees, less canopy cover (Carver et al. 2004;

Donovan and Butry 2009), and more impervious surfaces (Theobald 2005; Wilson and Boehland 2005). Reduced lot space and more impervious surfaces in new developments are all indicators that, to maximize energy conservation benefits from shade, tree selection and placement must be carefully considered.

Educating land developers and homeowners about the role of shade trees in energy conservation can improve their decisions about planting shade trees in residential neighborhoods. Urban residents highly appreciate shade provided by trees (Gorman 2004; Lohr et al. 2004) and tend to plant more trees in the first five years of their ownership (Summit and McPherson 1998), so providing guidance on tree selection and placement would promote strategic shade tree planting and thereby improve energy conservation benefits. Additionally, the recommendations and expectations for shade trees must take into account different climate regions (Matsuoka and Kaplan 2008; Zheng et al. 2011): for example, in colder regions, south-positioned coniferous trees, which cause unwanted winter shade, should be avoided; whereas, in hotter regions, the same trees would be preferred because they provide beneficial summer shade (Hwang et al. 2015). A better understanding of the functions and values of urban trees will help developers and homeowners select and manage trees more resourcefully (Jones et al. 2012). To this end, the objectives of our study were: (1) to evaluate how newly-planted trees are affecting energy consumption of recently constructed homes across diverse climate regions of the U.S., and (2) to examine alternative tree placement strategies around these same homes for improving energy conservation. Our approach to these study objectives was to use remote sensing data to identify newly-planted trees around recently constructed homes and then use computer simulations to contrast energy conservation effects of these existing trees with optimally placed hypothetical trees.

Methodology

Study Areas

For this study, three U.S. metropolitan areas were selected along a north to south latitudinal gradient: Metro Minneapolis, MN; Charlotte, NC; and Metro Orlando, FL (Table 1). Between 2000 and 2010, the population of Charlotte increased by 35.4% and Orlando by 28.2%, while the population in Minneapolis decreased by 0.04% (US Census Bureau 2014). These trends in population mirrored residential construction in the areas. Occupied housing units increased by 39.0% in Charlotte and 37.0% in Orlando; whereas, the units in Minneapolis increased by only 5.7%. These areas are in diverse Building America Climate Regions representing cold, mixed-humid, and hot-humid weather, respectively (Baechler et al. 2010). These varied climates influence residential energy consumption in distinct ways (Livingston and Cort 2011). Metro Orlando, with its longer cooling season (nine months from March to November when mean monthly temperatures exceed 18.3 °C), has greater cooling demands; whereas, Metro Minneapolis, with its longer heating season (nine months from September to May when mean monthly temperatures are below 18.3 °C), necessitates more energy for space heating. Charlotte is intermediate in terms of cooling and heating demand between the two latitudinal extremes.

Characterizing Residential Landscapes in the Study Areas

To characterize shade tree effects on residential energy consumption in the study areas, we sampled newly-developed residential parcels in Charlotte, Metro Orlando (including Lake County, which lies at the same latitude as Metro Orlando), and Metro Minneapolis (including Hennepin County, which lies at the same latitude as Metro Minneapolis).

With an aim to obtain sample parcels representing a typical new residential development in each study area, we controlled several landscape variables. Most notably, we sought parcels without any residual forest trees so that we could examine purposeful placement of new trees around the newly-constructed homes. Other controlled features included building type, building vintage, parcel size, parcel shape, and presence of overhead utility lines. We started with a population of single-family, one-story, detached houses constructed between 2001 and 2010 (10,928 in Metro Minneapolis, 243,323 in Charlotte, and 94,391 in Metro Orlando). The single-family, one-story, detached house was chosen because: (1) among single-family units built between 2001 and 2010, about 45% were one-story structures (US Census Bureau 2012), and (2) as a follow-up to our previous tree shade simulation study (Hwang et al. 2015), we wanted to use the same residential structure model for our energy simulations in the current study. Extremely small (below the 10th percentile) or exceptionally large (above the 90th percentile) parcels in the population were then excluded from the sampling frame because parcel size influences the number of trees planted on the parcels; a larger parcel might have more trees planted. As well, some parcels were excluded that had residual forest trees, street trees, or overhead utility lines nearby because they could influence a property owner's selection and placement of new trees following construction. Once these variables were controlled, we randomly selected 100 parcels from the sampling frame in both Charlotte and Metro Orlando. For Metro Minneapolis, we were only able to obtain 54 sample parcels because, after all variables were controlled, there were not enough parcels that met our sampling frame criteria.

Once the sample parcels were selected, we used remote sensing data, high-resolution aerial photos, and LiDAR (Light Detection and Ranging) to derive tree and landscape variables of interest. The derived variables were house orientation, parcel orientation, tree stature, tree form, and tree placement relative to the house on the parcel. These variables were then used as inputs for the simulation of tree shade effects on building energy consumption.

Simulation of Building Energy Consumption

A simulation program, EnergyPlus (Version 8.0, US Department of Energy, Washington, DC), was used to evaluate the effects of existing shade trees on energy consumption of houses on the sampled parcels (note: these simulations were only carried out for Charlotte and Metro Orlando because Metro Minneapolis did not have enough parcels available for sufficient statistical inference. Metro Minneapolis was used for parts two and three of the study described below). EnergyPlus calculates, based on weather data, the cooling and heating loads that are required to maintain pre-defined thermal setpoints (23.9 °C for cooling and 21.1 °C for heating) of a residential structure model. These weather data were downloaded from the EnergyPlus website and comprised hourly values of solar radiation and meteorological data (e.g., temperature, precipitation, and wind speed) for a one-year period in each city (US Department of Energy 2014). In these energy simulations, trees were considered to be adjacent objects that influence heat gain by casting shade upon the structure and nearby ground surfaces and regulating airflow around the structure. EnergyPlus computes the impacts of trees on heat gains as well as airflow and then applies the values to estimate the annual cooling and heating energy consumption (US Department of Energy 2014).

For the energy consumption simulations, one residential structure model and four shade tree models (two leaf types x two sizes) were used to represent the actual residential structures and their associated trees (Figure 1). To simplify the energy simulations, a fixed-sized prototypical residential structure was employed for all sampled parcels across the study areas (Table 2). This structure model had a floor area of approximately 200 m^2 (11 m x 18.2 m), a total surface area of 410.6 m^2 (four walls and two roof halves), and two windows (1.2 m x 2.1 m) on each wall. Thermal specifications for maintaining thermal setpoints of 23.9 °C for cooling and 21.1 °C for heating were determined based on energy standard ASHRAE 189.1, formulated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Long et al. 2010), which corresponds to the local climate of each study area. Because we could not identify tree species and measure their crown dimensions on the sampled parcels using remote sensing data, we simulated every existing tree using four models: (1) a small-stature deciduous tree, (2) a large-stature deciduous tree, (3) a small-stature evergreen tree, and (4) a large-stature evergreen tree (Figure 1). Crown opacity was set at 75% (leaf-on season) or 25% (leaf-off season) for deciduous trees and 80% (year round) for evergreen trees (Metro Orlando only).

Alternative Tree Placement Strategy for Energy Conservation

To examine whether energy conservation of existing trees on the sampled parcels could be improved, we developed an alternative tree placement strategy (hereafter, alternative strategy) that would be compatible with the typical layout of residential parcels in dense urban areas. Our alternative strategy was designed based on (1) our understanding of the impacts of a single tree on annual energy consumption of the adjacent structure (Hwang et al. 2015) and (2) consideration of parcel orientation constraints upon tree placement and subsequent shade provision and energy consumption. In addition, we compared our alternative strategy to the conventional tree placement strategy for energy conservation, which typically recommends planting a tree either on the west (highest priority) or east aspect of a structure. For comparative purposes, we specified the conventional strategy to place a tree first at 5 m from the west aspect of the structure and then second (if more than one tree existed) at 5 m away from the east aspect. Although this conventional strategy usually renders the most energy conservation from tree shade, it is often impossible to implement because many parcels do not have enough space for tree planting on the west side.

To contrast the energy conservation effects of existing tree between the alternative and conventional placement strategies, we again employed EnergyPlus simulations. First, we calculated the annual cooling and heating energy consumption of the residential structure model on the sampled parcels in the absence of a shade tree. Because building orientation influences energy consumption (Littlefair 2001), simulations were first performed with the structure model oriented in eight directions at

45° intervals. Additional simulations were then conducted with tree models placed at 24-predefined locations around the structure oriented north-south, with each of the tree models located at three distance (5, 10, 15 m) in eight directions (four cardinal and four intercardinal) relative to the structure (Figure 1). From this set of simulations, we identified the two scenarios (one with and one without a tree model) in which the most annual energy was consumed and used them to calculate the proportion of energy consumption estimated by each simulated configuration. These proportions were then used as an energy consumption multiplier (hereafter, called Energy Multiplier) in an equation we developed for estimating annual building energy consumption (Equation 1, hereafter called Energy Equation). This Energy Equation was developed to streamline the simulation process for comparing the existing tree placement configuration with the alternative and conventional placement strategies.

The alternative strategy was developed to address the unique challenges that orientation of the sampled parcels presented for tree placement. Initial examination of the sampled parcels using aerial photos showed that parcel orientation impacts tree placement. For example, a north-south oriented parcel (longer axis facing to east or west) typically had more trees planted on the north or south aspect of a building and there seemed to be insufficient space on either the east or west for tree planting. With an assumption that there was no space for tree planting along longer axes of parcels (due to space constraints between properties, especially as the tree matured), the alternative strategy placed the first tree where it would minimize energy consumption (the most beneficial), as determined by the initial energy simulations. The second tree (if one existed on the sampled parcel) was then selected and placed on the opposite side of the structure from the first tree (Figure 2). It had to be placed a minimal distance from the first tree to avoid overlapping of crowns, which decreases the 'per tree' shade benefits in comparison to when they stand alone (McPherson and Dougherty 1989; Simpson and McPherson 1998; Maco and McPherson 2002).

Using the alternative tree placement strategy, we virtually reconfigured the placement of existing trees on the sampled parcels and evaluated their impacts on annual energy consumption. A total of 164 randomly sampled parcels were used in this evaluation: 54 in Metro Minneapolis; 77 in Charlotte; and 33 in Metro Orlando. These parcels had one or two trees within their boundaries and were representative of recent residential developments that retain few existing native trees on the parcels. Of the Metro Minneapolis parcels, about half of them had one or more trees at a distance of more than 15.2 m from the house. These trees were excluded from the simulations because trees at this distance would not provide significant shading or windbreak effects (Heisler 1986; Simpson and McPherson 1996).

After determining tree placement on the sampled parcels for all these scenarios (existing configuration, alterative strategy, and conventional strategy), shade tree effects on energy consumption was evaluated using the following Energy Equation:

*Energy Consumption = Most Energy Consumption (no tree) x Building Multiplier (no tree) x 1st Tree Multiplier * 2nd Tree Multiplier* ------------------- (Equation 1)

where, *building* and *tree multipliers* are the proportion of building energy consumption in the simulated configuration to the most energy consumptive configuration. Shown here is an example of the calculation of energy consumption for north-south oriented residential structure with two large deciduous trees on the east and west aspects in Orlando: 2,208 kWh = 2,449.59 kWh (the most energy consumptive structure without an adjacent tree in Orlando) × 0.960 (multiplier for the north-south oriented structure) × 0.958 (multiplier for the large deciduous tree on the west at 5 m away) × 0.980 (multiplier for the large deciduous tree on the east at 15 m away). Once energy consumption for each of the sampled parcels, having either one or two trees, had been estimated using the Energy Equation, a matched-pair T-test (JMP version 11.0, SAS Institute, Inc., Cary, NC) was used to compare the Energy Equation to the EnergyPlus outputs to gauge the validity of our Energy Equation approach.

Comparative Simulation of Tree Benefits

A web-based program, i-Tree Design (US Forest Service 2015), was employed to assess other ecosystem benefits that the existing trees on the sampled parcels provide and to compare energy simulation outputs with EnergyPlus. Based on user inputs, including data about trees and the associated structure, i-Tree Design incorporates Google Maps in a graphical interface to estimate four ecosystem benefits: stormwater interception, air quality improvement, carbon sequestration, and energy conservation (detailed information is available at the i-Tree Design web page: https://www.itreetools.org/design.php). For these i-Tree Design simulations, a total of 40 parcels were randomly selected from the previously sampled parcels in Charlotte and Metro Orlando having either one or two existing trees (20 parcels in each study area). Tree variables were selected as appropriate for each study area, and, as much as possible, similar to the tree models used in the EnergyPlus simulations. For example, we selected flowering dogwood (Cornus florida) for Charlotte and crape myrtle (Lagerstroemia spp.)

for Metro Orlando, which represent small deciduous trees (23 cm trunk diameter) (McPherson et al. 2006) and willow oak (Quercus phellos) and laurel oak (Quercus laurifolia), respectively, for large deciduous trees (91 cm trunk diameter) (Peper et al. 2009). They were then digitized in the program to match existing tree locations on the sampled parcels. The residential structures were digitized onto the building footprints based upon images and specified as the post-1980; building vintage, which was the option most similar to the sampled parcels.

Results

Existing Conditions on Residential Parcels

The sampled residential parcels in Charlotte and Metro Orlando showed differences in parcel size, building footprint size, and parcel orientation (Table 3). Charlotte had smaller parcels (728.3 ± 14.4 m^2) and building footprints (180.5 ± 4.0 m^2) than Metro Orlando (982.6 ± 6.6 m^2 and 255.8 ± 6.6 m^2, respectively; $p < 0.0001$). The study areas also differed in distributions of parcel orientation ($p < 0.0001$). In Metro Orlando, the dominant parcel orientation (55% of parcels) was north-south (longer axis lying north to south), which could explain the large number of south-facing residential structures (57%). There was no dominant orientation in Charlotte.

Some similarities in abundance, form, and placement of existing trees were found in both study areas (Table 3). Total tree count on all sampled parcels was 148 in Charlotte and 265 in Metro Orlando. Ninety parcels (Charlotte) and Ninety-nine parcels (Metro Orlando) had at least one tree within the property boundary. According to the LiDAR data, average tree height on these parcels was only 5.9 ± 0.3 m (Charlotte) and

3.7 ± 0.1 m (Metro Orlando). Therefore, most trees were likely young and had been purposefully planted after development (Note: Because of differences in acquisition of LiDAR data and Aerial photos, only 196 out of 266 trees were measurable. Unmeasurable trees would have been planted after 2008 when LiDAR data were collected). In Metro Orlando, trees were identified as mostly deciduous or broad-leaf evergreen; in Charlotte, all trees were deciduous. Trees were located at average distances of 7.6 ± 0.2 m (Charlotte) and 7.8 ± 0.2 m (Metro Orlando) from the residential structures. After an initial examination of remote sensing data, tree placement within the property boundaries was shown to correlate with parcel orientation ($p < 0.0001$). For example, parcels with an east-west orientation had more trees planted on either the east or west aspect. This relationship was one factor that dictated how the alternative tree placement strategy was designed**.**

Energy Impacts of Existing Trees

Without trees, the annual energy consumption of the structure model simulated on sampled parcels in Charlotte averaged 9,924 kWh (valued at $1,072 based on the annual average electricity price of $0.108 cent per kWh) and in Metro Orlando averaged 8,824 kWh (vaulted at $1,015 based on the annual average electricity price of $0.115 cent per kWh). Annual cooling and heating energy consumption as a percent of total household energy was about 35% in Charlotte (3,415 ± 2.1 kWh) and 26.4% in Metro Orlando (2,263 ± 7.6 kWh). The nine-month cooling season in Metro Orlando tended to necessitate increased spending on cooling energy, using approximately twice as much energy, in comparison to Charlotte. In contrast, the colder weather during the longer heating season in Charlotte required more heating energy than in Metro Orlando. Simulations in both study areas showed that an east-west oriented structure (longer sides facing either north or south) typically consumed the least cooling energy: up to 3.6% (Charlotte) and 7.2% (Metro Orlando) less than structures with other orientations.

In both study areas, the existing trees on sampled parcels were shown to influence both cooling and heating energy consumption. In Metro Orlando, energy savings during the longer cooling season were large enough to compensate for any heating penalty caused by winter tree shade such that in most cases annual energy consumption was reduced; annual energy savings ranged from $0 (no impact) to $46.52 (average savings of $9.65 ± 0.83, n=91) for the sampled parcels, depending on the tree models. On the other hand, in Charlotte, with its longer heating season, existing trees sometimes induced a heating penalty in excess of cooling savings. Energy conservation values on the sampled parcels in Charlotte ranged from - $1.08 (additional energy expenditure) to $9.82 (energy savings) with average savings of $1.66 ± 0.16 annually (n=90).

The impact of existing trees on annual energy savings was then compared by both parcel and building orientations. Looking at parcel orientations, in both study areas, the east-west oriented parcels showed the most annual energy savings: average of $2.58 ± 0.26 per parcel in Charlotte and $17.15 ± 2.28 in Metro Orlando (Table 4) because these parcels had more trees planted on either the east or west, which is the shade tree placement most commonly associated with energy conservation (Hilderbrandt and Sarkovich 1998; Simpson 1998, 2002). In contrast, the average annual energy savings by building orientations did vary between study areas. In Charlotte, there was no statistical difference in energy savings by building orientation; whereas, in Metro Orlando, there was a significant difference in energy savings between the north-south oriented buildings and the east-west oriented buildings.

Alternative Tree Placement Strategy

When comparing the annual energy consumption simulations of EnergyPlus and our Energy Equation, we found that the Energy Equation slightly overestimated energy consumption (Figure 3). On average, EnergyPlus and the Energy Equation differed by less than 1%. Overestimation was most significant with evergreen trees in Metro Orlando. Because large trees have greater energy effects and the Energy Equation appeared to most reliably simulate energy effects of deciduous trees, below we focus our comparison of placement strategies on large deciduous trees.

The effectiveness of the alternative strategy was determined by comparing the energy savings provided by existing trees to the energy savings provided when these trees were reconfigured with the alternative strategy. There was evidence that existing trees were not strategically placed (one placed on the west and the other, if available, on the east) on the sampled parcels, most likely due to space constraints. With the assumption that all trees were modeled as mature specimens, existing trees on the sampled parcels were shown to reduce annual energy consumption by up to $5.12 ± 0.81 (44.5 ± 7.0 kWh) per parcel, depending on the study area (Figure 4). The alternative strategy resulted annual energy savings up to $11.86 ± 0.76 (103.2 ± 6.6 kWh) per parcel (increase of 148% over the existing configuration). The alternative strategy was also shown to reduce heating penalties of trees on some parcels in northern latitudes, especially Metro Minneapolis, with its longer heating season. When compared with the conventional tree placement strategy (placing one tree at 5 m on the west and the other at 5 m on the east), the alternative strategy was equally effective as the conventional strategy in Metro Minneapolis ($p = 0.4439$) and Charlotte ($p = 0.9099$); whereas, the alternative strategy was less effective than the conventional strategy in Metro Orlando ($p < 0.0001$).

The efficacy of the alternative strategy was also evaluated by comparing the energy savings based on parcel orientation (Figure 5: data shown for Charlotte only). The alternative strategy was superior to the existing configuration for most parcel orientations ($p < 0.05$, except only for the sampled parcels with a northeast-southwest oriented in Metro Minneapolis: $p = 0.4325$). For all parcel orientations, there was no statistical difference in energy savings between the alternative strategy and the conventional strategy (all, $p > 0.05$). In comparison to the sampled parcels with an east-west orientation, which tended to have more existing trees on the optimal placements (either the east or west aspect), the alternative strategy had the greatest benefits when it was applied to parcels with other orientations. For example, in Charlotte and Metro Orlando, average energy savings per parcel increased by more than 240% (from $1.35 to $4.59 and from $3.47 to $12.03, respectively) when the alternative strategy was applied to the sampled parcels with a northeast-southwest orientation. In Metro Minneapolis, the alternative strategy was superior to the existing configuration when it was applied to the sampled parcels with a north-south orientation: average energy savings per parcel increased from $0.40 to $7.01.

Comparative Simulations of Tree Benefits

Shade tree energy savings estimated by EnergyPlus were shown to be lower than i-Tree Design simulations (Table 5). For example, in Charlotte, EnergyPlus estimated average annual energy savings per parcel of $1.40 ± 0.27 by small deciduous trees; whereas, i-Tree Design assessed estimated at $2.43 ± 0.99 per parcel for the same tree. These differences were even greater for large trees: $2.63 ± 0.40 (EnergyPlus) versus $19.61 ± 3.13 (i-Tree Design). Potential reasons for the differences will be covered in the discussion section.

Along with energy conservation benefits, it is equally important to understand how existing trees could provide other ecosystem benefits, such as stormwater reduction, air quality improvement, and carbon sequestration. Using i-Tree Design and simulated tree models, we found that the existing trees on the sampled parcels in each study area could provide annual ecosystem benefits, including energy savings, up to $242.35 ± 20.13 per parcel (large tree models in Charlotte) and $149.99 ± 7.43 (large tree models in Metro Orlando) (Table 4). Typically, the larger the tree, the greater the ecosystem benefits provided. Regardless of tree placements and study areas, a large tree provided stormwater runoff savings twice as much as a small tree. However, when considering energy conservation, benefits were influenced by tree size. Energy savings by small tree models accounted for about 28% (Charlotte) and 50% (Metro Orlando) of the total ecosystem benefits; whereas, those by large tree models accounted for only 8% and 21%, respectively, of the total ecosystem benefits.

Discussion

In this study, we have proposed an alternative strategy for placement of shade trees for residential energy conservation (Figure 2) that takes into account the existing local conditions of dense urban neighborhoods. We found that existing trees in the sampled parcels were typically too immature to provide significant energy savings. But over time, when those trees mature into large-canopied specimens, our simulations suggest that there will be energy savings of up to $5.12 per parcel annually, depending on the study area. Our study also suggests that, if those same trees had been planted using our proposed alternative placement strategy, there would be an additional energy savings of up to $6.74 per parcel annually. This difference is evidence that many existing trees in newly constructed residential developments are not optimally placed for energy conservation.

The fundamental approach is to understand the preferences and expectation of urban residents based on their circumstances (built and natural environments) and then select the tree placement strategy that put trees to their highest and best use. Urban residential landscapes often reflect the personal tastes and expectations of homeowners without consideration of the practical benefits of urban trees (Getz et al. 1982; Sommer 2003; Pincetl et al. 2013). In this study, we examined configuration of existing trees as an intermediate step to develop alternative tree placement strategies aimed specifically at improving the energy conservation benefits. However, in urban areas, tree selection and placement must be considered in the full context of the landscape conditions so that potential benefits are maximized while concurrently minimizing risks and costs to individuals and communities (Dwyer et al. 1992, Kuo et al. 1998).

Our study did not account for spill-over shade effects, which can provide energy conservation benefits (or costs) to neighboring structures (Nikoofard et al. 2011; Sawka et al. 2013). A study conducted in Toronto, Canada (Sawka et al. 2013) found that trees planted through a tree planting program provided energy savings not only to the participants but also to neighboring homes: more than 50% of the total energy savings was calculated from neighboring homes. In our study, we found that over 60 of the 100 sampled parcels in Charlotte had one or more of trees placed within 15 m from the neighboring house. Due to tree placement (direction and distance) relative to the neighboring houses, the trees could possibly provide partial energy conservation benefits to neighboring structures. These energy savings benefits would be even more prominent when broadening the scope to an entire community. However, this desirable spill-over shade in summer months could easily become unwanted winter shade. Therefore, the impact of shade trees on both target homes and neighboring homes must be taken into consideration in order to estimate distinct shade benefits for dense residential areas.

Compared to i-Tree Design simulations, shade tree energy savings from our EnergyPlus simulations appeared to be small and might not convince property owners to plant shade trees strategically. It was difficult to compare our study with i-Tree Design directly because of differences in the simulation mechanics. First, EnergyPlus does take into account evapotranspiration cooling, which is an aggregate effect of multiple trees: the larger the tree canopy, the greater the evapotranspiration cooling (Huang et al. 1987; McPherson and Rowntree 1993). When considering that an increase in canopy cover by 25% produced substantial energy conservation benefits (Huang et al. 1987), planting a single shade tree, which covers only 5-10% of an individual parcel, would be less significant. Second, the tree and structure models used in i-Tree Design versus EnergyPlus might influence the extent of energy savings estimated by each. Due to limited information for tree models used in i-Tree Design, we were not able to match tree models precisely. Furthermore, the three distances with 5 m intervals in our estimations might not fully address impacts of tree distance on energy consumption. For example, past experiments have shown that a south-positioned tree at 5.1 m distance would have a greater impact on energy consumption than a tree at 9.9 m away. However, the Energy Equation used in our study treated them as the same distance because they fell in the same 5 m interval. Lastly, building energy efficiency, which has increased by more than 10% since the 1980s (US Department of Energy 2008), also influences the extent of energy savings. The structure model used in our EnergyPlus simulations used the recent specification (ASHRAE Standard 189.1), which is highly energy efficient. In contrast, post-1980 construction is the most recent structure vintage in i-Tree Design simulation, which is much less energy efficient and therefore more easily influenced by shade trees.

Our results provide evidence that the alternative strategy is effective for improving energy conservation benefits. Assuming that trees on the sampled parcels were predominantly large-maturing species, reconfiguring trees with the alternative strategy would provide additional energy savings of up to \$6.74 per parcel. Even though these values seem negligible on a per parcel basis, the accumulated value of these additional energy savings, community-wide, would be nearly \$65,600 annually in Metro Orlando (\$6.74 × a total of 9,725 parcels having either one or two trees and built between 2001 and 2010). As such the incorporation of an optimal shade tree placement strategy could greatly enhance community-wide benefits.

The alternative strategy was designed to be optimal for dense residential areas where potential tree planting spaces are limited. Many U.S. cities have already implemented tree planting programs, which have succeeded to produce various ecosystem and social benefits including energy conservation (Pincetl, 2010; Pincetl et al., 2013). Although energy conservation is not the sole focus of most civic tree planting programs, it turns out that they are fortuitously effective for modifying urban temperatures and accordingly for conserving energy for space conditioning (Pincetl et al., 2013; Sawka et al., 2013). Tree planting programs were found to typically recommend planting a tree on the west aspect of a building in order to cast shade on the structure's west wall in the late afternoon when cooling demands peak (Akbari et al. 1997; Simpson and McPherson 1996). Our results affirmed that this conventional strategy typically reduces energy consumption the most (Figure 4); however it is not always possible to implement in dense urban areas, where limited space is available for planting even a single tree on the west, especially a large tree as it matures. For example, of the 100 Charlotte parcels used in our study, only 28 of the 148 existing trees (about 19%) could be feasibly placed on the west. And, 18 of those 28 trees were planted on the east-west oriented parcels, where they afford the most space on the west aspect. Chances for planting a tree on the west would often be limited especially where the east-west oriented parcels were not a dominant parcel. Our alternative strategy could be tailored as more easily for shade tree planting in dense urban neighborhoods.

Although our study focused on how to improve energy conservation specifically, it is well-documented that trees also provide numerous other benefits in urban environments (Solecki et al. 2005; Roy et al. 2012). For example, a parcel in Charlotte could expect gross annual benefits of about $370.00 from a combination of air pollution, stormwater runoff, and energy savings when two large red maples are located on the west and the northwest aspect of the house (average ecosystem benefits per parcel assessed by i-Tree Design were shown in Table 5). Unlike other simulated ecosystem benefits of trees, energy conservation benefits are strongly influenced by tree form and tree placement. Therefore, we suggest that a more strategic approach to shade tree placement will amplify energy conservation benefits for the target parcel and possibly provide spill-over benefits for adjacent parcels.

Conclusion

This study has presented an alternative strategy for placement of shade trees, specifically aimed at improving energy conservation benefits for dense urban neighborhoods. We found that the conventional placement strategy, which recommends planting a tree on the west, seems to be the most reliable approach, but it is often inapplicable due to space constraints. In situations where the conventional tree placement strategy is not applicable, our alternative strategy will improve energy conservation and can even be as effective as the conventional strategy, depending on geographic locations. Planting trees might be one of only a few approaches that urbanites can easily implement for energy conservation once an urban residential development has been constructed. And, energy conservation is just one of the many well-known ecological benefits that urban trees provide (Roy et al. 2012). Therefore, for enhancing energy conservation effects, this study concludes that appropriate tree placement strategies, corresponding to physical surroundings, should simultaneously take into account the trees on an individual parcel and their combined effects throughout the community.

Even though our study showed that the alternative strategy could improve energy conservation, we recognize that there were several limitations to the study. First, our study was a snapshot of trees and did not account for future tree growth. Tree models used in our simulations were considered as fully matured; therefore, we were not able to ascertain changes in energy savings as trees grew. Also, the contrived simulation environments used in our study could not fully describe the variations of residential parcels or tree types and sizes that can be found in urban areas. Various structure designs and construction materials, which would influence energy consumption (Akbari and Taha 1992; Sadineni et al. 2011), were not taken into consideration. As well, the four tree models (two leaf types × two sizes) used in our simulations could not fully typify urban trees. Despite these limitations, we expect that, through future studies that address our limitations, our strategy could further support the development of tree planting guidelines and aid in the creation of supportive policies that would be applicable in dense urban settings. Understanding of tree form and tree placement, which influence the quantity and quality of tree shade, along with latitudinal effects on cooling and heating seasons (Heisler 1986; Hwang et al. 2015), would support the development of the most effective tree planting strategies for energy conservation.

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Figures

Tree Form

		small	large
Deciduous tree	Tree height (m)	7.3	15.2
	Bole height[1] (m)	1	3
	Crown diameter (m)	7.6	10.6
	Crown opacity[2]	75% (Apr. - Oct.) & 25% (Jan. - Mar. / Nov. - Dec.)	
	Crown shape	Ellipse	
Evergreen tree	Tree height (m)	7.3	15.2
	Bole height[1] (m)	1	3
	Crown diameter (m)	7.6	10.6
	Crown opacity[2]	80%	
	Crown shape	Parabola	

[1] Bole height: the distance between the ground level and the crown base.
[2] Crown opacity (shade coefficient): the percent of available solar radiation blocked by the tree crown (McPherson et al., 1985).

Tree Placement

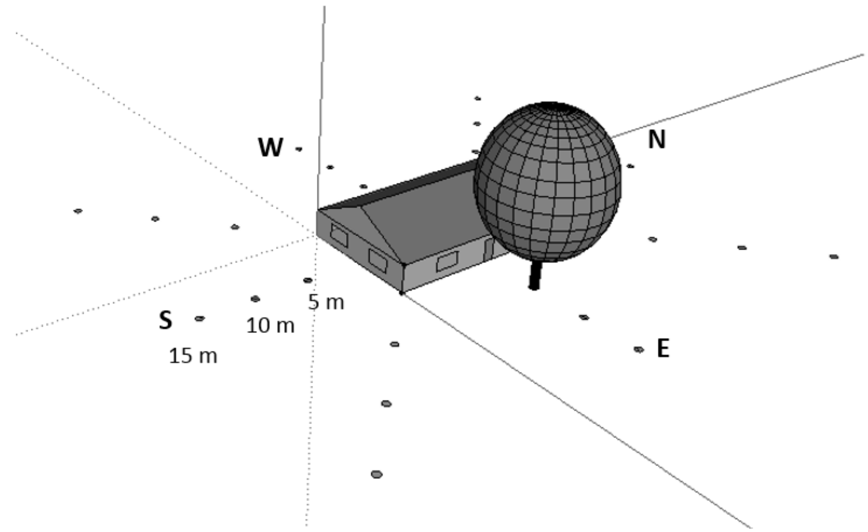

Figure 1 Specification for shade tree models used in simulations of residential energy consumption. The table lists the five tree form variables used to construct four tree models (small and large deciduous tree; small and large evergreen tree). The schematic shows placement of the tree models at 24-predefined locations (three distances × eight directions) around the structure model. In this depiction, a large deciduous tree is drawn to scale at 5 m east of the north-south oriented structure model.

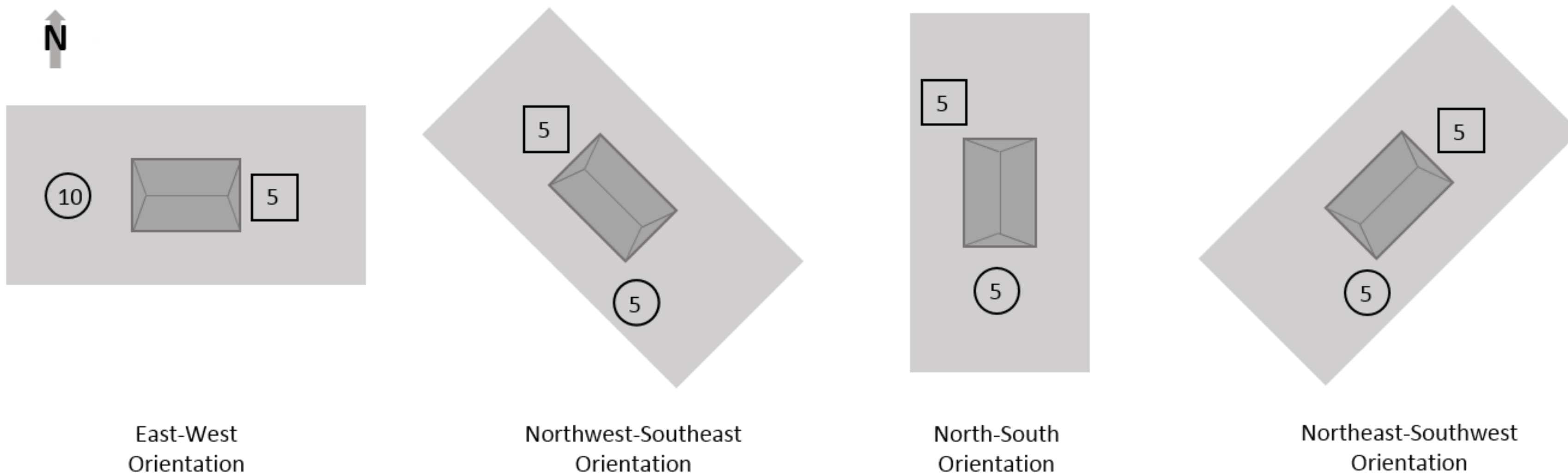

Figure 2 Schematic (aerial view) of the alternative tree placement strategy applied in Metro Orlando for optimal placement of large deciduous trees (circles and squares) around a residential structure model (dark gray box). The strategy is described in the methodology section. Numbers in the circles (highest priority tree placement) and squares (second-highest priority) indicate tree distances (m) from the structure model.

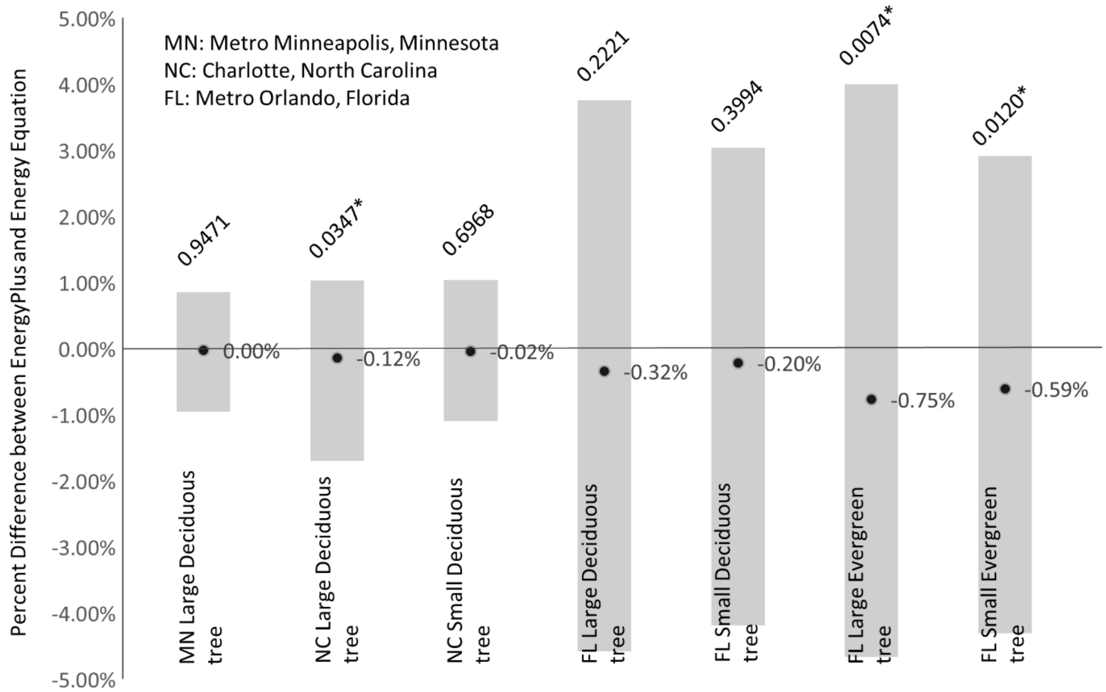

Figure 3 Comparison of the two techniques (EnergyPlus and Energy Equation) used for estimating shade tree effects on the annual energy consumption of houses in Metro Minneapolis (n=54), in Charlotte (n=77), and in Metro Orlando (n=33). The Energy Equation was developed to save simulation processing time. Columns show data value ranges. Numbered points indicate the average percent difference between the two estimations and show that the Energy Equation consistently overestimated annual energy consumption, but only by a slight margin. Numbers above each column are the p-value for the matched-pairs T-Test (an asterisk [*] indicating a significant difference between the two estimations).

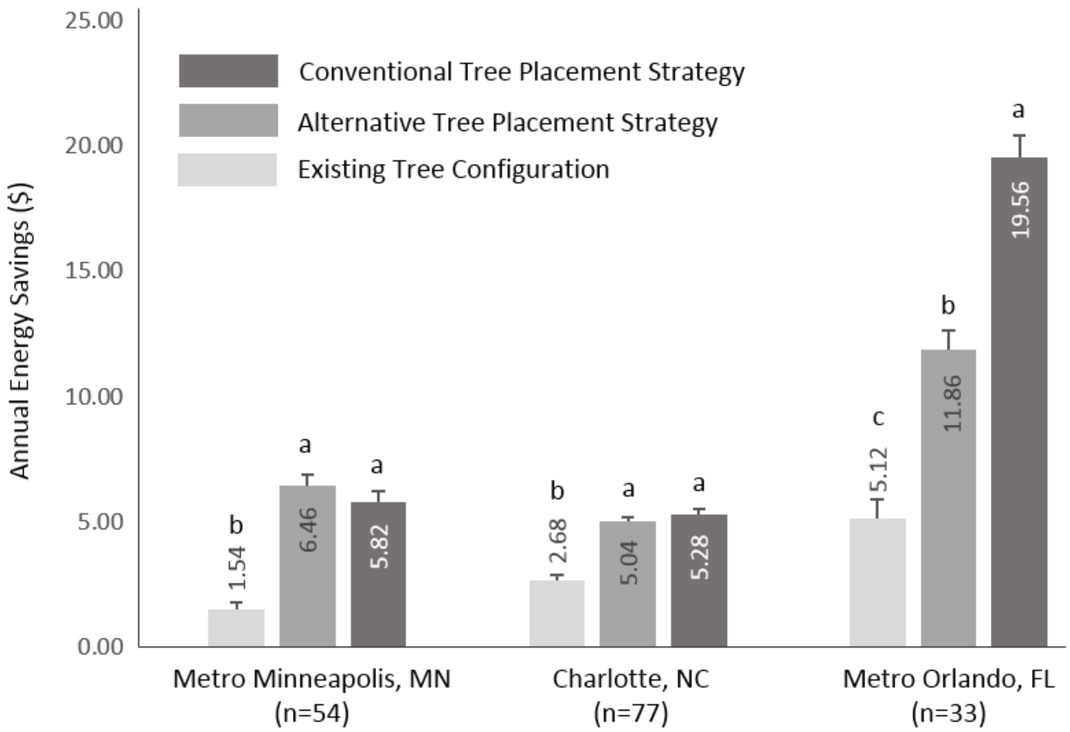

Figure 4 Annual energy savings per parcel from large deciduous shade trees in three U.S. cities (mean values labeled). Within a study area, values labeled with different letters are significantly different using Tukey's HSD test.

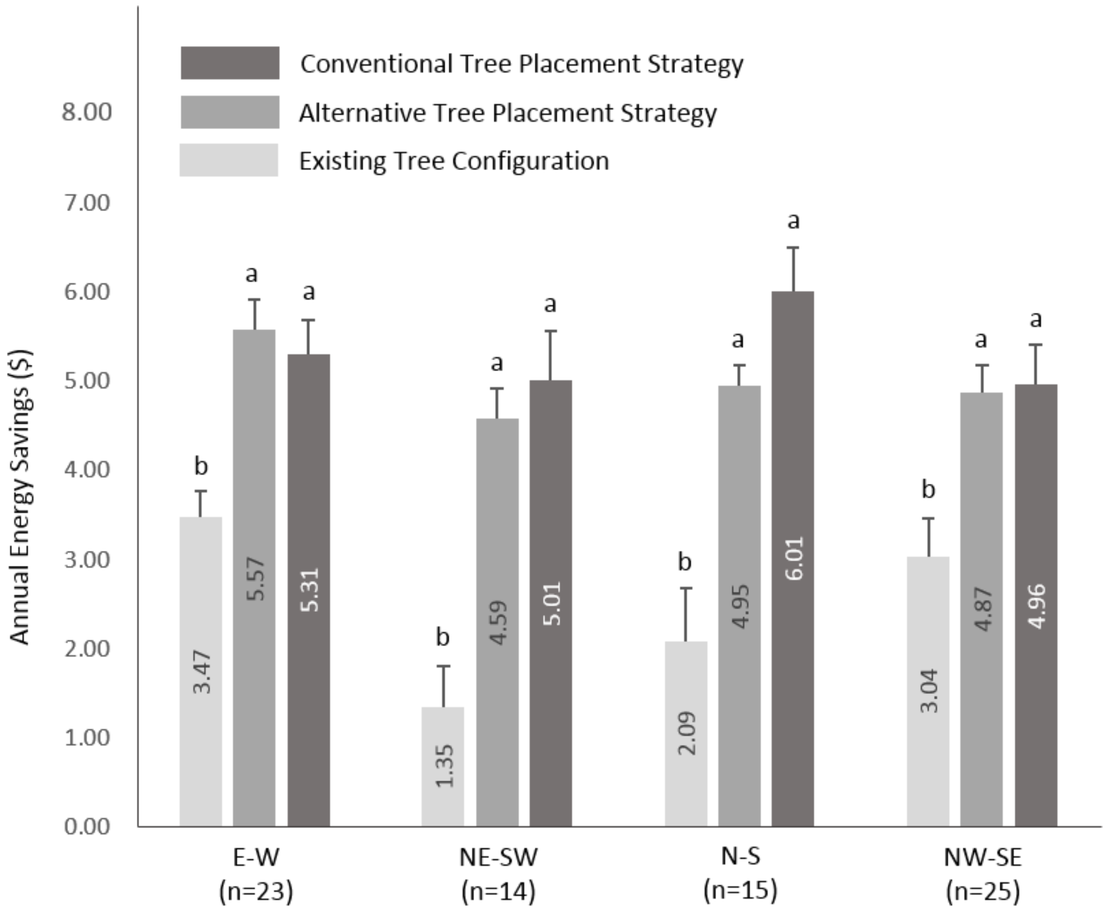

Figure 5 Annual energy savings per parcel from large deciduous shade trees in Charlotte, NC by parcel orientation (mean values labeled). Within a parcel orientation, values labeled with different letters are significantly different using Tukey's HSD test.

Tables

Table 1 Climatic information for the study areas where computer simulations of tree shade effects on annual energy consumption of a residential structure model were performed.

Study Areas	Latitude	BACR Climate Zone[1]	Min. Temp[2] (°C)	Mean Temp[2] (°C)	Max. Temp[2] (°C)	Cooling Season[3]	Heating Season[3]
Metro Minneapolis, MN	45.12° N	Cold	2.1	7.4	12.6	Jun - Aug	Sep - May
Charlotte, NC	35.37° N	Mixed-humid	10.6	16.3	22.1	Jun - Sep	Oct - May
Metro Orlando, FL	28.92° N	Hot-humid	16.9	22.7	28.4	Mar - Nov	Dec - Feb

[1] Building America Climate Regions are determined based on cooling and heating degree-days (Baechler et al. 2010).

[2] Min./Mean/Max. Temp.: Annual average minimum/mean/maximum normal temperature (National Oceanic and Atmospheric Administration, 2012).

[3] Cooling season is defined as when monthly mean temperatures exceed 18.3 °C, while heating season is when monthly mean temperatures are below 18.3 °C.

Table 2 Characteristics of the residential structure model used in simulations of shade tree effects on building energy consumption in three U.S. study areas.

Variables	Metro Orlando, Florida	Charlotte, North Carolina	Metro Minneapolis, Minnesota
Physical dimensions of the structure	11 m x 18.2 m x 2.4 m (floor height) / 5.2 m (roof peak)		
Climate Zone[1]	2A	3A	6B
Effective R-value[2]			
External wall (m^2K/W)	2.624	3.073	3.689
Roof (m^2K/W)	8.104	8.104	8.104
Window (U-factor, W/m^2K)	2.56	4.26	1.42
Insulation Min. R-value[2]			
External wall	R-13 + R3.8 ci	R-13 + R3.8 ci	R-10 + R10 ci
Roof	R-49	R-49	R-49
Internal loads[2]			
Lighting	Climate Zone 1-3 Mid-Rise Apt Light		Climate Zone 4-8 Mid-Rise Apt Light
Electric Installation	Climate Zone 1-3 Mid-Rise Apt Electric		Climate Zone 4-8 Mid-Rise Apt Electric
No. of Occupants	3		
HVAC system[2]	Electric Heat Pump		
Thermostat setting			
Cooling season (°C)	23.9		
Heating season (°C)	21.1		
Annual Energy Consumption of Unshaded Structure[3]			
Cooling (kWh / percent of total energy consumption)	1012 / 11%	567 / 6%	376 / 3%
Heating (kWh / percent of total energy consumption)	329 / 3.7%	1535 / 16%	4698 / 36%
Annual Average Electric Price ($/kWh)[4]	0.1152	0.1082	0.1137

[1] International Energy Conservation Code (IECC) Climate Regions (US Department of Energy 2013).

[2] Physical characteristics of the structure models were downloaded and employed from the U.S. Department of Energy's online library (Fleming et al. 2012) and their specifications met ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 189.1 for Mid-Rise Apartments.

[3] Annual energy consumption of unshaded structure was estimated using a north-south oriented model structure.

[4] 2012 Annual Average Electric Price from US Energy Information Administration (US Energy Information Administration 2014).

Table 3 Existing landscape conditions in study areas derived using remote sensing data. Average building (floor area) and parcel sizes were calculated using the ArcGIS tool (Calculate Geometry). Standard errors of mean shown for parcel, building, and tree variables. Unmeasurable trees (eight trees in Metro Minneapolis and 70 trees in Metro Orlando, due to the image vintage) were excluded from mean calculations.

Study Areas	Parcel Count	Mean Parcel Size (m^2)	Mean Building Size (m^2)	Existing Trees		
				Mean Count per Parcel	Mean Height (m)	Mean Distance (m)
Metro Minneapolis	54	1193.1 ± 36.2	237.0 ± 6.4	1.4 ± 0.1	4.3 ± 0.2	10.0 ± 0.4
Charlotte	100	728.3 ± 14.4	180.5 ± 4.0	1.5 ± 0.1	6.0 ± 0.3	7.6 ± 0.2
Metro Orlando	100	982.6 ± 6.6	255.8 ± 6.6	2.7 ± 0.2	3.7 ± 0.1	7.8 ± 0.2

Study Areas	Parcel Orientation Count				Building Orientation Count			
	E-W	NW-SE	N-S	NE-SW	E-W	NW-SE	N-S	NE-SW
Metro Minneapolis	17	5	20	12	23	12	14	5
Charlotte	29	19	16	36	30	30	23	18
Metro Orlando	20	13	55	12	57	9	26	8

Table 4 Annual energy savings provided by existing shade trees on residential parcels in Charlotte, NC and Metro Orlando, FL. Parcel and tree counts represent a total number of parcels and shade trees observed within property boundary by study area, parcel orientation, and building orientations. Average annual cooling and heating energy savings per parcel were estimated using EnergyPlus simulations of tree models and structure models. Within the study areas, a parcel orientation, and a building orientation, values labeled with different letters are significantly different using Tukey's HSD test.

		by Study Area	by Parcel Orientation				by Building Orientation			
			E-W	NE-SW	N-S	NW-SE	E-W	NE-SW	N-S	NW-SE
Charlotte	Parcel Count	90	26	18	15	31	27	27	21	15
	Tree Count	149	41	45	36	27	42	31	22	54
	Mean Savings ($) per Parcel	1.66±0.16b	2.58±0.28a	1.16±0.32bc	0.51±0.21c	1.74±0.26ab	1.98±0.35a	1.39±0.27a	1.56±0.26a	1.74±0.35a
Metro Orlando	Parcel Count	91	18	13	50	10	52	8	23	8
	Tree Count	265	64	39	136	26	145	22	71	27
	Mean Savings ($) per Parcel	9.65±0.83a	17.15±2.28a	9.19±1.68b	7.20±0.93b	9.32±1.91b	7.65±0.95b	11.09±2.35ba	13.15±2.05a	11.08±2.11ba

Table 5 Results of i-Tree Design simulations of ecosystem benefits from study area trees. Benefits were simulated for 20 sampled parcels each in Charlotte and Metro Orlando. Dominant species of small and large deciduous trees in each study area were used for simulations. Each value represents average ecosystem benefits per parcel simulating either one or two existing trees. Mean benefits represent average ecosystem services of all 20 sampled parcels. Standard error of the mean is shown for total ecosystem services.

Study Area	Tree Count[1]	Parcel Count	Small Deciduous Tree[2]					Large Deciduous Tree[3]				
			SW[4] ($)	AQ[5] ($)	CO_2[6] ($)	Energy[7] ($)	Total ($)	SW ($)	AQ ($)	CO_2 ($)	Energy ($)	Total ($)
Charlotte	1	13	5.91	0.33	0.87	1.97	9.08 ± 1.40	155.71	2.73	6.50	13.67	178.62 ± 3.85
	2	7	11.82	0.66	1.69	3.23	17.45 ± 1.93	311.42	5.49	13.18	30.63	360.72 ± 4.39
	Mean Benefits		7.98	0.45	1.15	2.43	12.01 ± 1.44	210.21	3.7	8.84	19.61	242.35 ± 20.13
Metro Orlando	1	4	1.46	0.47	0.29	3.04	5.26 ± 0.77	55.89	7.15	3.00	21.57	87.61 ± 4.43
	2	16	2.92	0.93	0.50	5.32	9.68 ± 0.38	111.78	14.13	4.90	34.76	165.58 ± 2.33
	Mean Benefits		2.63	0.84	0.46	4.87	8.79 ± 0.53	100.6	12.73	4.52	32.13	149.99 ± 7.43

[1]Number of trees on the sampled parcel.

[2]Small Deciduous Tree (23cm trunk diameter) species used for simulations: flowering dogwood (*Cornus florida*) for Charlotte / crape myrtle (*Lagerstroemia spp.*) for Metro Orlando (McPherson et al. 2006)

[3]Large Deciduous Tree (91cm trunk diameter) species used for assessments: willow oak (*Quercus phellos*) for Charlotte / laurel oak (Quercus laurifolia) for Metro Orlando (Peper et al. 2009).

[4]SW: Stormwater runoff savings by intercepting rainfall.

[5]AQ: Air quality improvement savings by absorbing and mitigating pollutants; reducing energy production needs; and lowering air ambient temperature.

[6]CO_2: Reducing atmospheric carbon dioxide through CO2 sequestration and decreased energy production needs and emissions.

[7]Energy: Combined summer energy savings by direct shading and air cooling effect through evapotranspiration and winter saving by slowing down winds and reducing home heat loss.

Chapter 5 Conclusion

The investigation of the effects of urban trees on residential energy consumption started several decades ago with the conclusions being used to develop a prevalent planting strategy for energy conservation. This strategy involved planting a tree on the west aspect of a building because it casts desirable shade upon building surfaces in late afternoon when cooling demands peak in summer (McPherson et al. 2005, 2006; Peper et al. 2009, 2010). In contrast, undesirable shade cast by misplaced trees could cause additional energy expenditure through blocking passive solar heating in winter (Simpson and McPherson 1996, 1998; Simpson 1998). As urbanization progresses, millions of acres of green spaces are being displaced by the construction of residential and commercial developments (Theobald 2005), contributing to increased urban temperatures. New residential construction has a tendency toward decreased lot sizes and larger house sizes (Sarkar 2011), and this trend often imposes space constraints on property owners for planting a tree on the west aspect. Two previous studies, which examined energy conservation effects of urban trees (Simpson and McPherson 1998; Simpson 2002), motivated this dissertation for investigating interactions between tree form and tree placement over diverse geographic settings. These interactions were examined, using computer simulations, to quantify and qualify shade provision. Findings from simulation results were then used for developing shade tree planting strategies that could be applied to new residential developments for improving energy conservation benefits in dense urban areas**.** Given the prediction of a warmer planet in the future (IPCC 2007) and a 2-4% increase in electricity demand with each 1 °C increase in average temperature (Akbari et al. 2001), temperature mitigation and associated energy conservation benefits from planting shade trees strategically will have significant implications for human health and energy security.

The first study presented in Chapter 2 used a computer simulation program called Shadow Pattern Simulator. Shade simulation results showed that shade provision is influenced by not only tree form and placement, but also daily, seasonal, and latitudinal patterns in sunlight exposure. Also, the results supported the conventional recommendation of planting large trees on either the east or west in close proximity to a structure. Trees in either placement were shown to provide high levels of shade during the cooling season while, at the same time, minimize heating penalties of unwanted shade during the heating season. Evidence from the study indicates that to minimize heating penalties in northern latitudes with their longer heating season, planting a tree on the south aspect should be avoided; whereas, in southern latitudes where heating penalties were less critical, southerly-placed trees should not be discounted because they provide beneficial seasonal shade cooling. In addition, this study revealed the nuanced relationships between tree variables (tree form and tree placement), geographic latitude, and shade provision over a varied range of urban settings. From these research findings, precise and practical tree planting recommendations could be developed as a collaborative contribution for improving energy conservation for dense urban areas where there are limited tree planting options.

The impact of energy conservation benefits are influenced by tree form and tree placement, as well as seasonal and geographic variability in sun path and solar heat gains. With this regard, the second study presented in Chapter 3 evaluated, using a computer program called EnergyPlus, the impact of a single shade tree on residential energy consumption. As a tree placed on the west aspect provides a substantial amount of tree shade upon the structure model in late afternoon when heat demands have peaked, the general recommendation for planting a deciduous trees on the west aspect would be the most reliable implication for energy conservation. In addition, the shading nuances, produced by the quantity and quality of tree shade, due to interactions of tree variables with seasonal and geographic variability in sun path and solar heat, varied the extent of energy conservation. These findings are evidence that understanding interactions between tree variables and geographic context would be a key principle of strategic shade tree planting for enhancing energy conservation.

With the current trend of decreasing residential lot sizes and increasing house sizes, space constraints often prevent homeowners from implementing the conventional recommendation for energy conservation: planting a tree on the west aspect of a structure. The study presented in Chapter 4 used remote sensing data to evaluate the shade benefit of the newly-planted trees in terms of energy conservation. In conjunction with the findings from the two prior studies (Chapter 2 and 3), as a means to enhance energy conservation benefits for recent residential developments, this study proposed shade tree placements that corresponded to the local landscape settings. Most existing trees were shown to provide limited energy conservation benefits, due to their suboptimal placement. However, as proposed, our result revealed that, with an application of the proposed tree planting strategy, energy conservation benefits could be improved in comparison to the energy savings estimated for current tree planting designs. Especially in northern latitudes with longer and more severe heating seasons, the proposed strategy could help to reduce some heating penalties caused by unwanted winter shade cast by misplaced tree. Our results lent further evidence that understanding tree form and placement in dense urban environments would support planners and policy-makers for developing the most effective tree planting strategies for energy conservation. Strategic single tree plantings on individual properties could eventually prompt substantial energy conservation benefits, especially if applied across entire communities.

Future studies related to this dissertation should increase the focus on both modeling and social perspectives. From a modeling perspective, the contrived structure and tree models used for this dissertation were limited for describing actual urban settings. As well, shade provision is not the only factor that influences residential energy consumption; various factors such as tree species and size, structure designs, and construction materials, also have significant impacts (Akbari and Taha 1992; Livingston and Cort 2011; Sadineni et al. 2011). In this dissertation, both shade and energy simulations were performed within an isolated situation, which would be an uncommon circumstance in dense urban neighborhoods and would not account for spillover-shade both from and onto neighboring parcels. Understanding the interactions between tree form and tree placement of shade tree, throughout a residential block level, will help identify maximum beneficial effects while minimizing detrimental effects thus lead to improve energy conservation benefits of trees on a larger scale. Furthermore, this dissertation solely relied on energy estimation that EnergyPlus computed. Along with adding additional details regarding tree and structure models, fine-tuned energy simulations would be able to provide more precise information. Findings from this dissertation could eventually help to develop an application that can be used for decision-support in terms of energy conservation. From a social perspective, understanding public attitudes toward the valuable use of trees would be an important factor for promoting strategic tree plantings. Various social factors, within the perception of and the expectation of urban residents for landscape trees, should be taken into consideration in order to promote tree planting with energy conservation benefits in mind. Therefore, future studies might broaden the scope of the study from an individual level to a community level to attain a fuller context of social aspects.

In conclusion, as a means to improve energy conservation benefits of new residential developments, this dissertation has evaluated and proposed placements for shade tree planting that could improve upon the conventional planting strategies currently used in dense urban residential areas. It is evidently important to plant more trees; however, it is even more important to understand and utilize shade trees in a low-risk, cost-effective way. Latitudinal nuances that affect shade provision are a critical component for optimizing the energy savings benefits of trees. As well, the shade-tree placement should be specifically identified for energy conservation, with strategic placement being used as a means for overcoming the limitations of urban settings. Although future research is required to close gaps between simulations and the physical urban settings, it is clear that understandings interactions between tree form and tree placement in a full context is essential for creating optimal shade tree planting strategies for dense urban neighborhoods.

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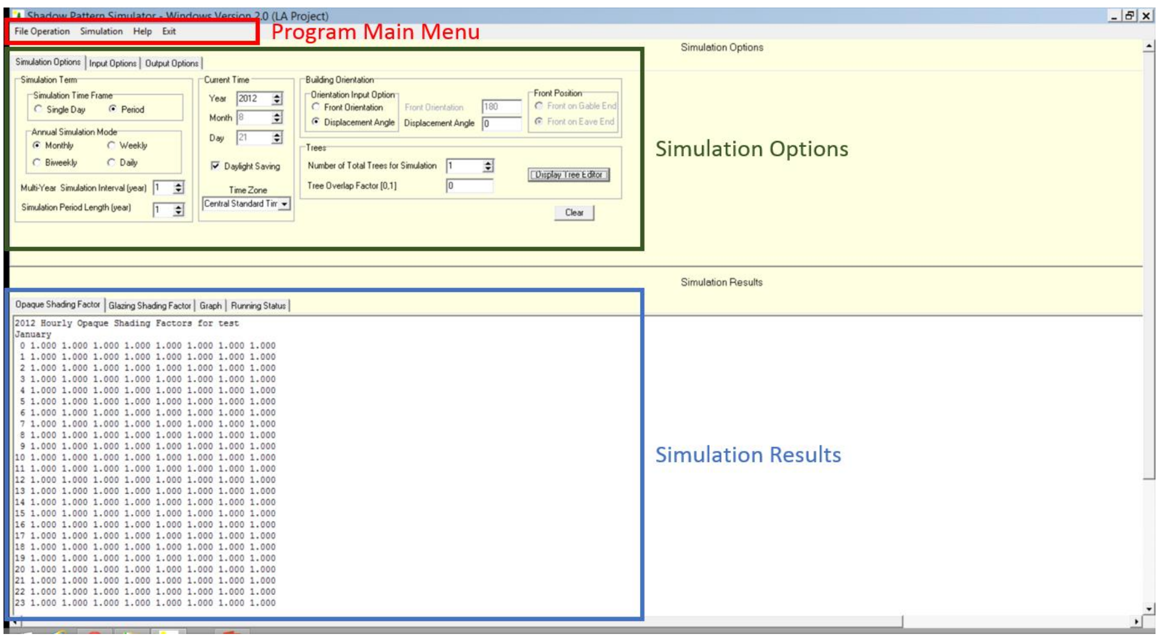
Appendices

Appendix A: Procedures for the Shadow Pattern Simulator (SPS) Simulations (Chapter 2)

These step-by-step instructions provide an overview for utilizing the Shadow Pattern Simulator (SPS) program to estimate shade provision that trees can cast upon building surfaces. The SPS program was developed by the USDA Forest Services, Pacific Southwest Research Station (additional information is available at its website http://www.fs.fed.us/psw/programs/uesd/uep/research/studies_detail.php?ProjID=21).

The SPS program is not currently available in the public domain. A legacy version of the program may be available by contacting the USDA Forest Service, Pacific Southwest Research Station.



Procedure for installing the SPS program (Windows Version 2.0)

1. Extract the zipped folder "WinSPS01".
2. Copy the folder "MyFiles" from the extracted folder "WinSPS01" into C drive.
3. Double click the executable file "WinSPS" to run the SPS program.
4. Once the program opens, select the tab "Input Options" from the simulation options.
   1) For Input File, select "Browse" and open "LastCase.dat".

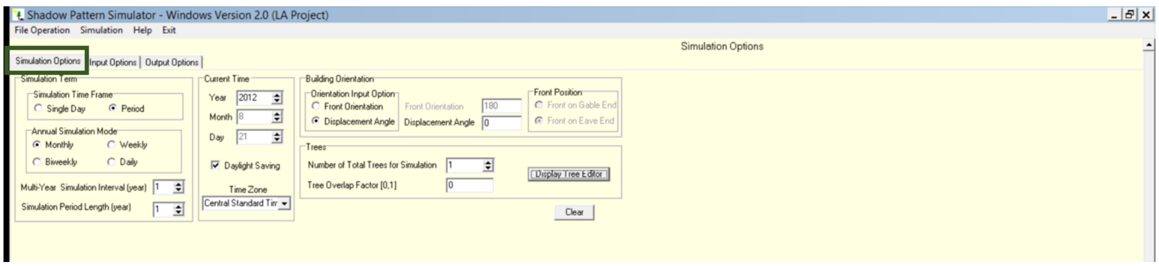
2) For SC File, select “Browse” and open “TSIall.shc”.
3) For Species File, select “Browse” and open “TSI.slf”.
4) For Growth Curve Coefficient File, select “Browse” and open “TSI.gcf”.

5. From the program main menu, select the “File Operation”, then select “Save Input into File” to overwrite the file “LastCase.dat”.

Procedure for running a simulation with the SPS program

1. Run the SPS program.

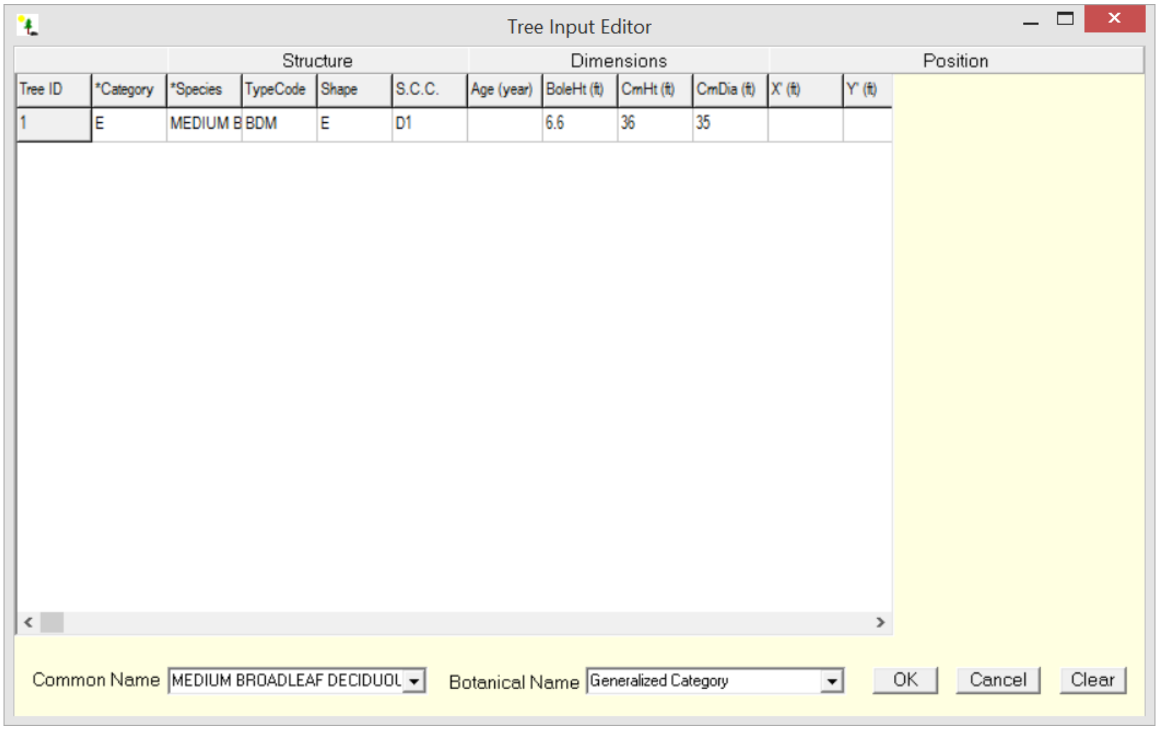
Simulation Options



2. Select the tab “Simulation Options” and provide specific input:
   1) Simulation Time Frame: Single Day or Period.
      a. Annual Simulation Mode
         - This option is available when the option “Period” is selected.
         - Note: Monthly option is not working due to a program bug. Select biweekly instead and then choose either option to represent monthly value.
      b. Multi-Year Simulation Level Interval (Year)
      c. Simulation Period Length (Year)
   2) Current Time
      a. Year, Month, Day, Daylight Savings, and Time Zone
         - Note: Year is only available when the option “Period” is selected.
   3) Building Option
      a. Select “Orientation Input Option”.
         - Front Orientation: the angle measured between the normal to the front wall of the building measured clockwise from North (a coordinate system used by the Micropas)
         - Displacement Angle: the angle measured counter-clockwise from North to wall section A (a coordinate system used by the SPS program)
      b. Key in value of structure orientation or angle.
      c. Select “Front Position”.
         - This option is available when the option “Front Orientation” is selected.
   4) Trees
      a. Key in value for Number of Total Trees for Simulation.
      b. Key in value (0, 1) for Tree Overlap Factor.
         - 0: non-overlapping tree crowns

- 1: overlapping tree crowns

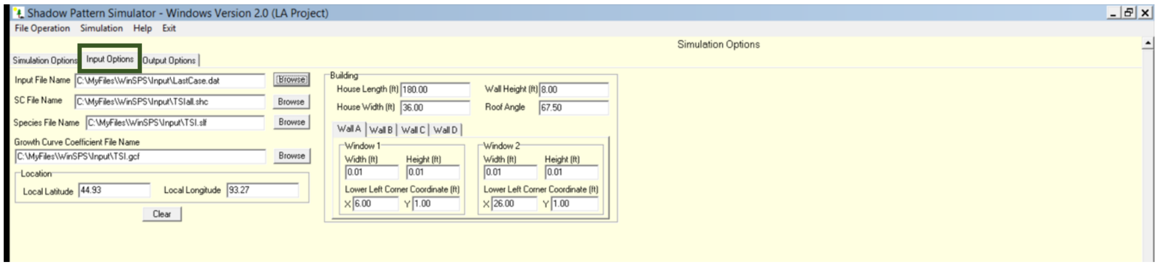
c. Select “Display Tree Editor” for editing tree variables.



d. From the “Tree Input Editor” window

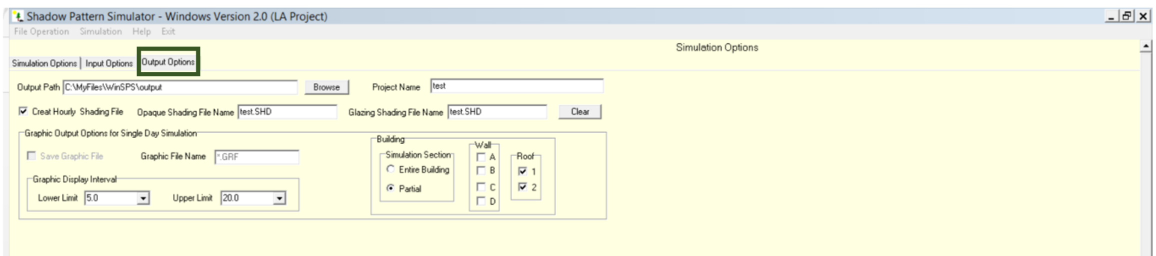
- Category Option
  - Double click the “Category” cell and choose an option: Existing Tree, Proposed Tree, or Retained Tree.
- Species Option
  - Select a tree species from the pull-down list at the bottom of the window.
  - Double click the “Species” cell to pick up species.
  - Once species is selected, cells (TypeCode, Shape, and S.C.C) will be automatically filled.
- Key in values for tree variables: Age (year), BoleHt (ft, bole height), CrnHt (ft, crown height), and CrnDia (ft, crown diameter)
- Key in values for tree placement.
  - X and Y are available when the option “Front Orientation” is selected.
  - X_o and Y_o are available when the option “Displacement Angle” is selected.
- Click “OK” to exit this window.

Input Options



3. Select the tab “Input Options” to specify simulation location and building parameter.
    1) Type Latitude and Longitude information of the simulation location.
    2) Type Building information: house length, house width, wall height, and roof angle.
    3) Type Window information: sizes and locations on four walls.

Output Options



4. Select the tab “Output Options”.
    1) Select “Browse” to change Output Path.
    2) Type Project Name information.
    3) Select the option “Create Hourly Shading File” (Optional).
        a. Type names of output files.
            - Opaque Shading File Name
            - Glazing Shading File Name
    4) Select the option “Entire Building” to estimate tree shade upon the entire building surfaces.

5. Once all options are defined,
    1) From the program main menu, select “Simulation” and “Submit Simulation Options”.
    2) Then, from the program main menu, select “Simulation” and “Run”.

6. Simulation Results will be displayed at the bottom of the window.
    1) The tab “Opaque Shading Factor” shows hourly shading factors for the walls.
    2) The tab “Glazing Shading Factor” shows hourly shading factors for the windows.

Procedure for analyzing the simulation results

```
2012 Hourly Opaque Shading Factors for test
Hourly Opaque Shading Factor for January 1, 2012
 0 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 1 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 2 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 3 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 4 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 5 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 6 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 7 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
 8 1.000 1.000 1.000 0.991 1.000 1.000 1.000 0.922
 9 1.000 1.000 1.000 0.942 1.000 1.000 1.000 0.892
10 1.000 1.000 1.000 0.872 1.000 0.999 1.000 0.921
11 1.000 1.000 1.000 0.856 1.000 1.000 1.000 0.965
12 1.000 1.000 1.000 0.966 1.000 1.000 1.000 0.996
13 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
14 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
15 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
16 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
17 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
18 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
19 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
20 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
21 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
22 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
23 0.667 0.667 0.667 0.667 1.000 0.667 1.000 0.667
   S     W     N     E     S     W     N     E
           Wall                    Roof
```

1. Copy and paste results into Excel:
    1) Each column represents a wall and roof-half (from the left column: south wall, west wall, north wall, east wall, south roof-half, west roof-half, north roof-half, and east roof-half).
    2) Each row represents hourly shading factors.
        a. Note
            - The value of 0.667 on the last row is a program bug. It should be 1.000.
            - A small number means greater shading.

2. Subtract the result from 1.000 (e.g., 1.000 – 0.344 = 0.656).

3. Multiply the area of each wall surface to estimate shaded surface on each wall (e.g. $0.656 \times (480 - 56)$ ft^2 = 258.464 ft^2).
    1) Note: The area of windows (e.g. 28 ft^2 × 2) on each wall should be excluded.

4. Sum all shaded wall and roof surfaces to estimate hourly tree shade upon the wall surfaces.

5. Sum all hourly tree shade provision (from the step 4) to estimate single-day shade provision upon the wall surfaces.

6. Repeat steps 1 through 5 for the results from Glazing Shading Factor to estimate hourly tree shade upon the windows.

7. Sum values from step 5 and 6 to estimate single-day shade provision upon the entire structure.

Appendix B: Procedure for the Energy Plus Simulations (Chapters 3 and 4)

These instructions provide an overview for performing energy simulations to examine the effect of an individual landscape tree on cooling and heating energy consumption of a residential structure model. Energy simulations in this dissertation were conducted using a suite of computer programs: EnergyPlus (US Department of Energy, Washington, DC), SketchUp Pro (Trimble, Sunnyvale, CA), and OpenStudio (National Renewable Energy Laboratory [NREL], Golden, CO).

Each software is available to download from these websites:

EnergyPlus
- https://github.com/NREL/EnergyPlus/releases/tag/v8.3.0
- http://apps1.eere.energy.gov/buildings/energyplus/energyPlus_download.cfm?previous (previous versions)
- Additional websites for EnergyPlus Support
  - Primary EnergyPlus Support: http://energyplus.helpserve.com
  - EnergyPlus User Group: https://groups.yahoo.com/neo/groups/EnergyPlus_Support/info

Weather Data for EnergyPlus Simulation
- http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

OpenStudio
- https://www.openstudio.net/download
- Additional information for OpenStudio Installation and Support
  - http://nrel.github.io/OpenStudio-user-documentation/getting_started/getting_started/#installation-instructions

SketchUp Pro
- http://www.sketchup.com/
- Additional information for rendering a three-dimensional model
  - SketchUp Video Tutorials: http://www.sketchup.com/learn/videos/58

Procedure for installing the programs

1. Download and install EnergyPlus.

2. Download and install SketchUp.
   1) Install SketchUp prior to installation of OpenStudio, which requires SketchUp.
   2) Must match program platforms: the 32-bit version of OpenStudio will only work with the 32-bit version of SketchUp Pro.

3. Download and install OpenStudio.

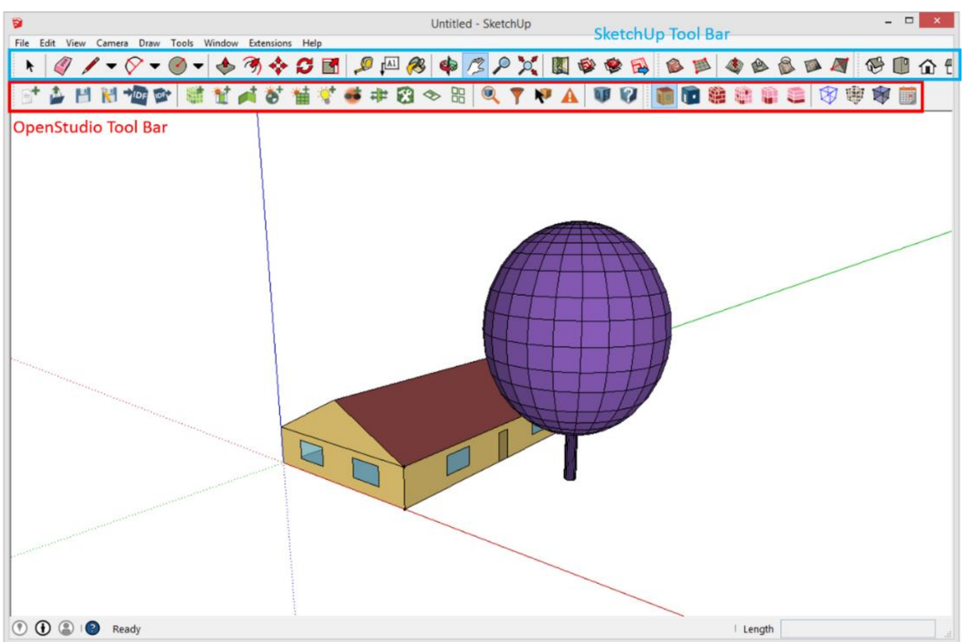
4. After OpenStudio installation, enter the Building Component Library (BCL) authorization key.
    1) Setup a BCL account if you don't have an account from the BCL website: https://bcl.nrel.gov/.
    2) Acquire the BCL key from the top right of the BCL website.
    3) Register the BCL Key to the OpenStudio Application under the menu: Components & Measures – Find Component.
    4) This step is optional but required for downloading additional building components in order to modify construction materials of the structure model.

Procedure for performing energy simulations of a structure model

These step-by-step instructions show a basic procedure for developing a model as well as conducting energy simulation with a residential structure model. These instructions are based on the previous version of the programs: EnergyPlus 8.0, SketchUp Pro 2013, and OpenStudio 1.5.0. Detailed information for setting sub-variables of a structure is available at the OpenStudio website http://nrel.github.io/OpenStudio-user-documentation.

As of August 2015, new versions (EnergyPlus 8.3, SketchUp Pro 2015, and OpenStudio 1.8.0) are available. Find out additional information at the program websites.

1. Open the SketchUp program.



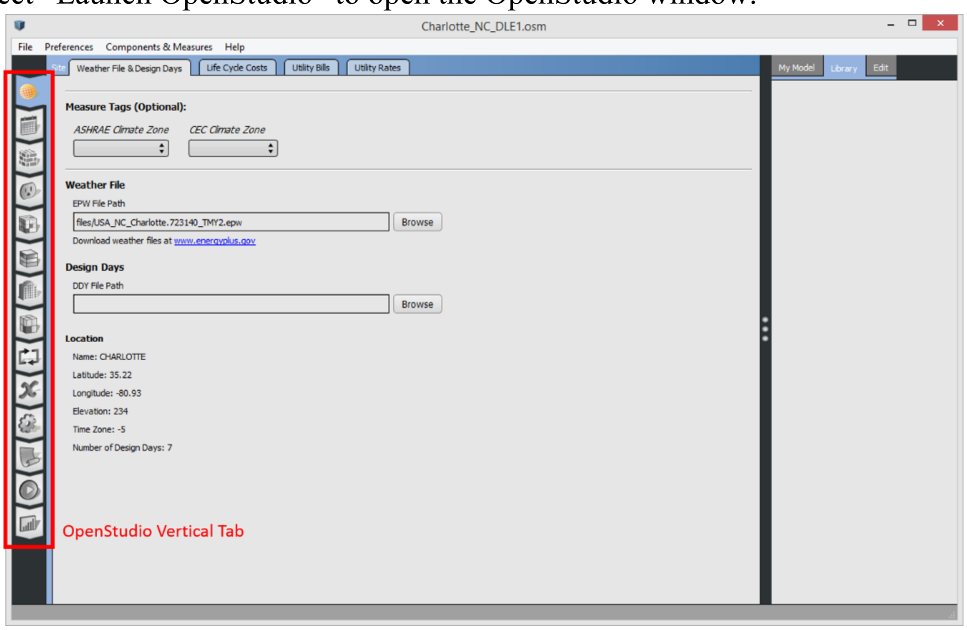
2. Select “New OpenStudio Model from Wizard” from the OpenStudio toolbar.
   1) Once the “User Input” window pops up:
      a. For the Building Type, select “Midrise Apartment” from the pull-down list. (Note: As of the OpenStudio version 1.5.0, a residential structure is not available. Therefore, modifying the building type “Midrise Apartment” is required.)
      b. For the Template, select “189.1-2009” from the pull-down list.
      c. For the ASHRAE Climate Zone, select an appropriate climate zone depending on the study area from the pull-down list.
   2) Click OK to exit the window.

3. Select “Save OpenStudio Model As” from the OpenStudio toolbar. (Note: this saved file can be used later as a template for additional models.)

4. Render a three-dimensional structure using the SketchUp tools.

5. Select “Set Attributes for Selected Spaces” from the OpenStudio toolbar.
   1) Assign various attributes to each space from the pull-down list depending on the simulation location. For example:
      a. Space Type: ASHRAE 189.1-2009 ClimateZone 1-3 Mid-rise Apartment
      b. Building Story: Building Story 1
      c. Construction Set: ASHRAE 189.1-2009 ClimateZone 3 (m apt) ConstSet 1F
      d. Thermal Zone: Thermal Zone 1
      e. Set Parent Thermal Zone’s – Ideal Air Loads Status: Yes
      f. Set Parent Thermal Zone’s – Thermostat: Yes
   2) Click OK to exit the window

6. Select “Launch OpenStudio” to open the OpenStudio window.



7. Once the OpenStudio opens, select the “Site” tab from the OpenStudio Vertical Tab.
    1) For the Weather File, click “Browse”, then select the Weather File for the simulation location (*.epw extension).
    2) For the Design Days, click “Browse”, then select the Design Days file for the simulation location (*.ddy extension).

8. Select the “Schedules” tab from the Vertical Tab to define simulation time frame and schedules.
    1) To set up simulation time frame, select the “Year Settings” tab on the top.
        a. Select the “Year” option: Calendar Year or First Day of Year
        b. Check the “Daylight Savings Time” option
    2) To define schedules, select the “Schedules” tab on the top.
        a. For the thermostat setting, select “Mid-riseApartment ClgSetp” option.
            - Modify thermal setpoints of the model if required.
        b. Define and select other schedules if required.

9. Select the “Construction” tab from the Vertical Tab to define construction materials.
    1) Modify construction materials, which correspond to a residential structure and its climate zone.
    2) Additional construction materials are available to download from the Online BCL.
        a. For accessing the Online BCL, select the “Components & Measures” menu from the OpenStudio Main Menu (on the top), then select the “Find Components”.

10. Select the “Loads” tab from the Vertical Tab to define various factors that influence energy loads of the structure model. Various factors include, for example, number of occupants, lights, and electric equipment.

11. Select the “HVAC Systems” tab from the Vertical Tab to create and edit “Air and Plant Loops”.
    1) From the pull-down list at the upper right corner of the window, navigate the HVAC systems for creating and editing a system.

12. Select the “Run” tab from the Vertical Tab to perform energy simulations.
    1) Click the “Run” icon to conduct an energy simulation.

13. Select the “Results Summary” tab from the Vertical Tab to check simulation results.

Procedure for performing energy simulations of a structure model with a tree model

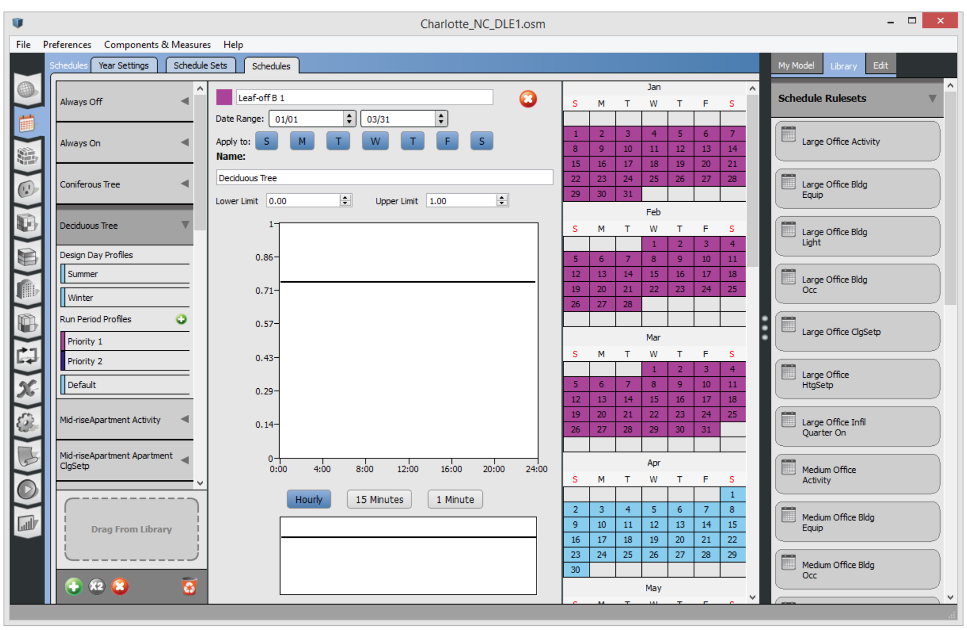
1. Open the SketchUp program.

2. Render a three-dimensional tree model using the SketchUp toolbar.
   1) Save as a SketchUp model (*.skp extension).
   2) This model will be imported to the OpenStudio with a structure.

3. Load the structure model and the tree model.
   1) From the OpenStudio toolbar, select "Open OpenStudio Model" to load the saved model with a structure.
   2) From the SketchUp Main Menu, select "File" – "Import" to open a tree model.
      a. Change "Files of type" to SketchUp Files (*.skp).
      b. Select the tree model and click "Open" to load the tree model.
   3) Place the tree model at pre-defined placement around the structure model.

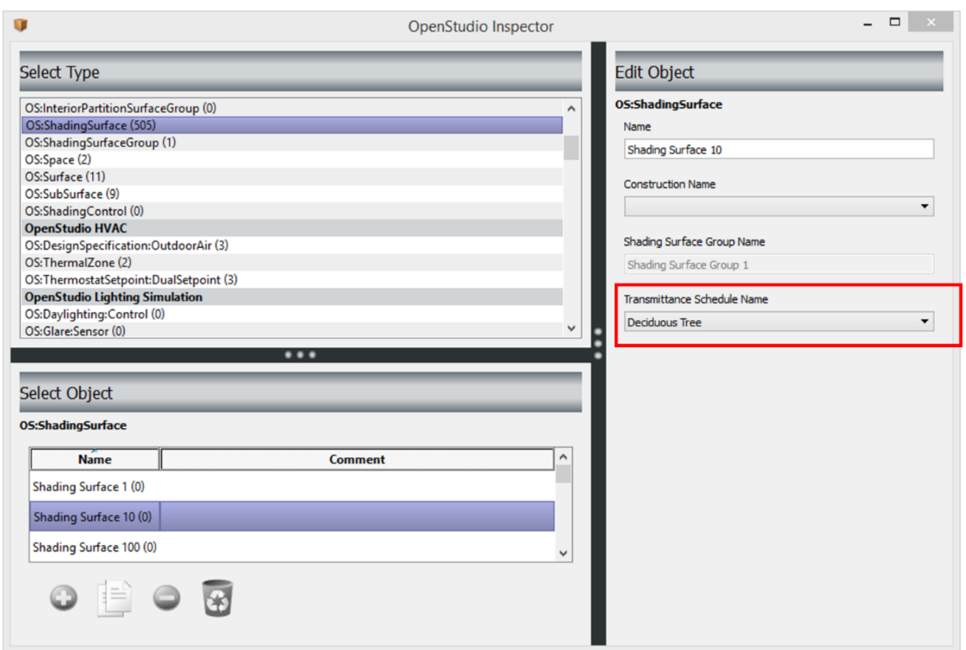
4. Select "Launch OpenStudio" to open the OpenStudio window.

5. Once the OpenStudio opens, select the "Schedules" tab from the Vertical Tab to set up schedules for representing canopy density.
   1) Click "+" icon at the bottom left corner to set up new schedules.
   2) From the "Define New Schedule":
      a. For Class Name, select the "ShadingSurface" from the pull-down list.
      b. The "Transmittance" is automatically selected for Schedule Type.
   3) Click "Apply" to close the window.



6. Select “Schedule Ruleset 1” from the list on the left panel.
   1) Change Name: Coniferous or Deciduous Tree.
   2) For a coniferous tree model:
      a. Expand the “Schedule Ruleset 1”.
      b. Select “Default”.
      c. Move the line on the graph to change transmittance.
   3) For a deciduous tree model:
      a. Expand the “Schedule Ruleset 1”.
      b. Click “+” icon to make a new profile.
      c. Change name of the first profile.
      d. Set a “Date Range” for first leaf-off season (from January to at the beginning of the leaf-on season).
      e. Move the line on the graph to change transmittance for the leaf-off season.
      f. Repeat steps d and d for the second leaf-off season (From at the end of the leaf-on season to December).
      g. Select “Default”.
      h. Move the line on the graph to change transmittance for the leaf-on season.

7. Back in SketchUp, select a tree model and then click the “Inspector” option from the OpenStudio toolbar.
   1) Once the “OpenStudio Inspector” window opens,
      a. Select the “OS:ShadingSurface” on the upper left panel.
      b. Select the “Shading Surface” on the bottom left panel.
      c. Change the appropriate “Transmittance Schedule Name” from the pull-down menu (a red box on the figure below) on the right panel.
      d. Repeat steps b and c for all shading surfaces at the bottom left panel.



8. Once all variables are appropriately set up, select the “Run Simulation” tab to perform an energy simulation.