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

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Abstract

Modern residential land development has trended toward densification, resulting in limited greenspace on individual parcels. As a result, land developers and homeowners are often constrained for space to plant shade trees. This can result in suboptimal placement of shade trees for the provision of energy conservation benefits. Using a simulation program called EnergyPlus, we examined the effects of existing trees on the energy consumption of recently constructed homes in three U.S. cities with distinctly different climates: Metro Minneapolis, MN, Charlotte, NC, and Metro Orlando, FL. Remote sensing was used to identify placement of existing trees around the homes, revealing that there were 1.5 to 2.9 trees within 15 m of the homes on average. These existing trees, when modeled as large-stature deciduous trees in the simulator, provided average annual energy conservation benefits per parcel of 14 kWh (MN), 25 kWh (NC), and 44 kWh (FL). We then developed an alternative tree placement strategy that spatially reconfigured the existing trees to both minimize space conflicts and maximize energy savings. This alternative strategy significantly improved annual energy savings per parcel to 57 kWh (MN), 47 kWh (NC), and 103 kWh (FL). Our alternative tree placement strategy was equally effective as the conventional strategy (always plant a shade tree on the west aspect) in MN and NC, but not in FL. However, the alternative strategy was more responsive to space constraints and therefore could be used to maximize energy savings while concurrently minimizing space conflicts between trees and site uses.

1. Introduction

Residential areas account for more than 20% of the total energy consumed in the United States (US), and about 40% of that energy is consumed for space cooling and heating of

residential structures (US Energy Information Administration, 2012). Growing interest in residential energy conservation has spurred research across multiple disciplines. Architects are increasingly recognizing the potential of low-energy buildings such as passive solar homes (Satori & Hestnes, 2007); urban planners are paying more attention to aspects of urban form in order to reduce residential energy consumption (Ewing & Rong, 2008; Ko, 2013); and, researchers in 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 (Ko, 2013). Previous shade and energy simulation studies have shown that tree form and tree placement influence shade provision upon building surfaces and thus impact energy consumption of residential buildings (XXX, 2015, 2016 masked for blind review). Building on previous studies, this paper examines how shade tree placement is impacting residential energy consumption in recently developed single-family neighborhoods of several cities in the US.

Several factors influence energy demand for maintaining thermal comfort inside residential structures. Building variables such as vintage, style, and size have been shown to influence energy consumption (Kaza, 2010; Norman, MacLean, & Kennedy, 2006). Passive solar design is one approach that has been found to increase building energy efficiency. Through careful selection of building layout and materials appropriate for the local climate, this design approach reduces energy consumption while retaining thermal comfort (Pacheco, Ordóñez, & Martínez, 2012). Beyond individual building design and construction, large-scale variables of urban form such as density, community layout, and street networks can also impact residential energy consumption (Ewing & Rong, 2008; Ko, 2013). A natural extension of these design considerations is the use of shade trees by urban residents to modify daily and seasonal solar

energy loads on their homes and thereby conserve energy (Akbari, 2002; Simpson & McPherson, 1998).

While it is well documented that urban trees provide multiple ecosystem services, including carbon sequestration, air quality improvement, and stormwater reduction (Roy, Byrne, & Pickering, 2012), the main focus of the current study is to demonstrate shade tree impacts on building 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). When properly selected and placed around a structure, trees can provide heat-attenuating shade in summer by intercepting direct sunlight, while allowing sunlight penetration for passive solar heating of the structure during winter (XXX, 2016). Trees also decrease cooling and heating demands by slowing wind speeds and reducing the infiltration of hot (summer) or cold (winter) air into a structure (Heisler, 1986). Finally, evapotranspiration during summer months, an endothermic reaction, decreases ambient air temperatures and thereby reduces energy demand for air conditioning (Huang, Akbari, Taha, & Rosenfeld, 1987). In order to maximize energy conservation benefits of trees through these aforementioned processes, it is necessary to identify the physical characteristics of the local setting and then select the most suitable tree form and placement for the adjacent structure (McPherson & Rowntree, 1993).

Many US cities have implemented tree planting programs to increase canopy and thereby decrease the urban heat island effect. 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 & Sarkovich, 1998). Simpson and McPherson (1998) examined the residential parcels 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 expense following a 10% increase in tree cover (McPherson, Nowak, Heisler, Grimmond, Souch, Grant, & Rowntree, 1997). Currently, a shade tree program called Energy-Saving Trees, 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 US 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 US each year by land developers and homeowners without much consideration for how the energy conservation benefits of these trees could be maximized, representing a significant missed opportunity for money and energy savings.

New residential developments are important settings for implementing strategic shade tree plantings. Due to extensive urbanization, millions of acres of green space in the US have been displaced by residential and commercial construction (Theobald, 2005). As well, residential construction has trended toward decreased parcel sizes and larger house sizes (Sarkar, 2011). Within these smaller parcels, there are typically fewer mature trees, less canopy cover (Carver, Unger, & Parks, 2004), and more impervious surfaces (Theobald, 2005; Wilson & Boehland, 2005). With less space, trees are likely being planted in sub-optimal locations for energy conservation. In addition, because most modern structures are equipped with air conditioning units (US Energy Information Administration, 2011), residents are not attuned to the impact of tree placement on solar heat gain by their homes. To our knowledge, no studies have investigated patterns of tree placement around residential structures in the context of building energy conservation on a large geographic scale.

Educating land developers and homeowners about the role of shade trees for energy conservation can help them make informed decisions about tree planting in residential neighborhoods (Jones, Davis, & Bradford, 2012). Urban residents who live around urban trees report positive attitudes toward trees (Davis & Jones, 2014), and they highly appreciate shade provided by trees (Gorman, 2004; Lohr, Pearson-Mims, Tarnai, & Dillman, 2004). When considering that homeowners tend to plant more trees in the first five years of their ownership (Summit & McPherson, 1998), providing guidance on tree selection and placement early in the home building and tenure process could promote strategic shade tree planting and thereby improve energy conservation benefits. To this end, the objectives of our study were: (1) to evaluate how newly-planted trees affect energy consumption of recently constructed homes at ranging geographic latitudes in the US, 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 trees around recently constructed homes and then use computer simulations to examine their energy conservation benefits under existing and alternative placement conditions. We hypothesized that newly-planted trees in recent residential developments are sub-optimally placed for energy conservation and that employing an alternative placement strategy would improve their energy benefits.

2. Methodology

2.1. Study Areas

For this study, three US metropolitan areas were selected along a north to south latitudinal gradient: Metro Minneapolis, Minnesota (MN); Charlotte, North Carolina (NC); and Metro Orlando, Florida (FL) (Table 1). Between 2000 and 2010, the population of Charlotte

increased by 35.4% and Orlando by 28.2%, while the population of Minneapolis decreased by 0.04% (US Census Bureau, 2014). These trends in population somewhat 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%. The median sale values of these occupied housing units, county-wide, were reported as \$266,879 (Metro Minneapolis), \$223,748 (Charlotte), and \$150,345 (Metro Orlando). Other socioeconomic variables of the study areas are shown in Table 2. These study areas are in Building America Climate Regions (BACR) representing cold (Metro Minneapolis), mixed-humid (Charlotte), and hot-humid (Metro Orlando) weather (Baechler, Williamson, Gilbride, Cole, Hefty, & Love, 2010). These different climates influence residential energy consumption in distinct ways (Livingston & 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 annual 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 use for space heating. Charlotte is intermediate in terms of cooling and heating demand between the two latitudinal extremes.

2.2. 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 Hennepin County, MN (part of Metro Minneapolis); Charlotte, NC; and Lake County, FL (Metro Orlando). With an aim to obtain sample parcels representing ‘typical new residential development’ in these study areas, 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) for energy simulations in the current study, we wanted to use the same residential structure model used in our previous energy simulation study (XXX, 2016). 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 is likely to have more trees (Nassauer, Cooper, Marshall, Currie, Hutchins, & Brown, 2014). Parcels that had residual forest trees, street trees, or overhead utility lines nearby were also excluded because these factors 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 ($n = 3,808$) and Metro Orlando ($n = 9,725$). For Metro Minneapolis ($n = 6,229$), 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, in particular especially parcels having a one-story detached house (most houses of this vintage were multi-story).

Once the sample parcels were selected, we used high-resolution aerial photos (acquired after 2010) and LiDAR (Light Detection and Ranging; collected mostly after 2010 except for data covering Metro Orlando were collected in 2008) to extract data for tree and landscape

variables of interest: house orientation, parcel orientation, tree stature, tree form, and tree placement relative to the house and their effects on energy conservation. These variables were then used as inputs for the simulation of tree shade effects on building energy consumption. In order to examine the relationships of these variables and their effects on energy conservation, we employed ANOVA, multiple comparisons of means using Tukey's HSD, and χ^2 contingency test (JMP version 11.0, SAS Institute, Inc., Cary, NC).

2.3. 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 the typical meteorological year derived from the 1961-1990 National Solar Radiation Data base (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 by regulating airflow around the structure. EnergyPlus computes the impacts of tree variables on heat gains as well as airflow; the

184 impact values are then applied to a simulation model that estimates the annual cooling and
185 heating energy consumption (US Department of Energy, 2014).

186 For the energy consumption simulations, one residential structure model and four shade
187 tree models (two leaf types $\times$ two tree sizes) were used to represent the actual residential
188 structures and their associated trees (Figure 1). To simplify the energy simulations, a fixed-sized
189 residential structure was employed for all sampled parcels across the study areas (Table 3). This
190 structure model had a floor area of approximately 200 m² (11 m $\times$ 18.2 m), a total surface area of
191 410.6 m² (four walls and two roof halves), and two windows (1.2 m $\times$ 2.1 m) on each wall. The
192 specifications for maintaining interior thermal setpoints were determined based on the energy
193 standard ASHRAE 189.1, which was established by the American Society of Heating,
194 Refrigerating and Air-Conditioning Engineers (ASHRAE) (Long, Bonnema, Field, & Torcellini,
195 2010). For the existing trees on the sampled parcels, because we could not identify tree species
196 or measure crown dimensions using remote sensing data, we simulated each tree using four
197 models: (1) a small-stature deciduous tree, (2) a large-stature deciduous tree, (3) a small-stature
198 broadleaf evergreen tree, and (4) a large-stature broadleaf evergreen tree (Figure 1). Crown
199 opacity was set at 75% (leaf-on season) or 25% (leaf-off season) for deciduous trees and 80%
200 (year round) for broadleaf evergreen trees (Metro Orlando only).

202 2.4. Alternative Tree Placement Strategy for Energy Conservation

203 To examine whether energy conservation of existing trees on the sampled parcels could
204 be improved, we developed an alternative tree placement strategy (hereafter, alternative strategy)
205 that would be compatible with the typical layout of residential parcels in dense urban areas. Our
206 alternative strategy was designed based on (1) our understanding of the impacts of a single tree

on annual energy consumption of an adjacent structure, and (2) the consideration of parcel orientation constraints, which seemingly impact tree placement. We compared our alternative strategy to a widely prescribed placement strategy for energy conservation (hereafter, conventional strategy), which recommends planting a tree either on the west (highest priority) or east aspect (second highest priority) of a structure. For comparative purposes, we specified the conventional strategy of placing a tree, first, at 5 m from the west aspect of the structure and then second (if more than one tree existed on the sample parcel) at 5 m away from the east aspect. Although the 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 aspect.

To contrast the energy conservation effects of the alternative and conventional strategies for tree placement, 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 distances (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 (see Equation 1 below, hereafter called energy equation). This energy equation was developed to streamline the simulation process for comparing the configuration of existing trees between the alternative and conventional tree 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 east-west) typically had more trees planted on the north or south aspect of the house and there seemed to be insufficient space on either the east or west aspect for tree planting. Assuming that there was no space for tree planting along longer axes of parcels (due to anticipated space constraints between properties, especially as trees 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 at a minimal distance from the first tree to avoid overlapping of crowns, which decreases the ‘per tree’ shade benefits compared to when they stand alone (McPherson & Dougherty, 1989).

Using the alternative 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 simulation: 54 in Metro Minneapolis; 77 in Charlotte; and 33 in Metro Orlando. These were the parcels that had only 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; however, these trees were excluded from the simulations because trees at this distance would not provide significant shading or windbreak benefits for the houses (Heisler, 1986).

After determining tree placement on the sampled parcels for all these scenarios (existing placement, alternative strategy, and conventional strategy), shade tree effects on energy consumption were evaluated using the following energy equation:

$$\text{Energy Consumption} = \text{Most Energy Consumption (with no tree)} \times \text{Building Multiplier} \times \text{1st Tree Multiplier} \times \text{2nd Tree Multiplier} \text{ ----- (Equation 1)}$$

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 a north-south oriented residential building with two large deciduous trees on the east and west aspects in Orlando: 2,208 kWh = 2,449.59 kWh (the most energy consumptive building without an adjacent tree in Orlando) $\times$ 0.960 (multiplier for the north-south oriented building) $\times$ 0.958 (multiplier for the large deciduous tree on the west at 5 m away) $\times$ 0.980 (multiplier for the large deciduous tree on the east at 15 m away). Once energy consumption for each of the sampled parcels was estimated using the energy equation, a matched-pair T-test (JMP version 11.0, SAS Institute, Inc., Cary, NC) was utilized to compare the energy equation to the EnergyPlus outputs; then, these outputs were used to gauge the validity of our energy equation approach.

2.5. Comparative Simulation of Tree Benefits

To provide additional perspective on the energy simulation outputs from EnergyPlus, we employed the web-based program, i-Tree Design (US Forest Service, n.d.) to also model the

sampled parcels. By employing i-Tree Design, we were also able to understand energy conservation benefits relative to other ecosystem benefits of the existing trees. Based on inputs, including data about trees and their associated structures, i-Tree Design estimates 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 to model small deciduous trees (23 cm trunk diameter) as well as willow oak (*Quercus phellos*) and laurel oak (*Quercus laurifolia*), respectively, to model large deciduous trees (91 cm trunk diameter) (McPherson, Simpson, Peper, Gardner, Vargas, Maco, & Xiao, 2006; Peper, McPherson, Simpson, Albers, & Xiao, 2010). Trees were then placed in the program to match existing tree locations on the sampled parcels. The residential structure model used in EnergyPlus simulation was roughly digitized onto the building footprints (rectangular-based) based upon imbedded Google Maps images and specified as the post-1980 building vintage, which was the option most similar to the sampled parcels.

3. Results

3.1. Existing Conditions on Residential Parcels

The sampled residential parcels in the study areas showed differences in parcel size, building footprint size, and parcel orientation (Table 4). In examining these existing parcel conditions, all treed parcels were considered (ranging from one to eight trees per parcel, depending on study area). Metro Minneapolis had the largest parcels on average, followed by Metro Orlando and Charlotte ($p < 0.0001$). The study areas also differed in distributions of parcel orientation and building orientation ($p < 0.0001$). The north-south parcel orientation was predominant in Metro Orlando (more than 50% of the total sampled parcels) and somewhat so in Metro Minneapolis. As a result, buildings were predominantly oriented east-west in both Metro Orlando and Metro Minneapolis. However, Charlotte had relatively even distribution of parcel and building orientations: no orientation was particularly dominant nor minor (less than 10% of the total sampled parcels).

Characteristics in abundance, form, and placement of existing trees were identified in the study areas (Table 4). Metro Orlando averaged about three trees per parcel, which was significantly greater than Charlotte and Metro Minneapolis. Some sampled parcels in Charlotte (10%) and Metro Orlando (9%) lacked trees within the property boundaries. According to the LiDAR data, the average tree height on the sampled parcels was less than 6 m in all study areas, reflecting the newness of the developments and youth of the recently-planted trees (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). While trees in Metro Orlando were identified as mostly deciduous or broadleaf evergreen, all trees were deciduous in Metro Minneapolis and Charlotte. Trees in the sampled parcels were typically located less than 10 m from the residential structures, with trees in Metro Minneapolis being about 2.3 m further away on average, perhaps due to the large parcel sizes

there. An examination of remote sensing data showed that tree orientation (direction from the structure) within property boundaries correlated with parcel orientation ($p < 0.0001$) across all study area (data not shown). For example, parcels with an east-west orientation (longer sides facing north and south) tended to have more space and thus had more trees planted on either the east or west aspect. However, this relationship was not found with building orientation. The finding of this relationship between tree and parcel orientation dictated how the alternative tree placement strategy (examined below) was designed.

3.2. Energy Impacts of Existing Trees

Without trees, the annual energy consumption of the residential structure model simulated on the sampled parcels averaged $9,924 \pm 1.4$ kWh in Charlotte (valued at $\$1,072 \pm 0.15$ based on the local annual average electricity price of $\$0.108$ per kWh) and $8,824 \pm 6.0$ kWh in Metro Orlando (valued at $\$1,015 \pm 0.69$ based on the local annual average electricity price of $\$0.115$ per kWh) (data not shown). For this analysis, we excluded Metro Minneapolis due to the insufficient sample size of parcels. Annual cooling and heating energy consumption, as a percent of total household energy, was about 35% in Charlotte ($3,415 \pm 2.1$ kWh) and 26% in Metro Orlando ($2,263 \pm 7.6$ kWh). The nine-month cooling season in Metro Orlando tended to necessitate increased usage of 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 north and south) typically consumed the least cooling energy, up to 3.6% (Charlotte) and 7.2% (Metro Orlando) less than structures with other orientations (data not shown).

The existing trees on sampled parcels (ranging from one to five trees per parcel in Charlotte and one to eight trees per parcel in Metro Orlando) were simulated to examine their influence on both cooling and heating energy consumption (Table 5). In Metro Orlando, energy savings during the long cooling season were large enough to compensate for any heating penalty caused by winter tree shade such that in most cases total annual energy consumption was reduced. With large deciduous tree models, annual energy savings ranged from 0 kWh (no impact) to 236 kWh with an average savings of 67 ± 5.5 kWh for the sampled parcels. 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 -10 kWh (additional energy expenditure) to 90 kWh (energy savings), with average savings of 27 ± 2.3 kWh annually. Average annual energy savings associated trees was over two times higher per parcel in Metro Orlando than in Charlotte, but it must be reiterated that Orlando also had more trees per parcel on average (2.9 vs. 1.7 trees), which magnifies the difference.

The impact of existing trees on annual energy savings was then compared by both parcel and building orientations. In both study areas, the east-west oriented parcels showed the most average annual energy savings (Table 5) because these parcels had trees more frequently planted on either the east or west aspect of the building. The effect of the east-west parcel orientation on energy savings was much more pronounced in Metro Orlando where afternoon shade is very impactful during the long cooling season. Energy savings of the trees on east-west parcels was two times or greater than other parcel orientations. This effect was much more subdued in Charlotte, where the cooling season is shorter. Building orientation did not have a strong influence on energy conservation benefit of trees. In Charlotte, there was no statistical difference

in energy savings by building orientation; whereas, in Metro Orlando, there was only significantly greater energy savings for the north-south oriented buildings compared to the east-west oriented buildings. Standard errors of energy savings were higher in Metro Orlando, because there was great variability in tree count per parcel.

3.3. Alternative Tree Placement Strategy

To shorten our simulation run times, we developed an energy consumption equation to rapidly predict the results of the EnergyPlus simulations. When comparing EnergyPlus and our energy equation, we found that the energy equation slightly overestimated energy consumption (Figure 3). However, on average, EnergyPlus and the energy equation differed by less than 1%. Overestimation was most significant with broadleaf evergreen trees in Metro Orlando. Because large trees have greater effects on building energy and the energy equation appeared to most reliably simulate energy effects of deciduous trees, below we focus our comparison of tree placement strategies on large deciduous trees.

The effectiveness of our alternative tree placement strategy was determined by comparing the energy savings provided by existing trees to the energy savings provided when these trees were reconfigured with the conventional or the alternative strategy. These comparison were limited to sampled parcels bearing only one to two trees in order to focus on the effect of tree placement on energy savings of dense residential developments. There was evidence that existing trees were not strategically placed (for energy conservation) on the sampled parcels, most likely due to space constraints but also perhaps for aesthetic reasons. Running the simulations with the trees modeled as large mature specimens (a best-case future scenario) for energy conservation, existing trees on the sampled parcels were shown to reduce annual energy

consumption by up to 44 ± 7.0 kWh per parcel, depending on the study area (Figure 4). In stark contrast, the alternative strategy resulted in annual energy savings up to 103 ± 6.6 kWh per parcel (increase of 129% over the existing tree placement). 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 strategy (placing one tree at 5 m on the west aspect of the building and the other – when present at 5 m on the east), the alternative strategy was equally effective as the conventional strategy in Metro Minneapolis ($p = 0.4439$) and Charlotte ($p = 0.9099$); however, the alternative strategy was about 65% less effective on average than the conventional strategy in Metro Orlando ($p < 0.0001$). Metro Orlando had a dominant parcel orientation of north-south (longer axis facing east-west), which, thereby had fewer trees on either the east or west aspect of the building. Therefore, the conventional strategy appeared to be the most effective approach for maximizing energy conservation benefit, but it probably would not practically applicable due to the limited space for trees on the east and west.

The efficacy of the alternative strategy was also evaluated by comparing the energy savings based on parcel orientation. We excluded Metro Orlando for this evaluation due to the insufficient sample size of non-dominant parcel orientations. When comparing the alternative strategy to the existing tree placement, the alternative strategy proved superior for most parcel orientations ($p < 0.05$), with only one exception: the sampled parcels with a northeast-southwest oriented in Metro Minneapolis ($p = 0.4325$). Comparing the alternative strategy to the conventional strategy, there was no statistical difference in energy savings for any of the parcel orientations (all $p > 0.05$). As well, compared to the sampled parcels with an east-west orientation, which tended to have more existing trees already 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, average energy savings per parcel increased from 16 to 47 kWh in Metro Minneapolis and 28 to 45 kWh in Charlotte when the alternative strategy was applied to the sampled parcels with a northwest-southeast orientation (Figure 5).

3.4. Comparison with i-Tree Design Simulator

Shade tree energy savings estimated by EnergyPlus were found to be lower than i-Tree Design simulations for the same parcels (Table 5 and Table 6). For example, in Charlotte, EnergyPlus estimated an average annual energy savings per parcel of $\$2.98 \pm 0.25$ (27.6 ± 2.3 kWh @ $\$0.108$ per kWh of the local annual average electricity price) with large deciduous trees compared to $\$19.61 \pm 3.13$ per parcel for the same large trees using i-Tree Design. Possible explanations for these differences will be covered in the discussion section.

It is important to understand energy conservation in the broader context of other ecosystem benefits provided by existing trees (especially large trees) such as stormwater reduction, air quality improvement, and carbon sequestration. Using i-Tree Design simulations, we found that the existing trees on the sampled parcels could provide annual ecosystem benefits on average of up to $\$242.35 \pm 20.13$ per parcel in Charlotte and $\$149.99 \pm 7.43$ in Metro Orlando (Table 6). In i-Tree Design simulations, large deciduous trees showed profound impacts on ecosystem benefits: they provided at least 16 times greater the total annual ecosystem benefits than small trees modeled at the same distance and orientation from buildings. Energy savings produced by large deciduous trees accounted for about 8% (Charlotte) and 21% (Metro Orlando) of the total annual ecosystem benefits estimated by i-Tree Design.

4. Discussion

Through our examination of remote sensing imagery and computer simulation of building energy consumption, we found that existing trees on sampled parcels were usually close enough to houses to positively impact energy savings, but were typically in the wrong places to maximize energy savings. Suboptimal placement of these trees might possibly reflect space constraints encountered by homeowners in these newly constructed residential developments. Remote sensing data indicated that tree placement was correlated with parcel orientation. The longer sides of parcel orientation had limited space for tree planting and thus fewer trees were observed on these sides. In this regard, the conventional recommendation for energy conservation benefits, planting a tree on the west aspect of a house (McPherson et al., 2006; Peper et al., 2010), would not always be implementable, especially where the east-west parcel orientation (which affords adequate tree space) was not the dominant parcel orientation. For example, only 28 trees (about 19%) of the 148 existing trees (on the 100 sampled parcels) in Charlotte could be feasibly placed on the west aspect. However, of those 28 trees, 18 trees were planted on east-west orientation parcels, and only 10 trees were on the parcels with other parcel orientations. Those parcels with other orientations tended to have less available space for tree planting on the west aspect. Overall, we found that more than 70% of existing trees in each study area, when planted using the alternative strategy, would comparatively provide more energy savings. In the case of Charlotte, reconfiguring those trees (moved virtually in the energy simulations) resulted in an average additional energy saving of 22 ± 2.4 kWh per parcel annually (Figure 4).

Even though the monetary value of energy savings seemed negligible on a per parcel basis, the accumulated value of the additional energy savings from alternative tree placement,

community-wide, would be significant. For example, in Metro Orlando, there would be nearly 574,000 kWh of additional energy savings annually (59 kWh × a total of 9,725 parcels having either one or two trees and a single-story residential house built between 2001 and 2010) and these savings would be valued at \$66,000 based on the local annual average electricity price of \$0.115 per kWh). These energy savings would also contribute to reduced carbon dioxide emissions and water consumption for electricity generation: each kWh generation emits 0.45 kg of carbon dioxide and requires 157 liters of water (US Government Accountability Office, 2012; Wilson, Leipzig, & Griffiths-Sattenspiel, 2012).

Our estimates of energy savings may be a bit conservative because the contrived simulation environment (a structure with one or two trees) in our models did not account for spill-over shade effects that could provide additional energy conservation benefits to neighboring structures (Nikoofard, Ismet Ugursal, & Beausoleil-Morrison, 2011; Sawka, Millward, McKay, & Sarkovich, 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 attributable to them. In our study, we found that over 60 percent of sampled parcels in Charlotte had one or more trees placed within 15 m of a neighboring structure. These trees could consequently provide at least partial energy conservation benefits to a neighboring structure as a result of their placement (direction and distance). 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, leading to additional heating costs. Therefore, the impact of shade trees on both target homes and neighboring homes must be taken

into careful consideration when evaluating energy benefits for dense residential areas at the community scale.

Although our study focused on how to improve energy conservation specifically, the results need to be understood and appreciated in the full scope of urban tree benefits (Roy et al., 2012). Careful species selection, particularly related to tree size at maturity, would significantly impact the extent of the tree benefits. For example, a sample parcel with two large shade trees on the west and the northwest aspect of the house in Charlotte could expect gross annual benefits valued at about \$390 from a combination of ecosystem benefits. This amount was about ten times greater than the benefits of small shade trees on the same placement (average ecosystem benefits per parcel assessed by i-Tree Design were shown in Table 5). Because we were not able to identify existing tree species on sampled parcels, we modeled trees to illustrate a mature specimen rather than the current stature of the existing trees. However, simulation results still showed that a significant opportunity for ecosystem benefits would be missed if parcels had a small-maturing species such as crape myrtle (*Lagerstroemia spp.*) and flowering dogwood (*Cornus florida*) rather than willow oak (*Quercus phellos*) or laurel oak (*Quercus laurifolia*). In addition, compared to other ecosystem benefits simulated by i-Tree Design, energy conservation benefits are shown to be specifically influenced by both tree form and tree placement. Therefore, we assert that a more strategic approach to shade tree placement will amplify energy conservation benefits for the target parcel and likely include spill-over benefits for adjacent parcels.

Compared to i-Tree Design simulations, shade tree energy savings derived from our EnergyPlus simulations were relatively small. Even though it was difficult to compare our study with i-Tree Design directly, there were some differences between the two in the simulation

mechanics. First, in our study, EnergyPlus did not 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 & Rowntree, 1993). Also, the tree and structure models used in i-Tree Design versus EnergyPlus might impact the extent of energy savings estimated by each in several ways: (1) due to limited options for specifying tree models used in i-Tree Design, we were not able to match tree models between the two programs precisely; (2) trees were modeled in EnergyPlus at 5 m intervals, which might not fully address the impact of tree distance on building energy consumption. The energy equation used in our simulation treated trees at 5.1 m and 9.9 m away as the same distance because they fell in the same 5 m interval; and (3) the building energy efficiency specifications used by each program were different and therefore tree shade impacts them differently. Building energy efficiency has increased by more than 10% since the 1980s (US Department of Energy, 2008). The structure model used for our EnergyPlus simulations applied the recent thermal specification ASHRAE Standard 189.1, which is a high efficiency benchmark (Long et al., 2010); in contrast, i-Tree Design used a ‘post-1980’ construct as their most recent structure’s vintage, which would likely be less energy efficient than the ASHRAE specification, and thus more heavily influenced by shade trees. In this regard, i-Tree design may overstate the energy conservation benefit of trees around structures built in the last decade or more. As well, differences in structure sizes between i-Tree Design simulations (building footprints were roughly digitized based on the imbedded Google Map) and our energy simulations (a fixed structure size for all structures) would expectedly vary the degree of energy consumption.

Even though our study showed that the alternative tree placement strategy could improve energy conservation, we recognize that there were several limitations to the study. First, our

study was a snapshot of existing tree conditions and did not account for future tree growth or mortality. For our simulations, tree models were specified as fully matured and large-statured trees, denoting a best-case scenario for energy conservation; therefore, we were not able to ascertain the changes in energy savings as the trees grew. Second, contrived simulation environments used in our study could not fully describe the variations in shape, size, and orientation of residential parcels. Various structure designs, construction materials, and socioeconomic settings of the homeowners, which would influence energy consumption (Sadineni, Madala, & Boehm, 2011), were not taken into consideration. Also, the four tree models (two leaf types $\times$ two tree sizes) used in our simulations do not typify all urban trees. Third, our study did not fully consider any possible disservices of landscape trees such as excessive shade, irrigation demands, storm damage, or allergens and pollen (Roy et al., 2012). Our aim was not a rigorous economic analysis of benefits and costs of shade trees, but rather to point out the profound impacts that tree form and tree placement have on energy conservation in a theoretical sense. With that said, we aimed to make the simulation as reasonable as possible. For example, our alternative strategy set a minimum tree distance of 5 m away to avoid any conflicts with the structure on the sampled parcel while maintaining shade benefits. However, in some cases, the consequences of growing trees (either in size or in population) could create disservices that outweigh the energy benefits. As such, we stress that careful selection of tree species and tree placement should always consider the context of the entire landscape. And, lastly, our study did not describe the costs to plant and maintain trees in residential parcels. Even though anticipated maintenance costs may deter homeowners from planting trees (Conway, 2016), cost-benefit analysis has shown that the benefits that trees provide typically outweigh the costs in the long run (McPherson et al., 2006; Peper et al., 2010). Our study underscores a

previous study showing that strategic plantings would help to increase net benefits of trees (McPherson, Simpson, Peper, Maco, & Xiao, 2005).

Supportive guidelines, policies, and ordinances are essential for promoting strategic shade tree plantings. Because trees appeared to be sub-optimally placed based on our study, a relevant follow-up question could be, “What influences residential choice for tree placement?” Although other studies have examined the relationship between socioeconomic variables and urban tree distributions (Haynen & Lindsey, 2003; Heynen, Perkins, & Roy, 2006), our study was not intended or designed to ascertain the drivers of tree placement. Space constraints would be one factor that drives tree placement in residential parcels. The sample parcels from predominantly white and mixed communities appeared to have mostly up to two trees within their property boundaries. And, there seemed to be limited room on the longer sides of the sample parcels, leading to trees being sub-optimally planted for energy conservation. In this regard, developers could apply our study to residential site designs that create an environment for homeowners to plant trees optimally. Another potential factor could be that local tree ordinances and guidelines are inadequate for coercing appropriate tree placement; residential trees might presumably be planted solely for meeting minimal tree planting requirements or for primarily aesthetic appeal. Charlotte, NC requires that new single-family residential developments must plant trees to meet the required percentage area, at least ten percent of the total property area (City of Charlotte, n.d.). Also, Lake County, FL has set a minimum canopy tree requirement for a single-family lot: for example, two canopy trees for lots 557 m^2 or less (Lake County Florida, n.d.). Even though many municipalities have brought attention to establishing ordinances and guidelines for urban tree conservation, most ordinances appear to be focused primarily on stormwater mitigation. We submit that more attention should be aimed at energy conservation.

On this matter, if tree ordinances and guidelines could drive tree selection and placement on private residential parcels, it would highlight the role of local municipalities for developing and providing supportive policies and appropriate information about shade tree planting and management. Understandably, many municipalities do not have the compulsion to regulate tree placement; therefore public education is critical to affect change on tree planting practices.

A fundamental approach to shade tree planting is understanding the preferences and expectations of urban residents based on their circumstances (built and natural environments) and then selecting the tree placement strategy that puts trees to their highest and best use. Instead of ecosystem services of landscape trees, urban residential landscapes often reflect the personal amenity tastes and expectations of homeowners (Pincetl, Gillespie, Pataki, Saatchi, & Saphores, 2013; Sommer, 2003). A majority of urban residents, especially those who have experienced trees, reportedly have positive attitudes toward having large urban trees in their neighborhoods (Conway & Bang, 2014; Lohr et al., 2004) and recognize shade as an important benefit that urban trees provide (Avolio, Pataki, Pincetl, Gillespie, Jenerette & McCarthy, 2015; Lohr et al., 2004). However, due to limited space, maintenance costs, and disservices, smaller trees at maturity, especially flowering or fruit trees, appear to be the preference of many urbanites (Conway & Vander Vecht, 2015; Dilley & Wolf, 2013). These preferences could have profound impacts on energy consumption decades from now. Therefore, tree selection and placement must be considered in the full context of the landscape conditions so that potential benefits are being maximized while concurrently minimizing disservices and costs to individuals and communities (Dwyer, McPherson, Schroeder, & Rowntree, 1992, Kuo, Bacaicoa, & Sullivan, 1998).

5. Conclusion

Our study examined current landscape conditions of newly constructed residential developments and proposed an alternative strategy specifically aimed at improving energy conservation benefits for dense urban neighborhoods. We found that a lack of accessible parcel space appeared to restrict trees from being optimally placed for the provision of significant energy conservation benefits. The conventional strategy, which recommends planting a tree on the west, seems to be the most reliable approach but is often not achievable because of these space constraints. In these situations, and depending on geographic location, our alternative tree placement strategy would be as effective or improve upon the energy conservation benefits of the conventional strategy. Planting trees might be one of only a few approaches that urbanites can easily implement once an urban residential development has been constructed. Energy conservation is just one of the many well-known ecological benefits that urban trees provide, but the extent of savings is influenced by both tree form and tree placement. Therefore, a strategic approach for shade tree planting and management is fundamental for enhancing energy conservation benefits. This study concludes that appropriate tree placement strategies, corresponding to physical surroundings, should simultaneously take into account the effects of trees on an individual parcel and their combined effects throughout the community. Future studies will address limitations associated with simulation models and analyses, and strengthen the development and support of tree planting guidelines, as well as aid in the creation of supportive public policies that would be applicable in dense urban settings.

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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.

Table 2: Socioeconomic characteristics of the study areas. Racial composition and household income data representing the sample parcels were derived from the 2010 U.S. Census Block (racial composition) or Census Block Group (household income).

Table 3: Characteristics of the residential structure model used in simulations of shade tree effects on building energy consumption in three U.S. study areas.

Table 4: Existing landscape conditions in study areas derived using remote sensing data (Note: only the sampled parcels that had existing trees were analyzed). Average building (floor area) and parcel sizes were calculated using the ArcGIS tool (Calculate Geometry). Standard error of mean shown for parcel, building, and tree variables. Unmeasurable trees (8 trees in Metro Minneapolis and 70 trees in Metro Orlando, due to the image vintage) were excluded from mean calculations. Multiple comparison of means between study areas (Tukey's HSD test) are denoted with letters.

Table 5: Annual energy savings provided by existing shade trees (simulated as large deciduous trees using EnrgyPlus software) on residential parcels in Charlotte, NC and Metro Orlando, FL. Parcel and tree counts represent total number of parcels and shade trees observed within property boundary by study area, parcel orientation, and building orientation. Standard error of mean shown for energy savings. Multiple comparison of means using Tukey's HSD test are denoted with letters, showing energy savings compared between study areas and then between parcel and building orientations within study areas.

Table 6: Results of i-Tree Design simulations of ecosystem benefits from existing trees in Charlotte, NC and Metro Orlando, FL. Benefits were simulated for 20 randomly sampled parcels in each study area. 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 benefits of all 20 sampled parcels. Standard error of the mean is shown for total ecosystem benefits.

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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 broadleaf evergreen tree). The schematic shows placement of the tree models at 24 predefined locations (three distances $\times$ 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, FL for optimal placement of large deciduous trees (circles and squares) around a residential structure model (dark gray box) on parcels of varying orientation (light 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 distance (m) from the structure model.

Figure 3: Comparison of the two techniques (Energy Equation and EnergyPlus) used for estimating shade tree effects on the annual energy consumption of houses in Metro Minneapolis, MN (n=54 parcels), Charlotte, NC (n=77), and Metro Orlando, FL (n=33). The Energy Equation was developed to save simulation processing time. Columns show data value ranges. 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 (only parcels with 1 or 2 existing trees were used in this analysis) 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.

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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 (BACR) 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 Socioeconomic characteristics of the study areas. Racial composition and household income data representing the sample parcels were derived from the 2010 U.S. Census Block (racial composition) or Census Block Group (household income).

	Metro Minneapolis, MN	Charlotte, NC	Metro Orlando, FL
Racial Composition ¹			
One race			
White	80.0%	36.4%	71.8%
Black or African American	5.0%	49.0%	12.9%
American Indian / Alaska Native	0.0%	0.5%	1.4%
Asian	12.0%	5.5%	6.0%
Native Hawaiian / Other Pacific Islander	0.1%	0.1%	0.5%
Some other race	0.5%	5.6%	7.4%
Two or more races	2.4%	2.9%	-
Median Household Income ² (\$)			
Census Block Group	108,148	58,590	61,984
County	69,538	63,273	45,641
State	60,970	48,552	52,177
Median Value of Owner-Occupied Housing Units ² (\$)			
Census Block Group	336,133	149,790	205,350
County	266,879	223,748	150,345
State	204,401	161,983	215,349
Median Sale Value of the Sampled Parcels ³	445,917	113,575	189,051

¹ Racial Composition was derived from the 2010 Census Block Data (The 2010 Census Block data was downloaded from National Historic Geographic Information System: <http://www.nhgis.org>.)

² Median Household Income was derived from the 2010 Census Block Group data (The 2010 Census Block Group data was downloaded from the US Census Bureau: <http://www.census.gov>.)

³ Median sale values of the sampled parcels were derived from the tax parcel data provided by each county. (Median sale values were based on only the reported parcels (52 parcels for Metro Minneapolis, 87 for Charlotte, and 100 for Metro Orlando.)

Table 3 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 Minneapolis, MN	Charlotte, NC	Metro Orlando, FL
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	6B	3A	2A
Effective R-value ²			
External wall (m ² K/W)	3.689	3.073	2.624
Roof (m ² K/W)	8.104	8.104	8.104
Window (U-factor, W/m ² K)	1.42	4.26	2.56
Insulation min. R-value ²			
External wall	R-10 + R10 ci	R-13 + R3.8 ci	R-13 + R3.8 ci
Roof	R-49	R-49	R-49
Internal loads ²			
Lighting	Climate Zone 4-8 Mid-Rise Apt Light	Climate Zone 1-3 Mid-Rise Apt Light	Climate Zone 1-3 Mid-Rise Apt Light
Electric installation	Climate Zone 4-8 Mid-Rise Apt Electric	Climate Zone 1-3 Mid-Rise Apt Electric	Climate Zone 1-3 Mid-Rise Apt Electric
No. of occupants	3	3	3
HVAC system ²	Electric Heat Pump	Electric Heat Pump	Electric Heat Pump
Thermostat setting			
Cooling season (°C)	23.9	23.9	23.9
Heating season (°C)	21.1	21.1	21.1
Annual energy consumption of unshaded structure ³			
Cooling (kWh / percent of total energy consumption)	376 / 3%	567 / 6%	1,012 / 11%
Heating (kWh / percent of total energy consumption)	4,698 / 36%	1,535 / 16%	329 / 3.7%
Annual average electric price (\$/kWh) ⁴	0.1137	0.1082	0.1152

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, Long, & Swindler, 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. It excluded energy consumption for air circulation as described "Fan" in EnergyPlus simulations.

⁴ 2012 Annual average electric price from US Energy Information Administration (US Energy Information Administration, 2014).

Table 4 Existing landscape conditions in study areas derived using remote sensing data (Note: only the sampled parcels that had existing trees were analyzed). Average building (floor area) and parcel sizes were calculated using the ArcGIS tool (Calculate Geometry). Standard error of mean shown for parcel, building, and tree variables. Unmeasurable trees (8 trees in Metro Minneapolis and 70 trees in Metro Orlando, due to the image vintage) were excluded from mean calculations. Multiple comparison of means between study areas (Tukey's HSD test) are denoted with letters.

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, MN	54	1,193.1 ± 36.2a	237.0 ± 6.4a	1.5 ± 0.1b	4.3 ± 0.2b	10.0 ± 0.4a
Charlotte, NC	90	734.6 ± 15.7c	181.7 ± 4.2b	1.7 ± 0.1b	5.9 ± 0.2a	7.6 ± 0.2b
Metro Orlando, FL	91	988.2 ± 19.1b	257.9 ± 6.9a	2.9 ± 0.1a	3.7 ± 0.1b	7.8 ± 0.2b

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, MN	17	5	20	12	23	12	14	5
Charlotte, NC	26	18	15	31	27	27	21	15
Metro Orlando, FL	18	13	50	10	52	8	23	8

Table 5 Annual energy savings provided by existing shade trees (simulated as large deciduous trees using EnrgyPlus software) on residential parcels in Charlotte, NC and Metro Orlando, FL. Parcel and tree counts represent total number of parcels and shade trees observed within property boundary by study area, parcel orientation, and building orientation. Standard error of mean shown for energy savings. Multiple comparison of means using Tukey's HSD test are denoted with letters, showing energy savings compared between study areas and then between parcel and building orientations within study areas.

	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, NC	Parcel Count	90	26	18	15	31	27	27	21	15
	Tree Count	149	41	45	36	27	42	31	22	54
	Mean Savings (kWh) per Parcel	28±2.3b	37±3.8a	14±4.0c	18±4.7bc	32±3.0ab	33±4.1a	24±4.3a	25±4.1a	27±6.2a
	Mean Savings (\$) per Parcel ¹	2.98±0.63b	4.04±0.41a	1.48±0.43c	1.93±0.51bc	3.49±0.42ab	3.60±0.45a	2.61±0.46a	2.72±0.44a	2.94±0.67a
Metro Orlando, FL	Parcel Count	91	18	13	50	10	52	8	23	8
	Tree Count	265	64	39	136	26	145	22	71	27
	Mean Savings (kWh) per Parcel	68±5.5a	122±13.1a	46±6.7b	54± 6.2b	65±16.6b	53±6.7b	71±19.9ab	101±11.6a	60±6.2ab
	Mean Savings (\$) per Parcel ¹	7.78±0.64a	14.08±1.51a	5.33±0.78b	6.18± 0.71b	7.43±1.92b	6.10±0.77b	8.16±2.30ab	11.68±1.34a	6.87±0.72ab

¹Mean savings (\$) per parcel were estimated by 2012 annual average electric price from US Energy Information Administration (US Energy Information Administration, 2014).

Table 6 Results of i-Tree Design simulations of ecosystem benefits from existing trees in Chalrotte, NC and Metro Orlando, FL. Benefits were simulated for 20 randomly sampled parcels in each study area. 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 benefits of all 20 sampled parcels. Standard error of the mean is shown for total ecosystem benefits.

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, NC	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, FL	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	100.60	12.73	4.52	32.13	149.99 ± 7.43

¹Number of trees on the sampled parcel.

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

³Large Deciduous Tree (91cm trunk diameter) species used for simulations: willow oak (*Quercus phellos*) for Charlotte and laurel oak (*Quercus laurifolia*) for Metro Orlando (Peper et al., 2010).

⁴SW: Stormwater runoff savings by intercepting rainfall.

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

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

⁷Energy: 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.

Figures

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