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

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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 160 kWh (valued at \$18) in southern cities with longer cooling seasons. Whereas, the same tree on the south aspect could increase annual energy costs by up to 134 kWh (−\$15) 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.

INTRODUCTION

Landscape trees modify urban temperatures by casting shade onto man-made ground covers and buildings (Pandit and Laband 2010; Chagolla et al. 2012). By intercepting sunlight that would otherwise heat 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 – an effect that is often referred to as the heating penalty of shade trees (Simpson and McPherson 1996; Simpson 1998). Because cooling and heating indoor spaces account for about 40 percent of the total energy consumed by residential structures in the U.S. (US Energy Information Administration 2012), 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, in a previous study, we examined how tree form, tree placement, and geographic latitude influence the amount of shade cast upon a nearby prototypical residential structure on a daily and seasonal basis (Hwang et al. 2015). In the current study, we employed computer simulations to further examine how quality and timing of shade cast by a single tree impacts the annual energy consumption of this same prototypical structure.

Because dwellings shaded by trees tend to consume less energy for space cooling during summer months (Akbari and Taha 1992; 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 trees per residential parcel resulted in an annual energy savings of up to $10.00 (approximately 100 kWh) per tree (Simpson and McPherson 1998). Similarly, a tree planting program in Toronto, Canada planted 577 trees in residential areas between 1997 and 2000, which led to an annual energy 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 mature 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 grows, the greater the shade cast onto the adjacent structure (Donovan and Butry 2009). Additionally, tree canopy density influences the intensity of solar radiation reaching the structure, with a denser canopy providing more significant shading effects (Heisler, 1986; Pandit and Laband 2010). Shade trees placed in close proximity (9 m – 15 m) to the structure usually provide the greatest amount of summertime shade coverage on roofs and walls (McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010; Troxel et al. 2013), with the influence of tree height varying depending on the distance of the tree from the structure (Rudie and Dewer 1984); only tall trees provide substantial shade when situated far from the structure.

When it comes to energy conservation, the most important aspect of tree placement is the directional location of a tree relative to the structure. 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 months 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). Likewise, trees on the north aspect rarely intercept sunlight destined for the structure and thus provide minimal cooling effects from shading alone (Donovan and Butry 2009).

The converse occurrence of shade benefits would be that, during the winter months when the sun angle is low, the shade from trees may prevent solar radiation from reaching building surfaces, deterring passive solar heating and necessitating additional energy use for space heating. At far northern latitudes, the most intense sunlight during winter occurs when the sun is in the southern sky. Consequently, a south positioned tree casting shade onto the structure may cause a heating penalty, which could be particularly acute if it is a coniferous tree with dense evergreen foliage (Nikoofard et al. 2011). The heating penalty impact of a south-positioned tree, when placed in close proximity to a building, can be approximately twice as large compared to the same tree on either an east or west aspect (Hildebrandt and Sarkovich 1998).

These well-known biophysical effects of tree shade on solar heat gain and building energy consumption have been used by authoritative sources across the U.S. to develop regional guidelines for 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 the information about optimal shade tree planting for energy conservation in urban environments (Bowler et al. 2010). Examples of fundamental concepts that are often overlooked in tree planting guidelines include the effects of local climate and daily and seasonal sun movements that interact with tree characteristics and placement in the landscape. In addition, residential construction in the U.S. in recent years has trended toward decreased lot sizes and increased house sizes (Sarkar, 2011). Because these smaller lots have relatively more impervious surfaces and less room for trees (Wilson and Boehland 2005), trees are often planted in sub-optimal locations for energy conservation. Therefore, the strategic selection and placement of a single tree becomes more important. With this in mind, we built upon our previous study, which showed that shade provision is a function of not only tree form and tree placement but also daily, seasonal, and latitudinal variability in sunlight exposure. Here, we took the analysis of tree shade one step further, quantifying building energy conservation effects using computer simulations. Along with the quantity of shade, we considered additional important factors, such as the quality and timing of tree shade (Heisler 1986). Thus, in continuance with the previous findings, the goal of the current study was to evaluate how shade provision by a single landscape tree of varying form and placement influences cooling and heating energy consumption of a residential structure across a latitudinal gradient.

METHODS

Study Areas

To examine the effects of local climate and daily and seasonal sun movements on the energy conservation benefits of trees, we conducted building energy simulations in four U.S. cities: 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 measurements of the cooling and heating demands based on the departure of average daily temperatures from a thermal baseline of 18.3 °C (65 °F in the U.S.) (Erhardt 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, cooling 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 in northern cities. In contrast, the heating season in Minneapolis is comparatively longer (nine months from September to May) than in southern cities.

Building Energy Simulations

This study used a suite of computer simulation programs called EnergyPlus (version 8.0, US Department of Energy, Washington, DC) to quantify tree shade impacts on annual energy consumption of a prototypical residential structure model. Using weather data inputs, EnergyPlus calculated the cooling and heating energy consumption for maintaining thermal set points of 23.9 °C for cooling and 21.1 °C for heating of the structure model (Long et al. 2010). The weather data, downloaded from the EnergyPlus website, comprised hourly values of solar radiation and meteorological data (e.g., temperature, precipitation, and wind speed) for a one-year period (based on the 30-year average) for each study area (US Department of Energy 2014). Trees in the energy simulations were modeled as an object adjacent to the building structure, which influenced heat gain by casting shade upon the building surfaces and ground covers, and by altering airflow around the structure. EnergyPlus computed the impacts of trees on heat gains and airflow and applied those values into a model for estimating the annual cooling and heating energy consumption of the structure (US Department of Energy 2014). Energy simulations were conducted on a similar model environment as our previous shade quantification study (Hwang et al. 2015).

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 adjacent to the structure to determine, by comparison, the impact of a single tree on annual energy consumption. We considered the differences in the estimated annual cooling and heating energy consumption (reported in kWh) between the simulations a representation of the tree's impact on energy.

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. 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[3]	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[3]	*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 (National Oceanic and Atmospheric Administration 2012).
[3] CDD: Cooling Degree-Days; and HDD: Heating Degree-Days.

Residential Structure and Shade Tree Models

The single-level residential structure model had a floor area of approximately 200 m² (11 m × 18.2 m) and a total exterior surface area (four walls and two roof halves) of 410.6 m² (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 m² of floor area (Sarkar 2011; US Census Bureau 2012). Thermal specifications for the structure (Table 2) 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 were derived through a combination of tree form and tree placement variables, resulting in 144 different single-tree planting scenarios for the energy simulations (Figure 1). Three deciduous and three coniferous tree models were developed using a combination 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 25% (leaf-off) for deciduous trees and 80% (year-round) for coniferous trees. In order to typify many urban landscape trees found in the U.S., the five tree form variables used in the simulations were based upon data from previous studies (McPherson et al. 1985; McPherson et al. 2005; McPherson et al. 2006; Peper et al. 2009; Peper et al. 2010). In the energy simulations, each of the six tree models (two leaf types × three tree sizes) was placed at 24 pre-defined locations around the structure: three distances (5 m, 10 m, 15 m) in eight directions (four cardinal and four inter-cardinal).

Our previous shade simulation study found that smaller tree models (either coniferous or deciduous trees) placed at further distances from the structure (see Figure 1) provide minimal shade coverage (Hwang et al. 2015) and would presumably 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 a structure.

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]	2A	3A	5B	6B
Effective R-value[2]				
External wall (m^2K/W)	2.62	3.07	3.69	3.69
Roof (m^2K/W)	8.10	8.10	8.10	8.10
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]				
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)	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 Electricity Price ($/kWh)[4]	0.115	0.108	0.105	0.114

[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).

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.

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
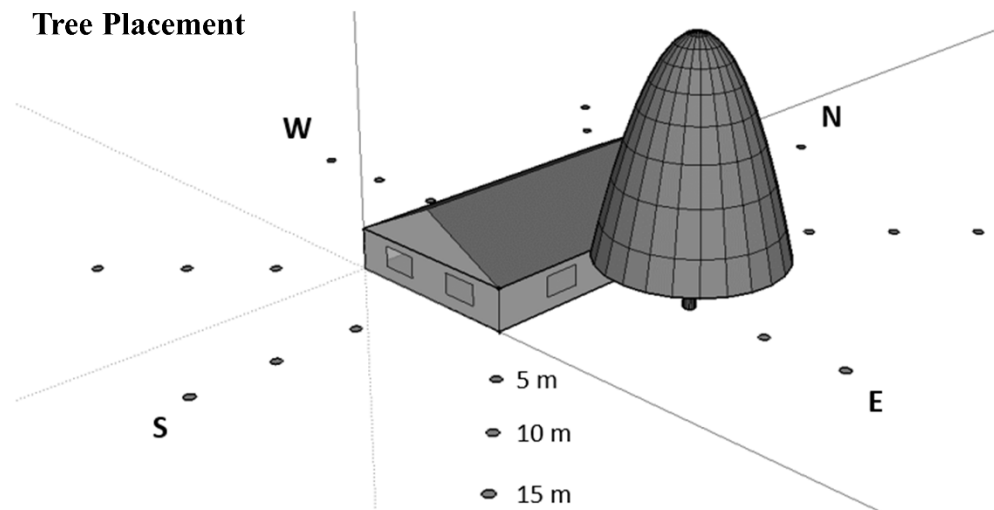
RESULTS AND DISCUSSION

Overall Trends in Cooling and Heating Energy Consumption

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 was found to consume from 8,846 kWh (valued at $1,017) in Orlando to 13,216 kWh ($1,507) in Minneapolis. Monetary valuation of energy consumption in this study was based on the local 2012 average electricity price per kWh: $0.114 for Minneapolis; $0.105 for Indianapolis; $0.108 for Charlotte; and $0.115 for Orlando (US Energy Information Administration 2014). As predicted, the amount of cooling and heating energy consumed varied depending on the study area and their associated local climates. The structure in Orlando required more energy for space cooling (1,774 kWh; $204) than for heating (578 kWh; $66), whereas the structure in Minneapolis required less energy for space cooling (792 kWh; $90) but more for heating (5,930 kWh; $676).

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. Coniferous trees with dense crowns year-round had greater impacts on energy consumption than deciduous trees. However, the intensity of the effects on energy consumption (for both cooling and heating) varied depending on tree form, tree placement, and study area. Differences in cooling energy savings versus heating penalties (i.e., additional costs) 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 (Figure 2) had a 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 (Figure 3), had an increased heating energy consumption by up to 171 kWh (maximum cost valued at $19).

Impacts of a Single Shade Tree on Cooling Energy Consumption

Energy simulations indicated that the differences in the length of the cooling season for each study area had a significant impact on annual cooling energy consumption. EnergyPlus estimated that the impact ranged from 0 kWh (no effect) to 142 kWh (savings valued at $16), depending upon tree form, tree placement, and study area (Figure 2). The same tree models could reduce cooling energy consumption more than three times in Orlando, where the cooling season is markedly longer, compared to other study areas. About 22% of the tree models in Orlando saved between 40 and 140 kWh of energy. When moving north where cooling seasons are shorter, the amount of energy savings from tree shade diminished. Annual cooling energy savings rarely exceeded 40 kWh in Charlotte, Indianapolis, and Minneapolis. For instance, the large deciduous tree model placed on the west aspect (5 m away) had an annual cooling energy savings of 89 kWh (valued at $10.24) in Orlando; 31 kWh ($3.35) in Charlotte; 23 kWh ($2.42) in Indianapolis; and 20 kWh ($2.28) in Minneapolis.

Due to the geometry of seasonal sun angles interacting with tree form, tree placement, and structure orientation (Figure 4), 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 4 kWh more than the large coniferous tree at 15 m away. Trees on the south showed the greatest differences (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 decreased (from 20 kWh to 5 kWh) when this south-positioned tree was placed further away from the structure.

Our simulations also revealed that a large tree close to the west aspect of the structure (5 m in this study) does not always provide the most substantial reduction in cooling energy consumption, particularly where the cooling season is shorter. For example, in Indianapolis, the large deciduous tree on the south aspect at 5 m away saved the most annual cooling energy (32 kWh) because of the interaction between tree form (elliptical canopy with tall height) and higher sun angle as the tree shade covered the narrow north-south oriented roof. However, when planting the same tree at 10 m or further, west positioning provided the most significant reduction in cooling energy consumption because at greater distance the tree can cast substantial shade once the sun is low on the horizon.

Impacts of a Single Shade Tree on Heating Energy Consumption

Heating seasons in the study areas range from three months (Orlando) to nine months (Minneapolis). During this period, 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 (Figure 3). Heating savings also occurred in southern latitudes; however, the savings were mostly less than 10 kWh per year due to a shorter heating season. In northern cities, heating penalties were more common in the simulations than were heating savings (Figure 3). Both coniferous and deciduous tree models showed some level of adverse effects on heating energy consumption. Coniferous trees with year-round foliage blocked passive solar heating causing greater heating penalties than deciduous trees. The heating penalty was magnified by the longer heating seasons. The simulations estimated annual heating penalties to be as much as 171 kWh (additional cost of $19.50) depending on tree form, tree placement, and study area. This was especially pronounced in Minneapolis, where lower sun angles resulted in undesirable shade being cast onto the structure over much of the prolonged heating season (Figure 4). A coniferous tree was shown to be even more detrimental when situated on the south aspect in close proximity to the structure. In order to reduce heating penalties, it would be more effective to increase the distance of a south aspect tree from the structure than to plant a smaller tree. For example, in Indianapolis, the difference in heating penalty between a large and a small tree at 5 m away was only 20 kWh. Whereas, when compared to the same large trees at 5 m and 10 m away, the difference was as much as 39 kWh. In southern latitudes, where the heating season is shorter and milder, planting a coniferous tree is not as detrimental to energy consumption. In Orlando, only a few coniferous tree models increased heating expenditure, yet often provided substantial cooling savings, as described in the previous section.

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. Models of 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 (y-axis in each graph).
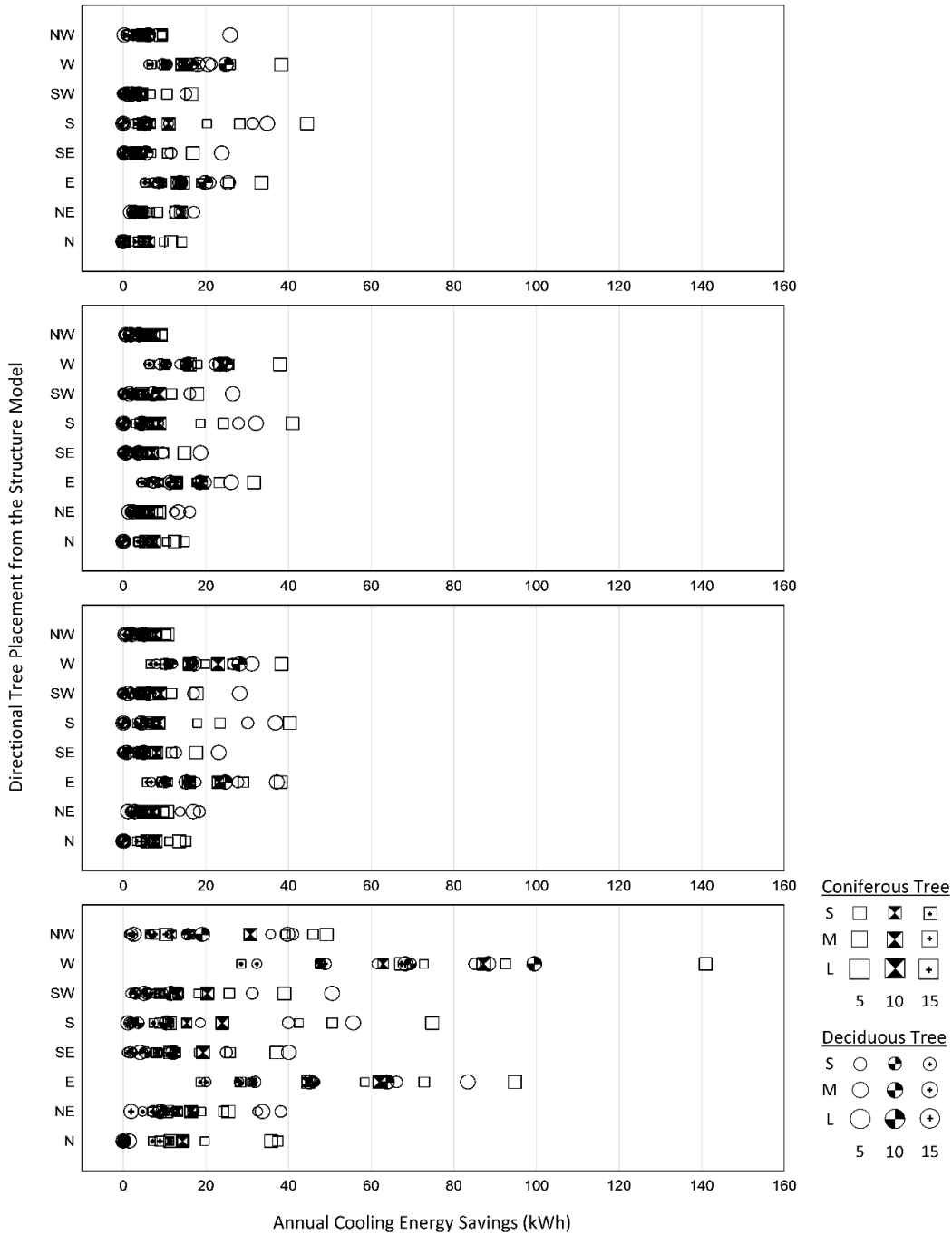
Figure 3 The impact of various single tree-planting configurations on annual heating energy consumption for a residential structure model simulated in four U.S. cities. The duration of the heating season is listed next to the city name in each graph. Models of six tree forms (two leaf types × three stature 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 (y-axis in each graph).
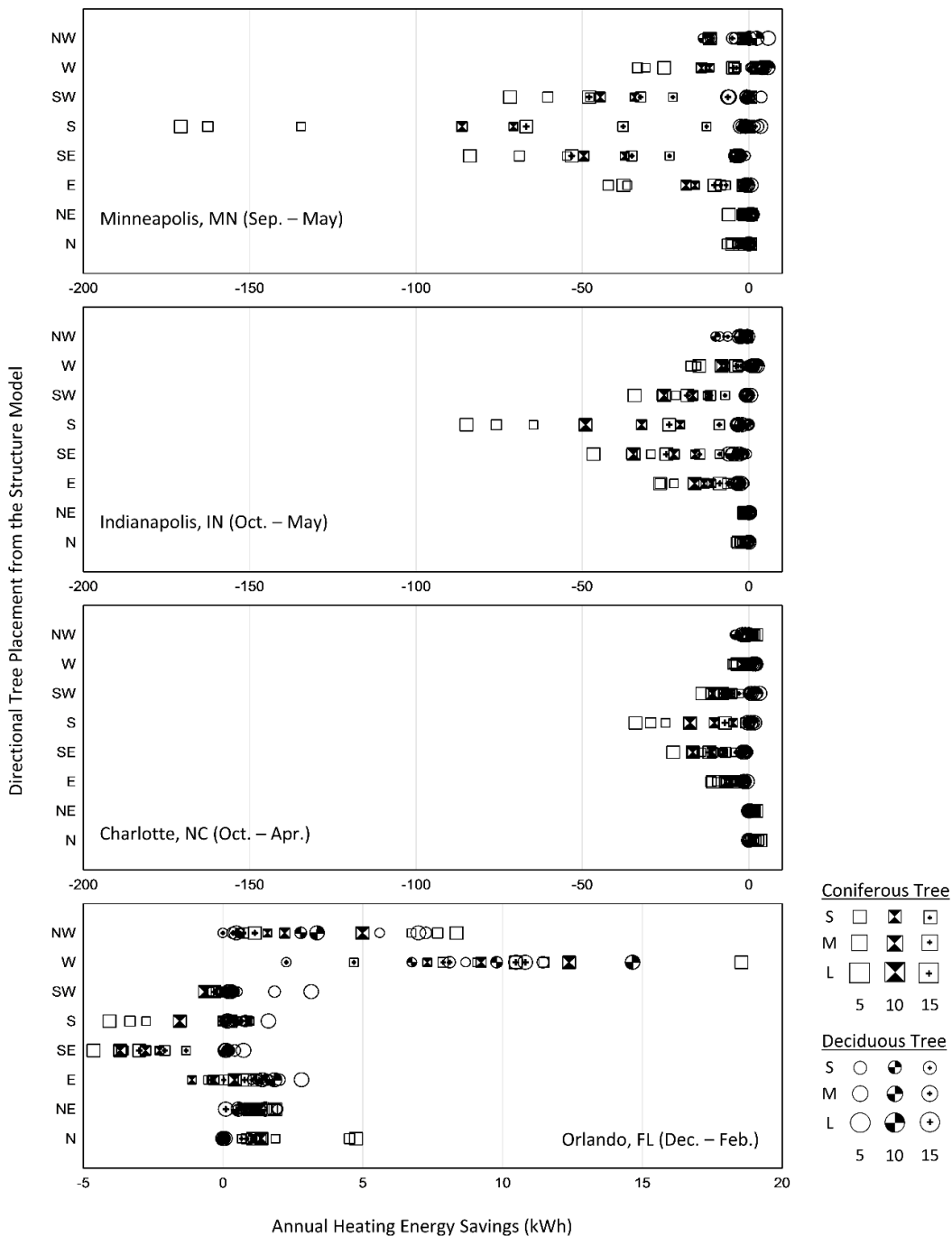
Figure 4 Geometry of sun angle interacting with tree form and tree placement to influence solar heating of a structure. A large deciduous tree with an elliptical crown (left) allows solar penetration when sun angle is low. In contrast, a parabolic coniferous tree blocks solar penetration when the sun 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.
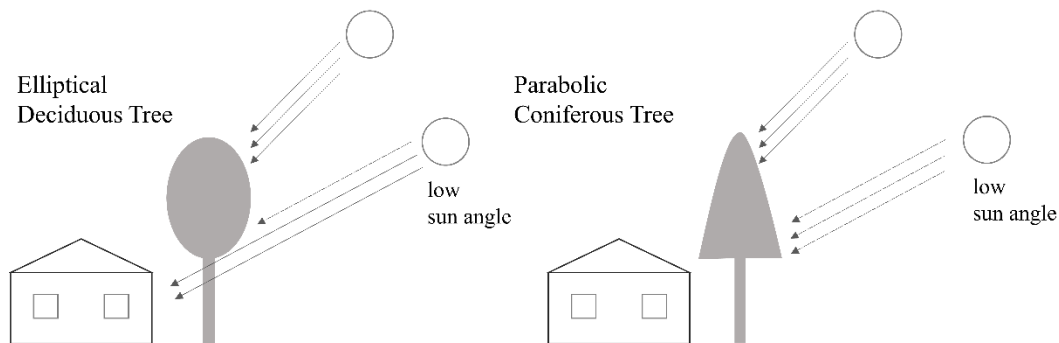
Impacts of a Single Shade Tree on Net Energy Consumption

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 single shade tree ranged from a net energy savings of 160 kWh (valued at $18) in Orlando to a net energy cost of 134 kWh (−$15) in Minneapolis (Figure 5). Across the study areas, trees on the west aspect almost always reduced annual energy consumption. The few exceptions were small and medium coniferous trees close to the structure in Minneapolis. Southerly placed (south, southeast, and southwest) coniferous trees typically increased annual energy consumption in northern cities.

Net annual energy consumption was closely related to geographic latitude, which reflects variations in lengths of cooling and heating seasons as well as daily and seasonal sun movements. In the southernmost study area of Orlando, none of the tree planting scenarios had a negative effect on net energy savings. Progressing to the north, certain tree planting scenarios (e.g., coniferous trees on southerly aspects) had increasingly negative effects on net energy savings. This was due to the heating penalty of coniferous trees disrupting passive solar heating of the structure. In Orlando, with the shortest heating season, more than 95% of tree planting scenarios provided cooling savings large enough to compensate for any heating penalty accrued during the heating season. The best-performing scenarios tended to be medium and large trees situated close to the structure on the west or east aspect. Trees in northern cities with longer heating seasons showed different trends in net energy consumption. First, certain tree models that had been

beneficial in Orlando caused additional energy costs of increasing magnitude in going from south to north. Most notable were southerly placed coniferous trees that prevented sun from heating exterior walls and windows in winter. Second, large deciduous trees close to the structure on the southerly aspects became increasingly effective at net energy savings. The elliptical canopy of the deciduous tree on the south aspect could cast shade onto the structure when the sun angle was higher during the summer, yet allow light from the low-angled sun to pass under the canopy to warm the structure in winter (Figure 4).

In contrast to deciduous trees, coniferous trees, (particularly in northern locations), caused acute heating penalties during the winter months, thus adversely impacting annual net energy consumption. In Minneapolis, the south-positioned coniferous tree caused the most notable additional energy consumption: as much as 134 kWh. When the sun angle is lower in the heating season, the parabolic canopy of the coniferous tree would block passive solar heating (Figure 4), resulting in heating penalties. Coniferous trees caused a heating penalty even as far as 15 m away, due to lower sun angles and longer heating seasons. This stands in contrast to the summer cooling effects provided by most south-positioned deciduous trees, which showed diminishing energy impacts moving further away from the structure. 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 caused additional energy consumption up to 18 kWh because trees on this placement blocked passive solar heating in early morning.

Is Planting a Shade Tree on North Aspects Useless?

Our simulations showed that trees on north aspects cast negligible shade on building surfaces due to daily and 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 contribute to energy conservation by casting shade onto low albedo ground covers during summer (Huang et al., 1987; Akbari and Konopacki 2004) and creating a windbreak in winter (Liu and Harris 2008). Our simulations substantiated some of these effects and showed, for example, that northerly tree placement reduced annual energy consumption as much as 58 kWh by coniferous trees (valued at $6.67) and 48 kWh by deciduous trees ($5.52) driven by shading 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 ground cover shading and windbreak effects were not the primary focus of our study, their impact on building energy conservation should be acknowledged.

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. Models of 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 (y-axis in each graph).
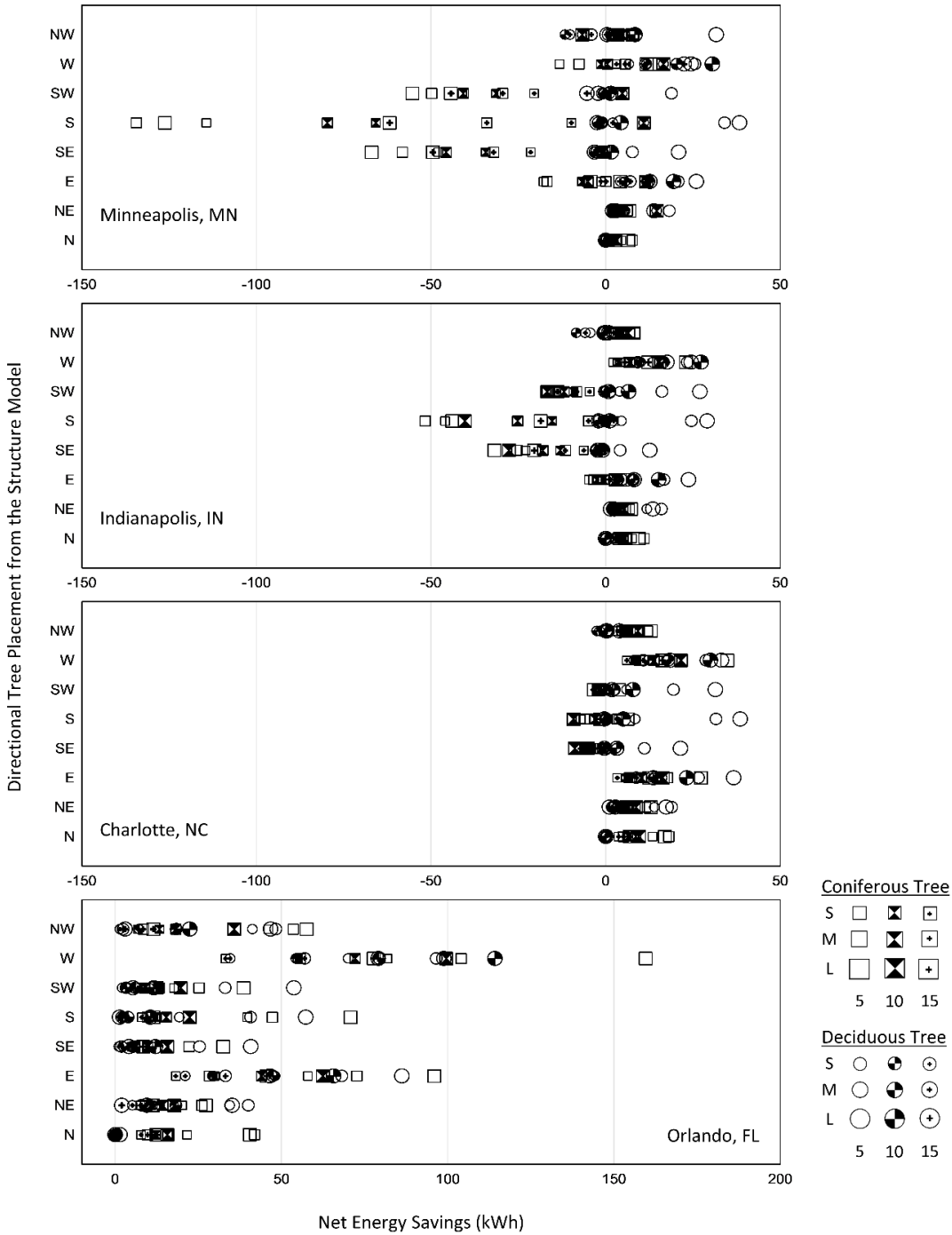
Is Strategically Planting a Single Shade Tree Worth It?

The net energy savings of a single shade tree revealed in our study may not provide a strong incentive for individual homeowners to think strategically about optimal tree placement on their properties for energy conservation. Indeed, residential tree placement may be dictated more often by aesthetics or convenience than by potential energy savings. Perhaps what's more important is that homeowners simply need to plant trees on their properties because the aggregate effect across the community can be significant. As more trees are planted and canopy cover increases across the urban environment, there are synergistic effects of decreased heat loading on low-albedo surfaces and increased evapotranspirational cooling. For example, in California, for 15 years after planting 50 million trees on urban private properties, the annual cooling reduction was expected to be over 46,000 GWh (valued at $3.6 billion) (McPherson and Simpson 2003). Plus, there are other direct economic benefits for individual homeowners from planting a shade tree, such as increased property value and decreased ultraviolet damage of roofs, driveways, and other structural materials (Andrady et al. 1998; Scott et al. 1999; Payton et al. 2008). And as municipalities increasingly grapple with managing stormwater runoff, some cities are issuing stormwater fee discounts to property owners for maintaining tree cover (Stone Environmental 2014). There may be a time in the future when property owners are also given credit for carbon sequestration or avoidance by trees on their property, further creating a financial incentive to plant trees. As financial incentives increase to plant trees on residential properties, there should be evidence-based guidelines for tree selection and placement to optimize the benefits that they provide for the homeowner and the community.

Limitations of EnergyPlus Simulations

While our energy simulation approach included concepts that differentiated our study from others, we've recognized three limitations: (1) omission of evapotranspiration cooling effects; (2) simplified simulation conditions; and (3) lack of housing energy efficiency specifications. For our study, we examined an isolated residential structure with a single tree in order to reduce simulation complexity. With the simplified tree and structure models, it is impossible to clearly address shade tree effects on all possible arrangements of a structure and associated trees; however, the concept presented in our study still provides valuable contribution in energy saving context.

Our simulation platform did not incorporate the effects of evapotranspirational cooling, which would be an aggregate effect 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. Furthermore, an isolated residential structure with a single tree used in our simulation would be an uncommon circumstance in dense urban neighborhoods. Trees in dense residential areas often cast shade not only onto the target building, but also neighboring buildings (Sawka et al. 2013); therefore, planting a single tree could have spill-over impacts (good or bad) on energy consumption of neighboring structures, depending on tree form and placement.

We used six simplified tree models (two leaf types × three tree sizes) for all study areas. While these tree models could not fully capture the diversity of landscape trees found in these diverse geographic areas, they were carefully constructed to approximate the dimensions of typical coniferous and deciduous trees. Furthermore, the software was not capable of the gradual seasonal foliage changes of deciduous trees during the simulation time frame, which would influence shade quality and therefore solar heat gain (Heisler 1986). In addition, this study solely relied on the computations of EnergyPlus because additional validation data were not available. We chose EnergyPlus because it is the reference program of the US Department of Energy and has been aggressively tested and validated (Crawley et al. 2004). Although this is an early attempt at using EnergyPlus to examine the effects of shade trees, its capabilities could have potential for expanding the scope of future shade tree studies. Therefore, in conjunction with refining our simulation models such that both trees and structures models better depict conditions in the study areas, future studies should also include sensitivity analysis that would help to identify increased data points of the study variables that influence tree shade and building energy consumption. Despite these limitations of our simulation framework, 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 merits the attention of both homeowners and civic tree planting programs.

Finally, since 1975, the U.S. residential energy code has strengthened, leading to more energy efficient structures and a decrease in energy consumption by approximately 14% (US Department of Energy 2008). Our simulation used the recent thermal 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 and costs of tree shade are attenuated. Previous studies that have modeled energy conservation benefits of trees using older housing specifications have probably overstated these benefits for the U.S. housing stock as a whole. Likewise, our study probably understates these benefits because we modeled using contemporary specifications. Therefore, to gain a clear understanding of actual energy conservation benefits, larger scale simulations with a range of housing specifications that reflect the mixed vintage of existing U.S. housing stock are needed.

CONCLUSION

This study has demonstrated a method for using EnergyPlus simulations to evaluate the impacts of a single shade tree on annual energy consumption of a residential structure across diverse geographic locations. Within a contrived environment that simplified the geometry of the structure and placement of a nearby tree, our simulation results revealed the nuances of not only tree form and tree placement but also seasonal and geographic variability in sun path and solar heat gains. These differences resulted in both positive (savings) and negative (costs) tree shade effects on building energy consumption.

In order to enhance energy conservation benefits of a shade tree, it is necessary to take into consideration both the potential for cooling savings and heating penalties. When planting a shade tree, it is important to identify a planting scenario that maximizes the cooling effects of shade while concurrently minimizing its heating penalties (particularly in northern latitudes with longer heating season). With this in mind, and as a result of our simulation findings, the general

recommendation is that planting a large deciduous tree on the west aspect of a building seems to be the most consistently reliable approach to energy conservation. Depending on local circumstances, trees on either the east or south aspect, or sometimes even smaller trees, could be equally effective. Our findings about latitudinal effects on optimal tree placement could be useful for developing planting guidelines that would provide more optimal shade tree benefits based on specific geographic locations. Therefore, we conclude that shade tree planting should take into consideration the mechanics of seasonal sun angles interacting with tree form, tree placement, and structure orientation in order to improve the energy conservation benefits of trees in urban settings. We expect that through refining our simulation process, researchers will be able to develop even more refined models for estimating the broad-scale energy conservation benefits of trees in planned residential developments.

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