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Growing Energy Conservation Through Residential Shade Tree Planting

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GROWING ENERGY CONSERVATION THROUGH RESIDENTIAL SHADE TREE PLANTING

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Abstract

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Urban residential shade trees extenuate the heating of buildings in the summertime by intercepting insolation and by evapotranspirative cooling of their immediate surroundings. By modifying location-specific climate data, and tree growth characteristics, this research adapts the Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator for application in Toronto, Canada. This tool is then put to use modeling the energy conservation savings delivered by 577 trees planted in Toronto backyards between 1997 and 2000. This study's results estimate that the trees contributed 77,139 kWh of electricity savings as of 2009, 54.4% of which was due to shading of neighbouring houses. This study's findings indicate that urban residential tree planting programs should not focus exclusively on location-driven strategic planting to yield large energy conservation benefits. Instead, it is argued that priority should be given to selecting planting locations that will maximize tree survival as neighbourhood energy conservation benefits of a tree that achieves mature stature often outweigh the homeowner-specific benefit of a strategically planted tree.

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Table of contents

List of Tables

List of Figures

Chapter 1

1.1 Introduction

Urban dwellers often view the city as distinct and separate from nature (Hough, 1989). This viewpoint has placed urban development at odds with the maintenance and integration of nature within cities; a circumstance that continues to create detrimental effects for the health and integrity of urban ecosystems (Bryant, 2006). Beyond the environmental degradation caused by the removal of native vegetation and the increase of impervious land cover, contemporary development practices have led to the estrangement of urban society from natural systems (Barlett, 2005). Today, many urban municipalities are starting to seek approaches to land use planning that integrate ecological sustainability by encouraging the preservation and creation of resilient natural systems within cities. To this end, urban planners are now exploring the environmental benefits of reintroducing native vegetation into urban landscapes; many cities are focusing their attention on a key component of urban ecosystems—trees (Peckham, 2010).

Trees growing in the urban landscape can have an important influence on the biophysical environment. Frequently planted for aesthetic reasons, city trees also provide many environmental, economic and social benefits to urban areas (Nowak et al., 2008; Lohr et al., 2004). One particular benefit of trees that bridges both concerns for the economy and the environment is their ability to influence energy conservation through mitigation of demand for summertime air conditioning. As a result of direct shading and evapotranspiration, shade trees can prevent the warming of buildings and the proximate urban microclimate. This effect minimizes the requirement for cooling energy, saving the homeowner money through lower electricity costs and at the same time lessening emissions from power plants. Increased knowledge of these benefits can assist planners and community organizers with landscape designs that leverage the energy conservation value of shade trees, while providing homeowners with an economic incentive for tree planting and maintenance.

1.2 Thesis Objectives

This research investigates the influence of residential tree planting on energy conservation in a densely built urban environment. Through modification of location-specific climate data and tree growth characteristics, the Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator was adapted for application in Toronto, Canada. Once developed, we used our tool, the Ontario Residential Tree Benefits Estimator (ORTBE), to model the energy conservation savings provided by trees planted in Toronto backyards between 1997 and 2000. Model estimation of energy conservation provided by shade trees was determined as an 'energy use offset' (energy that would otherwise have been used for air conditioning) and is reported in kilowatt hours (kWh) annually.

Using a sample of 8 species (577 trees total) planted by the non-profit, Local Enhancement and Appreciation of Forests (LEAF), energy conservation savings were estimated for these program trees (1) during years since planting; and prospectively, (2) at 25 and 40 years post-planting. In this research, a methodology is developed to account for the complexity of the physical environment in which a tree is growing (or may be planted) by considering the spatial relationship between it, other established trees in close proximity, and the surrounding houses for which the focal tree may provide shade.

When considering the potential impact of urban tree planting programs on energy demand management, it is critical to recognize that established neighbourhoods in most cities already have a large number of properties with existing tree cover. A tree planted on a property with pre-existing canopy cover may only have a minimal influence on temperature moderation. At the same time, houses located in relatively close proximity to one another increase the possibility of trees planted on one property moderating temperature (through shading and evapotranspiration) on a neighbouring property. This research incorporates both of these factors when estimating the energy conservation benefits achieved through LEAF's residential tree planting program.

1.3 Thesis Outline

This thesis is organized into five chapters. Taken as a whole it documents the adaption of an urban shade tree benefits estimator to model electricity conservation in Toronto, and further uses this model to quantify the energy saving benefits of a private residential tree planting program. Chapter One provides a cursory background to the research and outlines the overall objectives of the study. In Chapter Two, a literature review is provided that details the importance of urban trees and grounds this research in the narrative of demand side energy conservation. A detailed discussion of the model adaption methodology is covered in Chapter Three as well as a description of the tree planting data collection protocol. Chapter Four is formatted as a standalone manuscript for submission to the journal *Landscape and Urban Planning*. The manuscript has been structured so as to meet the specifications of this journal in accordance with Elsevier's Guide to Authors. In the final section, Chapter Five, model uncertainty, significance of the research and suggestions for future studies are presented.

Chapter 2

2.1 Urban Forestry and Tree Planting

The influence of humans on forests is now ubiquitous across the globe. Nowhere is this impact more concentrated than in forests growing within and proximate to urban centres. Historical evidence indicates that arboriculture activities characteristic of contemporary urban forestry began over 5,000 years ago (Miller, 1997). The first known intentional use of vegetation in a settled area was in the Hanging Gardens of Babylon, 6th century BCE (Campana, 1999). In ancient Egypt trees were important sources of shade in the desert, and Egyptians practiced the selection, planting, cultivation, and transplantation of trees into the city on a massive scale (Campana, 1999). A long history of gardens has accompanied the development of Western civilization, and beginning with the Renaissance and the concurrent development of urban areas, tree planting became common in western cities (Lawrence, 2006). Today, urban forests are defined as treed ecosystems characterized by their association with people and the built environment (Nowak et al., 2001); they are composed of both publicly and privately owned trees.

Although the presence of trees in urban centres is not new, the concept of urban forestry only emerged in the 1960s. It was first defined as, "A specialized branch of forestry [that] has as its objective the cultivation and management of trees and forests for their present and potential contributions to the physiological, sociological and economic well-being of urban society" (Jorgensen, 1970, p. 44). This early definition of urban forestry evolved out of a need for a systematic and specialized approach to the management of city trees and green spaces (Johnston, 1996); it recognizes trees as a vital component of the built environment. Despite some variance in definition over the ensuing decades, urban forestry is today understood to be the planning and management of urban trees and associated plants within areas greatly influenced by urban populations (Hauer, 2005; Dwyer et al., 2000).

According to Lawrence (1995), trees have historically played two main roles in cities: (1) as living organisms both subject to, and influencing, the ecosystems around them; and, (2) as symbols of nature in an otherwise constructed landscape. Although cities are often understood by academics to be both theoretically and ecologically part of nature, this proposition is less easily appreciated where vegetation and wildlife are absent. A primary motivation for planting trees in cities is aesthetic beauty (Lawrence 1995). Trees represent pleasing reminders for urban inhabitants of the natural world that exists outside of the city limits. Historically, trees in cities also symbolized power, and their presence in urban landscapes was an important manifestation of influence and prestige. Until the rise of large-scale residential suburbs, most vegetation within the urban landscape was planted and maintained by a few individuals from an elevated social class (Lawrence, 1995).

In contemporary urban environments trees remain subject to, and influencers of, local environmental conditions as well as being important symbols of nature. It is common for trees to be distributed disproportionately across the urban landscape, with areas containing the greatest canopy cover usually located in the wealthiest neighbourhoods (Jensen et al., 2003; Iverson and Cook, 2000). In many cities today there is a powerful social pressure influencing the planting and maintenance of trees. Property owners often mimic the landscaping practices and preferences expressed by their neighbours; in this way, landscape changes made by one individual can cascade throughout an entire neighbourhood (Zmyslony and Gagnon, 2000). In recognition that trees influence more than the physical environment, current urban forestry research has expanded to include the study of social, economic, and ecological benefits delivered by city trees (McPherson et al., 2011).

As a discipline, urban forestry has advanced through a growing appreciation and recognition of tree benefits to cities, and has evolved from a focus on management of tree growth into a science where the ecological benefits of trees in urban areas are recognized and integrated into environmental planning and management strategies (Millward and Sabir, 2010; Konijnendijk, 2003). Specific research is required to study urban forests because they are elements in a unique ecosystem experiencing a combination of pressures unlike other forest environments. As such, urban forests require special strategies and policies to govern their management (Miller, 1997).

Urban forests have evolved through a combination of natural regeneration (usually in parks and ravines) and by intentional planting and removal by humans. Failure of trees to regenerate naturally is common in urban parks, owing to reduced natural disturbances (e.g., gap formation, fire), and increased anthropogenic disturbances that include trampling, lawn maintenance and competition with introduced invasive species (Millward et al., 2011; Pickett et al., 2008). Outside of city parks, the urban forest generally relies only on the planting of trees by humans, which usually leads to greater plant species diversity relative to preexisting conditions; a circumstance due in large part to the planting of exotic species (Wu et al., 2008).

Urban forests are dynamic and influenced by many factors that include: (1) type and duration of land use, (2) intensity of urban development, (3) influence from surrounding natural ecosystems, and, (4) forest management practices (Dwyer et al., 2000). Regional ecosystem characteristics drive the potential growth and development of the urban forest through precipitation, temperature, soils and other biotic and abiotic components. The behavior of city inhabitants concerning trees is a major factor that influences the structure and function of the urban forest. These actions range from planting and maintenance to tree removal (Dwyer et al., 2003). On a broader level, changes in neighbourhood residents can prompt different approaches to the management of urban forests. Given the slow development of trees amid rapidly changing city neighbourhoods, effective management of a healthy urban forest is complex and challenging.

It is generally agreed upon that trees enhance the appearance of otherwise dull cityscapes (Dwyer et al., 1992). Most people, not just those with particular reasons for involvement with the urban forest, hold a positive view toward trees in cities (Lohr et al., 2004). Urban forests improve air quality, prevent stormwater runoff, mitigate warming of the urban microclimate, and enhance individual and community well-being; all of these contribute to healthier and more livable cities (Nowak et al., 2001). To maintain and enhance these services, existing city trees must be maintained and new trees must be planted. Community organizations play an important role in expanding tree cover in cities by operating planting programs designed for private residential properties (Greene et al., 2011). These programs frequently operate within the larger framework of municipal governments and non-profit organizations where tree-planting subsidies are provided to encourage participation.

Summit and Sommer (1998) found that participation in tree planting programs provides a number of social benefits, including encouraging neighbourhood interaction and empowering residents to beautify their surroundings. Studies that have investigated urban residents' motivations for tree planting have generally found that aesthetics and shade are the most important benefits they associate with trees in cities (Lohr, 2004; Lorenzo et al., 2000). The impact of trees on human comfort outdoors is mostly a result of shading (blocking direct solar radiation), and is not necessarily due to the tree lowering ambient air temperature (Heisler, 1986). Miller (1997) argues that controlling radiation transmission is the most important function a tree can perform when it comes to temperature and human comfort.

Tree placement is an essential element of urban landscape design. There are many important site conditions that must be considered when selecting a tree planting location. Some considerations include: (1) growing medium (soil quantity and quality); (2) solar exposure; (3) maintenance requirements; (4) pre-existing vegetation; (5) land-use conflicts; (6) aesthetics; (7) regulations and ownership; and, (8) social influences (Wu et al., 2008). The establishment of trees in urban centres generally follows from three strategies. The first involves prioritizing survival to ensure that the tree reaches maturity (LEAF, 2010). The other strategies concentrate on (1) planting to enhance property aesthetic (Wu et al., 2008), and (2) planting with the expressed goal of maximizing environmental services (e.g., energy conservation, urban heat island mitigation) (SMUD 2010, Rosenzweig, 2006).

2.2 The Urban Heat Island Effect

In urban areas, natural features have been largely replaced with impervious surfaces. The thermal characteristics of these impervious materials differ greatly from those found in nature, and are associated with elevated urban air temperature when compared with surrounding vegetated suburban and rural areas. This difference in temperature is a well-documented human induced climate modification known as the Urban Heat Island (UHI) effect (Oke, 1995). In temperate latitudes, urban areas have been found, on average, to be 0.5-1.5°C warmer than the surrounding countryside (Oke, 1995; Akbari, 2002). During the summer in New York City, for example, the temperature is an average of 4°C warmer than the surrounding suburban and rural areas (Rosenzweig et al., 2006).

Though it is not known what characteristics are the most important in UHI formation, because they are unique to each city, it is mainly contributed to by the following factors: (1) the specific heat capacity of urban buildings; (2) urban morphology; (3) heat release from anthropogenic sources; and, (4) a lack of evapotranspiring surfaces (Oke and Maxwell, 1975). Urban buildings are massive reservoirs for heat storage and release (Oke et al., 1989). During the day, standard building materials, including concrete, asphalt and steel, absorb solar radiation, which is transformed into kinetic energy. After sunset, when ambient air temperature decreases, stored kinetic energy is released from these built materials in the form of longwave thermal radiation (heat) (Solecki, 2005). The amount of solar energy absorbed and reradiated as heat depends on the albedo of the surface material, where albedo is a measure of the amount of radiation reflected by the surface of an object. Surfaces with low albedos, such as asphalt and concrete, reflect less and thus retain more incoming solar energy.

Urban morphology can contribute to the UHI effect because geometry and orientation of built features (streets and buildings) influence air temperatures (Shashua-Bar and Hoffman, 2003). Urban geometry affects wind speed as well as reflection and absorption of solar radiation. Buildings in urban areas can create street canyons, which lead to multiple reflections of short-wave radiation between canyon surfaces. This reduces the reflected radiant energy leaving the canyon and decreases the effective albedo, causing surfaces to absorb additional solar radiation (Oke, 1995). Anthropogenic heat sources are another driver of the magnitude of the UHI effect. Activities that include motorized transportation, manufacturing, refrigeration, and residential heating release heat into the urban environment.

Where trees and shrubs are removed from a landscape, the natural cooling effect of evapotranspiration is reduced. Lower ambient temperatures are common to more densely vegetated areas. For example, temperature differences of 5˚C were observed between city centers of Davis and Sacramento, CA and their surrounding more vegetated suburban areas (Akbari et al., 1992). Within urban areas, parks and forests can provide enough greenspace to create a cooling effect where they have a lower air and surface temperature. A study by Spronken-Smith and Oke (1999) reported 5-7˚C cooler temperatures in a forested urban park compared to the surrounding urban area in Sacramento, CA.

Tree planting is recognized as an important urban heat island mitigation strategy. A study in New York City by Rosenzweig (2006) found that planting curbside trees as an approach to heat island reduction was more effective than both green roof technology and high albedo building materials. Trees lower temperature in cities through evapotranspiration and by shading heat-absorbing surfaces such as concrete, bricks, and asphalt. Planting more trees in cities—and ensuring that they survive—will have the effect of lowering urban temperatures (Akbari and Taha, 1992). Increasing tree canopy cover effectively changes the surface type of the city; vegetated surfaces absorb energy for photosynthesis and re-radiate only a small percentage of solar energy back into the atmosphere as thermal energy, thus reducing the UHI effect (Solecki et al., 2005). Research conducted by Akbari and Konopacki (2004) in Toronto found that shade tree planting in urban residential areas had the greatest overall impact on UHI effect mitigation, accounting for over half of the total benefits of all heat island reduction strategies.

The intensity of the UHI effect is greatest on calm, clear days in the summer and fall, although it can manifest throughout the year (Rosenzweig et al., 2006). Its occurrence during the summer months is of particular concern. To achieve human comfort levels in the wake of increases to ambient air temperature, large amounts of energy for indoor air conditioning are increasingly being used in urban centers (Chen and Jim, 2008). A 1˚C increase in temperature (over 18˚C) can increase energy demand for cooling by 3-4% (Akbari, 2001). Greater air conditioning use increases greenhouse gas emissions from power plants, and effectively contributes to a positive feedback loop that is likely to exacerbate the UHI effect. Air conditioner units also increase anthropogenic localized heat sources, contributing to the elevation of urban air temperature.

2.3 Characteristics of Toronto

The city of Toronto is located on the north shore of Lake Ontario and covers an area of 630 km^2. Home to 2.6 million people in 2010 (City of Toronto, 2010a), the City of Toronto is the most densely populated region in Canada. By 2031, the current population of Greater Toronto (5.7 million) is forecasted to increase by 2.7 million, with as much as 20% of this increase expected to occur within the City of Toronto (City of Toronto, 2010b). Summer temperatures in Toronto range from 15-30˚C, with increased humidity contributing to frequent hot and muggy days during July and August (Environment Canada, 2000). Over the last century temperatures in southern Canada have warmed 0.5-1.5˚C. Over the same time period temperatures in the City of Toronto, influenced by the UHI effect, have increased an average of 3˚C (Environment Canada, 2005). The combination of a warming climate and an enhanced UHI effect are expected to exacerbate Toronto's warming trend in the future (Environment Canada, 2006).

2.4 Toronto's Urban Forest

Toronto's urban forest contains an estimated 10.2 million trees, the majority of which are growing on private property (City of Toronto, 2010b). Management of Toronto's privately owned trees occurs through the 'Private Tree By-Law', which regulates injury or removal of trees having a ≥30cm diameter at breast height (DBH; diameter at 1.4m above ground) (City of Toronto, 2004). Despite this by-law, private trees are still considered to have insufficient protection owing in part to inadequate enforcement. For example, if a construction project is approved, a municipal permit cannot be withheld due to tree removal; a circumstance that occurs frequently in new developments and associated landscaping projects (Clean Air Partnership, 2007). Toronto's tree cover is currently in decline: over only 6 years (1999-2005), forest cover decreased from 20.6 to 19.9% (City of Toronto, 2010).

An important strategy for fighting this downward trend in canopy cover is to increase tree planting. McPherson and Rowntree (1993) found that, when considering urban land use categories, tree-planting potential is greatest in residential areas. This finding is true for Toronto, where in terms of plantable space the largest land use category is single family residential (City of Toronto, 2010b). In addition to providing the greatest potential for planting opportunity, residential locations are usually more favorable from the perspective of growing conditions when compared with boulevards and sidewalks (Craul, 1992). Moreover, growing proximity to buildings gives residential trees a distinct advantage over street or park trees concerning energy saving potential (McPherson, 1995). Because of the large number of trees currently growing on private property, and the additional planting potential this land use offers, it is vitally important to engage private landowners concerning the benefits of trees. However, because of the sheer number of individual stakeholders, it has traditionally been difficult to convince residential homeowners of the benefits of planting and maintaining trees (Clean Air Partnership, 2007). Therefore, “programs to engage residents and property owners in tree stewardship and incentives to plant trees are critical if Toronto is going to sustain its tree canopy in the long term” (City of Toronto, 2010b, p.62).

2.5 Electricity Production and Use

Globally, energy production comes from six sources: petroleum (44%), natural gas (26%), coal (25%), hydroelectric (2.5%), nuclear (2.4%), and non-hydro renewable energy (0.2%) (Chow et al., 2003). Most of these conventional means of energy production are closely linked to environmental degradation and are primarily derived from non-renewable resources that can have significant and long lasting environmental impacts (UNDP, 2000). Ontario’s electricity generation was mainly hydroelectric-based until the mid-1950s when the first coal-fired and, shortly thereafter, nuclear generating facilities were constructed to meet a growing post-war energy demand (Winfield et al., 2010). At present, Ontario generates most of its electricity from nuclear (52%), followed by hydroelectric (21%), coal (18%), natural gas (8%), and wind facilities (1%) (Ministry of Energy and Infrastructure, 2008). Canadian households are currently among the highest per-capita electricity consumers in the world (Winfield et al., 2004).

Historically, demand for electricity peaked in Ontario during the winter months; however, a recent increase in demand for cooling (indoor air conditioning) has contributed to a system shift where peak demand now occurs in the summer. Specifically, Toronto has witnessed a substantial increase in electricity demand for cooling. Electricity use for the purpose of air conditioning increased by greater than 100% between 1990 and 2003, and has continued to grow to the point where 80.9% of Toronto households now have air conditioners (OPA, 2005; Statistics

Canada, 2009). Commensurate with the trend toward higher summertime air temperature has been an increase in established residences installing central air conditioning, central air becoming standard in all new residential developments, and a rising public expectation of cool indoor spaces (Ontario Power Authority, 2005). Air conditioner use places a substantial draw on the electrical grid, leading to peak loads occurring in Toronto during mid- to late afternoon in July and August. This is especially concerning for utility companies in transmission capacity constrained areas where installed capacity to deliver electricity may not be able to meet demand for electricity during peak loads.

Hot weather and high electricity demand contributed to the transnational blackout (affecting much of northeastern North America) in August 2003, which shut down many of Toronto's operations for nearly 3 days. Swift and Stewart (2004) state that electricity in Ontario had, "energized mass culture and mass experience to such an extent that it had become like air, something you only miss when it is no longer there" (p.32). By forcing Ontarians to recognize their dependence on electricity and exposing the vulnerability of Ontario's electricity system, the blackout motivated the provincial government to re-examine the stability of its electrical power grid (Bartley, 2005). Approximately two-thirds of Ontario's current electricity generation capacity will reach the end of its planned operating life by 2025 (Ontario Power Authority, 2005). Factoring in the provincial government's current commitment to phase out coal-fired generation, made in response to the growing public demand to reduce greenhouse gases and air pollution, the proportion of generation facilities that will need to be replaced or refurbished by 2025 rises to 80% (Electricity Conservation and Supply Task Force, 2004). This need for action concerning planning for Ontario's energy future has prompted major public debate across the province.

2.6 Energy Conservation

Energy conservation strategies began to emerge in the 1970's when rising energy prices, oil embargoes, and pollution awareness acted to raise public concern about dependence on fossil fuels (Silver and Worthman, 1995). Yet in Ontario, many energy saving (conservation) initiatives were dispensed with during a period of industry deregulation and government downsizing in the late 1990s (Winfield et al., 2010). Conservation initiatives are beneficial because they avoid the capital costs of new construction as well as the many associated damaging environmental impacts of increasing energy production (Winfield et al., 2004). Furthermore, there is wide evidence of the cost-effectiveness of energy conservation measures, even when compared to renewable energy programs (International Energy Agency, 2006).

Given the extent of Ontario's necessary investment in generation capacity, it is also recognized that less costly electricity conservation programs must play an essential role in the province's future infrastructure development plans (Ontario Power Authority, 2005). The Ontario government is heeding this challenge and has fashioned policies that are aimed at creating a "conservation culture" in Ontario (Green Energy Act, 2009). For example, the Ontario Green Energy Act has a mandated commitment to a continuous improvement approach to conservation with a minimum 2.5% annual (compounding) reduction in energy resource needs from 2011 until 2027 (Green Energy Act, 2009). Residential energy use will be an important target sector for the development of this conservation culture in Ontario. Ontario households use one-third of the province's electricity (Ontario Energy Board, 2005). Additionally, property owners are reported in a study by Guerin et al. (2000) to be significantly more likely to engage in energy conservation behaviour. Compared with residential tenants, property owners are more likely to invest in conservation features because of the personal benefits, and they are relatively more willing to make long-term capital investment when financial payback may not be immediate (Black et al., 1985).

2.7 How Trees Influence Electricity Use

During the warmest months (June through September in Toronto), solar radiation striking exterior walls and roofs causes a significant temperature gradient to develop between a building's interior and exterior. This gradient can result in a large amount of heat movement through the walls and windows into the interior of the building (Brown and Gillespie, 1995). Gomez-Munoz et al. (2010) used simulation models to evaluate blocked solar radiation due to tree shade on buildings and found that a large tree can provide up to 70% shade. Blocking this amount of solar radiation provides a measurable thermal load reduction in a building, which can translate into reduced demand for cooling energy. A tree cannot provide complete shade because of gaps in canopy, as well as reflection, and absorption/retransmission of solar radiation. Tree leaves typically allow some radiation to be transmitted (about 20%), while the majority is absorbed (about 50%) and reflected (about 30%) (Brown and Gillespie, 1995). However, in full leaf as much as 95% of incoming solar radiation (otherwise incident on a build surface) may be blocked by certain broadleaf deciduous species (e.g., *Acer* spp., *Tilia* spp.) that have achieved mature stature and leaf density (Huang et al., 1992).

Trees reduce demand for air-conditioning by two main methods. First, trees intercept incoming solar energy and block radiation from striking underlying surfaces. This intercepted energy is converted into chemical bonds through the biochemical process of photosynthesis (Miller, 1997). Direct shading (intercepted solar radiation) by trees also reduces longwave heat (thermal) gain by buildings and contributes to their lower overall surface temperature. In the second method, trees passively decrease ambient air temperatures through evapotranspiration (ET), a process that acts to cool air temperature by converting liquid water (on the surface of leaves) to water vapor using solar energy that would otherwise have heated the air (Huang et al., 1987). The relative importance of ET at lowering air temperature, and thus contributing to shade tree energy conservation benefits, is less certain than is the contribution from direct shading because of the complex meteorological factors associated with the former. In computer simulations, ET cooling has accounted for between one-third to two-thirds of total annual cooling savings provided by a shade tree (McPherson and Simpson, 1995). Where trees are growing in close proximity to a house, a cooler microclimate is created proximate to windows and walls, increasing the tree's cooling effect (Parker, 1983).

Trees also modify climate and conserve building energy use by lessening wind speed and by altering air flow patterns (McPherson and Rowntree, 1993). This alteration to air movement influences energy use in two ways, both related to air infiltration into the buildings. In the winter, lower wind speeds can decrease the infiltration of cold outside air into interior spaces, thus reducing heating losses. This effect is especially important in areas of a house with many windows, where conductivity is relatively high (Simpson, 1998). In the summer, lower wind speeds can reduce building penetration of hot (and sometimes pollutant laden) winds (Akbari, 2002). It is important to note that decreased wind speeds can also reduce the effectiveness of opening windows as a method for cooling buildings during the summer.

There are a number of detrimental effects worth mentioning that increased tree cover can have on energy use. Trees increase evapotranspiration, which can increase latent heating loads by adding moisture to the air (higher humidity levels) (Huang et al., 1987). Trees can also block winter insolation (incoming solar radiation), which increases demand for winter heating energy (Akbari and Konopaki, 2004).

2.8 Electricity Conservation Benefits of the Urban Forest

Urban tree canopy cover has a beneficial effect on reducing the amount of electricity used for air conditioning. For example, electricity use for indoor cooling was found to be 2.6 times greater in Alabama for buildings located in full sun compared with those (otherwise identical structures) situated in dense tree shade (Laband and Sophocleus, 2009). While highly shaded conditions are not representative of most houses in Alabama, a 'typical' house characterized by mean shade coverage of 19.3% was found to use 9.3% less electricity (6.14 kWh/day) for cooling than one with no shade (Pandit and Laband, 2010). Existing shade trees save California utility companies $500 million annually in wholesale electricity costs and generation purchases (McPherson and Simpson, 2003). The amount of electricity savings contributed by the urban forest varies with canopy cover; therefore, it varies between cities and even between neighbourhoods within a city (Rosenzweig et al., 2006).

The positive effect of shade trees on reducing demand for air conditioning in residential buildings has been shown in both controlled experiments and large model simulations. Experiments can be expensive and uncertain due to a large number of possible confounding factors. For example, variability in occupant behaviour, thermostat settings and changing weather conditions all make it difficult to isolate the effect of shade trees on air conditioning use (McPherson and Rowntree, 1993).

Despite these challenges, some studies have conducted experiments using electricity data. A study by Pandit and Laband (2010) used multivariate regression to identify specific estimates of the impact of tree shade conditions on electricity consumption in a suburban location. They controlled for a comprehensive set of factors that affect monthly electricity usage, including occupant demographics and behaviours. For every 10% increase in shade tree cover these authors found a 2.7% (1.6 kWh/day) decrease in total electricity use. In a field experiment involving two houses in Sacramento, California, Akbari et al. (1997) found that 16 trees decreased demand for cooling energy by between 26 and 47% (3.6 to 4.8 kWh/day). The study concluded that demand for cooling energy decreases by between 3-8% for every large tree. In Illinois, Carver et al. (2004) compared residential tree shading conditions for homes in two different aged neighbourhoods. They found that shade trees reduced demand for cooling energy in older neighbourhoods by 4.1% (66 kWh/year) while newer neighbourhoods saw a reduction of 15.5% (338 kWh/year). In this study, older neighbourhoods had a smaller reduction in energy demand, but they also had lower overall consumption of energy for air conditioning. In general, this finding was indicative of older neighbourhoods having a greater number of large shade trees compared with less treed newly developed residential areas (Carver et al., 2004).

A study conducted by Jensen et al. (2003) in Indiana developed a regression model to estimate household energy consumption from urban forest leaf area index (a measure of leafy overhead canopy derived from remote sensing). While the result of the regression model were determined to be insignificant, they did point toward an inverse relationship where the amount of nearby overhead canopy cover was inversely related to electricity consumption. This study did not account for the any of the complex factors that influence actual electrical use, an omission that may have contributed to the insignificant findings. Of note, the authors highlight that out of a sample of 118 households, there were no instances of high electricity usage in areas of dense overhead canopy.

Model simulation studies tend to be less expensive and are often considered more practical for analyzing the effects of tree cover on building energy use. This is because all variables can be kept constant except for changes in the quantity and quality of tree canopy (Simpson, 2002; Meier et al., 1991). Simulation-based studies tend to use software programs to estimate energy savings given different tree characteristics, building characteristics, and weather conditions. In Chicago, a simulation study of approximately three trees per building yielded annual energy savings of 7% (125 kWh/year) from reduction in demand for indoor cooling (McPherson, 1994). McPherson and Simpson (2003) found that existing trees in California reduce state-wide electricity demand for air conditioning by 2.4%, and that by planting 50 million additional trees in available positions on the west and east sides of houses would reduce this demand by a further 1.1% after 15 years.

In the southwestern United States, Huang et al. (1987) found that a 25% increase in canopy levels in Sacramento, Phoenix, and Lake Charles resulted in annual energy savings for air conditioning of 40% (603 KWh/year), 25% (1766 kWh/year) and 25% (1071 kWh/year), respectively. In Florida, shading from trees and shrubs resulted in a 30% reduction in demand for cooling energy (Parker, 1983). In addition to the direct benefits of tree shade, these modeling studies account for evapotranspiration cooling benefits and offsetting for winter heating penalties.

2.9 Strategic Planting Benefits

A number of studies go further than focusing on canopy cover alone—they consider the strategic placement of trees. This is because an increase in tree canopy strategically planted to maximize summer shading benefits can result in additional reductions in demand for cooling energy (Huang et al., 1987). Some of these studies are summarized in **Table 2.1**. When considering the optimal location to plant trees for energy conservation purposes, it is important to consider solar angles. Locating a tree on the west side of a residential building has been found to reduce demand for indoor cooling most significantly (Simpson and McPherson, 1996). A tree in a west position shades a further distance due to lengthening shadows, but is also optimal because it provides shade in the late afternoon when ambient air temperature peaks, and electricity demand peaks as people typically return from work and turn on air conditioners (Donovan and Butry, 2009). Trees growing to the east of a building tend to have the second most significant impact on reducing energy demand; their influence results from shadows cast during the morning hours, a time when demand for air conditioning is typically lower than during the mid-afternoon (Simpson and McPherson 1996; Donovan and Butry, 2009).

On the other hand, shading from a tree planted to the north of a building will never reduce demand for air conditioning (Akbari et al., 1997; Simpson and McPherson, 2003). Compared with trees growing west of a building, those planted to the south have a reduced and sometimes variable influence on electricity demand for air conditioning. Shading benefits of a tree positioned to the south of a building can be limited as shadows are shortened in the afternoon (sun is overhead) while temperature climbs. Thus, trees planted (growing) to the south of a building are only effective if they are within close proximity of the structure (Heisler, 1986).

According to McPherson et al. (2006), a tree's optimal distance from a building for shading purposes is 3-6 meters; this ensures that the tree is close enough to provide adequate shade without its root system interfering with the foundation. Placing trees as close as possible to a building's exterior wall (i.e., 3-6 m) increases the amount of time the shade influences the structure. Another consideration with a tree planted to the south of a building is that its energy conservation benefits may be marginally offset by an increased requirement for winter heating as the tree blocks desirable insolation (Akbari and Konopaki, 2004; Donovan and Butry, 2009). Blocking solar radiation in the winter is not ideal for the same reason that direct solar exposure is detrimental in the summer: sun striking a building acts to warm interior spaces (McPherson et al., 2007). To maximize the energy conservation benefits of residential trees, the best practice in climates with cold winters and warm/hot summers is to plant broadleaf deciduous species that block solar radiation in the summer but not the winter. It is important to note that the trunks and bare branches of trees still shade a building. In fact, some deciduous species that shade south and east facing walls during the winter have been found to block 40 percent of winter insolation (McPherson, 1984). If a home has a roof-mounted solar photovoltaic array, then shading the south wall of a building is generally not recommended, even at the expense of letting the temperature inside the house increase (Moffat and Shiler, 1981; Hofierka and Kanuk, 2009).

The potential for energy conservation resulting from residential shade tree planting can vary considerably between cities, and accurate estimates of benefits require location-specific parameters (Simpson and McPherson, 1996; Arboit et al., 2008). The potential energy cost (penalty) of planting trees in non-west orientations with respect to a building is greatest in geographic locations with cold winters, where blocking insolation during months with low sun angles (December though March) may create a demand for additional heating energy. Thus, strategic planting is important in cities such as Toronto, because tree location could mean the difference between significant or negligible energy savings; in some cases, it could even mean increased demand for energy.

Table 2.1: Summary of results for studies that analyzed the energy conservation benefits of strategic tree placement in terms of growing with respect to a residential building.

Authors	Study Area	Configuration*/age or size	Energy Savings (kWh/year)	Percent annual cooling energy use	Account for heating?
Donovan and Butry 2009	Sacramento	3 West and 3 South/ varying sizes	185	5.2%**	No
Akbari and Konopacki 2004	Toronto	4 West and South/ 4.6m canopy height	Pre-1980 construction 201	10%	Yes
			1980+ construction 147	10%	
McPherson and Simpson 2003	Centre Valley, (California)	West/ 4.6m crown diameter	139		Yes
		East/ 4.6m crown diameter	82		
		South/ 4.6m crown diameter	60		
Akbari et al. 1997	Sacramento	16 West and south walls/ 8 tall (6m), 8 short (2.4m)	396	29%	No
		16 Southeast wall and corner and southwest corner/ 8 tall (6m), 8 short (2.4m)	369	29%	

Simpson and McPherson 1996	California	2 west, 1 east/ 15 years	Cool climates 340	40%	Yes
			Warm climates 540	20%	
		West/ 15 years	Sacramento 180	12%	
Clark and Berry 1995	Phoenix	3 trees by sun struck walls/ unknown	384		No
McPherson 1993	Washington DC	West/ 10 years (19ft tall)	90		Yes
		West/ 15 years (24ft tall)	150		
	Boston	West/ 10 years (19ft tall)	30		
		West/ 15 years (24ft tall)	50		

* Values are for a single tree unless otherwise noted.
** Percent of summertime electricity use (not just cooling energy use).

Chapter 3

This chapter reviews the adaptations made to the Sacramento Municipa1 Utility District (SMUD) Tree Benefits Estimator for application in Toronto, Canada and provides a detailed discussion of the process used to collect and analyze Local Enhancement and Appreciation of Forests (LEAF) tree data. It begins with an overview of the two tree planting programs (LEAF and SMUD). A description of the original simulations that provided baseline data for the SMUD Tree Benefits Estimator is reviewed so as to provide context for location-specific model adaptations. An extended methodology section consists of descriptions of climate variables and urban tree growth curves used to adapt the SMUD model for use in Toronto.

3.1 Local Enhancement and Appreciation of Forests (LEAF) and Sacramento Municipal Utility District (SMUD) Tree Planting Programs

In Toronto, voluntary participation in privately managed tree planting programs is one important approach to afforestation of residential property (Greene et al., 2011). Since 1996, the not-for-profit organization, Local Enhancement and Appreciation of Forests (LEAF), has operated a residential tree-planting program in the City of Toronto (LEAF, 2010). During this time, LEAF has provided over 6,453 native trees to residents concentrated in and around the urban core of Toronto, but also extending to Etobicoke, Scarborough, and York (Greene et al., 2011). Clients of this residential planting program are proactive; to participate, they must contact LEAF directly and request to participate. LEAF's program prioritizes planting the 'right tree in the right place' in a participant's yard (a decision based on selection of a native species, tree adaptability to site conditions, and freedom from conflict with other land uses). When siting a tree, LEAF's staff considers shading conditions, hard surface landscaping, and soil characteristics;

strategic planting for energy conservation has never been actively pursued. The planting process involves an initial consultation with a certified arborist. If there is a mutually agreeable species and an appropriate growing space in the backyard, the homeowner pays a subsidized price for the tree and a LEAF employee returns to the property during spring or fall to carry out the planting (LEAF, 2010).

In 1990, the Sacramento Municipal Utility District (SMUD) and the not-for-profit, Sacramento Tree Foundation (STF), initiated a municipal tree planting program with the goal of planting 500,000 shade trees by the year 2000 (Hildebrandt and Sarkovich, 1998). Early on (until 1995), this program was focused on quantity, planting as many trees as possible. Following 1995, the program changed its strategic plan to emphasize planting of trees in locations that maximize their direct shading benefits, the goal being the reduction of demand for summer cooling energy. This shift in focus stemmed from analysis of the program's performance over the first few years (i.e., its ability to attenuate energy demand for indoor cooling). Specifically, analyses of early program data revealed that trees planted to the west of a residential building provided almost three times more energy conservation benefits when compared to the average benefits of any other planting orientation with respect to a residence (Simpson and McPherson, 1998). As of 2009, this California-based program has provided a total of over 450,000 trees to over 150,000 participants (Sarkovich, 2009). Participants are SMUD customers who express interest in the program. A community forester associated with the STF conducts a site visit and consultation with the participant in order to recommend an appropriate number of trees and suitable planting locations (those that prioritize energy conservation potential). Following this consultation, the program participant is given one or more free tree(s) in containers, and is responsible for planting and maintenance (Sarkovich, 2009).

3.2 Simulation and the SMUD Tree Benefits Estimator Model

Because natural systems can be complex, they are frequently inadequately understood due to resource limitations (i.e., money, time or knowledge) (Mihram, 1972). A model is a substitute for a real system, a simplification of reality (Ford, 2009). When direct experimentation is problematic or impossible, simulation methods provide an option for examining the function and sensitivity of a system. Simulations often involve developing a model, or set of models, that describe a complex system using mathematical relationships that define interconnections and feedback (McCarty, 2002). Typically, simulation modeling represents an attempt by the researcher to capture the most important system-based relationships.

Trees live for long periods of time, and they can take many years to reach maturity. Therefore, it can take a lifetime (or more) of commitment to study a tree through its entire lifecycle. Beyond these temporal constraints, the interaction of vegetation with the physical environment is complex and difficult to quantify; direct observation is often an impractical approach (McCarty, 2002). As a consequence, simulation modeling is widely used in urban forestry. For example, the USDA Forest Service has developed the i-Tree suite of software, which uses numerical models to calculate annual benefits provided by urban trees (Maco and McPherson, 2003). i-Tree models quantify urban forest structure and estimate the following ecological services delivered by city trees: carbon offset and sequestration, pollution removal, storm water runoff mitigation, aesthetic value, and energy conservation. Nowak et al. (2008) indicate that i-Tree has been used in over 50 cities across the globe to better understand their urban forest resources. In its current form, i-Tree is an aspatial model and is, therefore, incapable of distinguishing between energy conservation benefits delivered by shade trees planted at varying distances and orientations to residential buildings.

The SMUD Tree Benefits Estimator was developed to quantify and track the electricity conservation benefits of strategically planting shade trees. Development of SMUD's estimator used data collected during its years of running a shade tree planting program. Specifically, the electricity demand values used to estimate energy conservation were derived from computer simulations completed by Simpson and McPherson (1998) on a random sample of 254 residential properties that participated in the SMUD Shade tree program between 1991-1993. Tree planting locations and building characteristics were obtained using survey forms completed by program participants at the time of tree delivery and during site visits performed by SMUD staff. Estimation of demand for cooling energy, with and without tree shading, was determined using two computer programs. The USDA Forests Service's Shadow Pattern Simulator (SPS) provided data describing solar gain reduction resulting from tree shade (Simpson and McPherson 1998). It was used by Simpson and McPherson (1998) to quantify the percentage of tree shade cast on each building wall and roof at hourly intervals for each month during an average year. The SPS shading estimations were then used with Micropas (version 4.01) energy simulation software (Enercomp, 1992) along with specific building thermal characteristics and hourly weather data. Output from Micropas provided estimates of hourly demand for cooling energy (kWh) as well as instantaneous electricity demand (kW). SMUD also used Micropas to run a simulation that estimated a heating penalty value (kWh) resulting from tree placement (growing location) that blocked insolation during the winter months (Simpson and McPherson 1998). This penalty was implemented in their Tree Benefits Estimator for a resident reporting reliance on electricity for winter heating.

Using findings from these simulations, SMUD developed a matrix that contains estimated energy conservation benefits delivered by full-sized shade trees growing in three distance classes from a residence and at eight cardinal orientations with respect to the building.

To accommodate trees of smaller stature, energy conservation benefits of full-sized trees are discounted based on estimates of canopy volume at different tree ages. The age of the tree (from planting date) or the tree DBH can be used to determine a growth interval, which will, in turn, determine the level of energy conservation benefits for a given year. For application in climate regions outside of Sacramento, California, the SMUD's Tree Benefits Estimator uses Cooling and Heating Degree Days, as well as Latent Enthalpy Hours to model the impact of ambient air temperature and relative humidity on the summer cooling load and winter heating requirements (Sarkovich, M., personal communication). The following information about a tree is required to use the SMUD Tree Benefits Estimator: (1) species; (2) age of tree from planting date; (3) orientation with respect to the building; and, (4) distance from the building.

3.3 Extended Methods

3.3.1 Climate Variable Calculations: Cooling Degree Days and Latent Enthalpy Hours

Cooling Degree Days (CDD) is a metric used to quantify the severity and duration of hot weather (Sailor and Pavlova 2003). CDD is particularly useful for characterizing the potential impact of regional climate differences on energy demand for air conditioning (Sailor, 1998). A positive CDD value indicates the likelihood of electricity demand to cool indoor spaces. A daily CDD value is calculated based on mean temperature, which is estimated by taking the average of the minimum and maximum temperature over a 24-hour period. If the daily mean temperature is below the base temperature (typically 18°C), then the daily CDD value is set to zero. Where above the baseline measure, subtracting the base temperature from the daily mean temperature results in the daily CDD (Hor et al., 2005). An annual CDD value is calculated based on the following summation of daily CDD values for a year:

$$CDD = \sum_{i=1}^{i=365} (T_{mean} - T_{base})(\alpha) \tag{1}$$

where T_{base} represents the baseline temperature, T_{mean} represents the daily mean temperature, and α is 1 if the CDD value is greater than 0, and 0 if the CDD value is equal to or less than 0 (Sailor, 1998). In this research an annual CDD value for Toronto of 358 was used, which was obtained from Environment Canada climate normals (1971 to 2000) (Environment Canada 2000).

The presence of shade trees in an urban area increases evapotranspiration, which lowers ambient air temperature and at the same time elevates atmospheric humidity. The evapotranspirative cooling benefits of trees are less significant in more humid climates. At decreased temperatures people are more likely to continue to use an air conditioner when there is high relative humidity. Even at relatively low ambient air temperatures, high relative humidity values impair the human body's ability to evaporate perspiration (a natural cooling process), which leads to thermal discomfort. Therefore, the potential influence that a shade tree can have on mitigating energy demand for cooling will depend on the underlying relative humidity, which can be measured as Latent Enthalpy Hours (LEH). Hor et al. (2005) describe a positive correlation between Latent Enthalpy Days (LEH divided by 24) and electricity demand. Increasing the water content in the air leads to latent heat gains. This hidden heat, called latent enthalpy (a measure of energy), has to be supplied or removed to change the relative humidity of air. LEH is a measure of the amount of energy that must be removed from the air to lower it to 25°C and 60% relative humidity (Andersson, 1986). This means that in cities with humid climates (or with seasonal humidity), shade tree caused reductions in CDD will result in less offset of demand for air conditioning compared with less humid climates (Sailor, 1998). LEH is calculated in this research by summing enthalpy differences between the actual and target enthalpy values for every hour over the course of a year:

$$LEH = \sum_{i=1}^{i=365} \sum_{j=1}^{j=24} (E - E_0)(\alpha) \tag{2}$$

where E is the actual enthalpy and E_o is the enthalpy at 25°C and 60% relative humidity (Andersson, 1986). In this calculation, α is 1 if the LEH value is greater than 0, and 0 if the LEH value is equal to or less than 0. The LEH for Toronto, used in this research, is 1600 and was calculated using a decade (2000-2009) of Environment Canada hourly temperature and humidity data (Environment Canada, 2000).

3.3.2 Climate Variable Factors

Because the SMUD Tree Benefits Estimator used parameters specific to Sacramento, adapting the model for use in Toronto required consideration of the climatic differences between the two cities. Two steps were required to calculate the climate-adjusted energy savings for the Toronto-specific model: (1) incorporate the CDD value for Toronto to adjust the number of days that require cooling energy; and, (2) integrate the evapotranspiration benefits for shade trees based on Toronto's LEH. Minimizing demand for cooling energy based on tree shade is modeled as a function of CDD. In this project, a CDD-factor is developed, which is the proportion of Toronto CDD relative to Sacramento CDD:

$$\text{CDD-factor} = \text{CDD}_{\text{Toronto}} / \text{CDD}_{\text{Sacramento}} \tag{3}$$

Toronto's CDD value of 358 yielded a corresponding CDD-factor value of 0.56.

The evapotranspiration benefits of shade trees are modeled in this study using a LEH-factor. A simple linear equation that can predict LEH-factor values (dependent variable) from LEH values (independent variable) was developed based on known LEH and associated LEH-factor values for major US cities (generated by SMUD; M. Sarkovich, personal communication). The LEH value for Toronto was input into the model to determine the associated LEH-factor:

$$\text{LEH-factor} = -0.0069*\text{LEH}+42.265 \quad R^2= 0.96; p<0.01 \qquad (4)$$

Toronto's LEH value of 1600 yielded a corresponding LEH-factor value of 0.31.

3.3.3 Adapting the SMUD Tree Benefits Estimator for Toronto's Climate

SMUD provided this study with a matrix of data describing electricity conservation estimates (in kWh) for full size trees growing in eight orientations (north, northeast, east, southeast, south, southwest, west, and north west) relative to a residential property, and in three distance categories (0-4.6m, 4.7-9.1m, and 9.2-13.7m), for a total of 24 estimates. The steps used in this research to modify SMUD energy conservation benefits based on Toronto's climate are outlined in **Figure 3.1**.

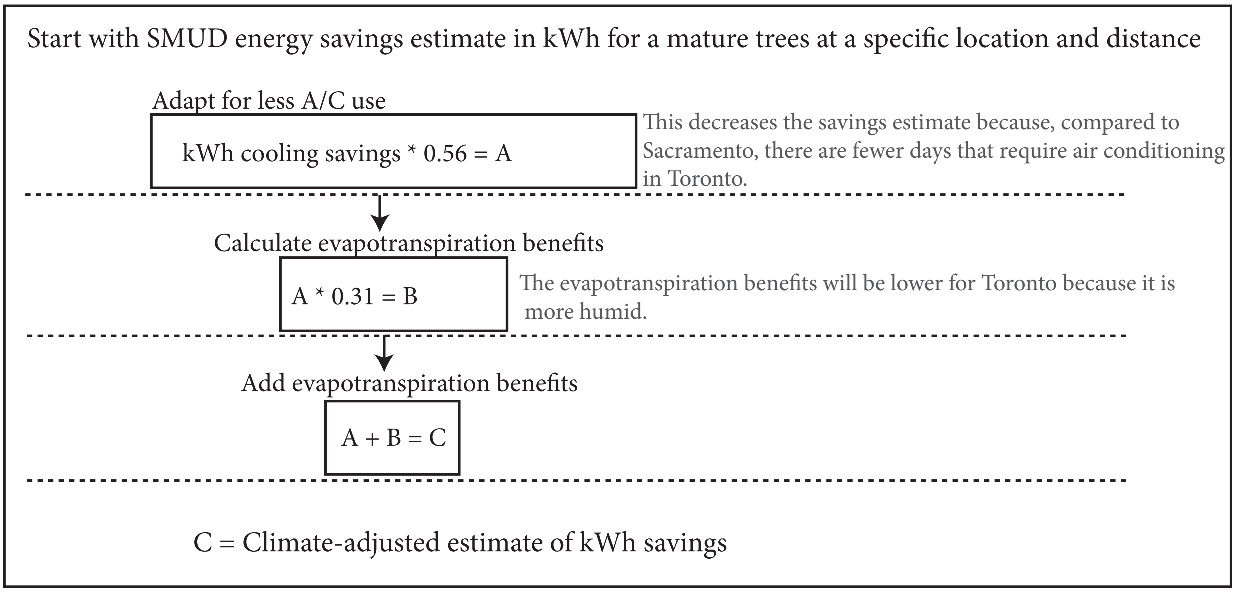

Figure 3.1: Methodology for adapting the SMUD model for use in Toronto's climate.

3.3.4 Adapting the SMUD Model for Urban Tree Growth in Northeastern North America

Tree growth rates are highly variable because they depend on species, climate, soils, and planting locations. Trees growing in urban ecosystems are exposed to higher temperatures, more pollutants, poor soil conditions, and restricted growing space compared to those growing in rural areas (Craul, 1992). These differences in growing conditions contribute to a significant variation in the growth rate of urban trees as compared with those found in a natural forest (Gregg et al., 2003). Because of this, growth curves developed for trees in Ontario forests are not appropriate for use in Toronto. To date, there has never been a study that has quantified the growth characteristics of urban trees in Toronto. As the closest appropriate proxy, specific growth curves for urban trees in the northeast US were used in this study. These growth curves were developed from a stratified sample of 21 species (910 trees total) growing in the Borough of Queens, New York City, New York (McPherson et al., 2007). In this project, growth curves were used to estimate the approximate size of a tree, given its known age from time of planting. Trees provide maximum shade when they are mature and their crown volume is greatest (Simpson and McPherson 1996). As younger trees grow, they provide energy conservation benefits roughly proportionate to their change in overall leaf area.

Given that the energy conservation benefits of shade trees were simulated for full size trees by SMUD, an adjustment was needed to discount benefits for trees that have a lesser stature (smaller canopy volume). In this project, SMUD's data describing tree size (according to species), and the corresponding proportion of total energy conservation benefits, were used to develop a linear regression model to predict the proportional benefits (dependent variable) at any DBH measurement (independent variable). The growth curves from New York City trees were used to determine the approximate size of the LEAF trees, given knowledge of species and planting year. Tree DBH (proxy for canopy size) was then estimated for every year of a tree's existence (up to 75), and entered into the regression model to predict the tree's energy conservation potential at each year of its life. These values were then multiplied by the climate-adjusted estimates for Toronto of conserved energy (kWh) for trees at all ages, and growing in each of the 24 potential locations.

3.3.5 Tree Planting Program Data Collection

This study used data describing the oldest and largest trees planted as part of LEAF's residential tree planting program, those planted between 1997 and 2000. Many of these trees now reach heights of 12m or greater. Data were collected for seven broadleaf deciduous and one coniferous tree species; all tree species are native to the geographic region. The species studied were Bur Oak (*Quercus macrocarpa)*, Hackberry (*Celtis occidentalis*), Kentucky Coffee Tree

(*Gymnocladus dioicus*), Red Maple (*Acer rubrum*), Red Oak (*Quercus rubra*), Sugar Maple (*Acer sacchrum*), Tulip Tree (*Liriodendron tulipifera*), and White Pine (*Pinus strobus*).

LEAF collected data at the time of planting for each tree delivered as part of its residential tree-planting program. These data were analyzed in conjunction with 2007 City of Toronto colour leaf-off aerial images, Google Earth 2009 images, and City of Toronto GIS building and property boundary files to determine whether the tree was still present on the property (Figure 3.2). Where it was found alive, its exact position was mapped and the following data were collected: (1) species; (2) age of tree from planting date; (3) orientation with respect to building(s); (4) distance from the building(s); and, (5) crown width.

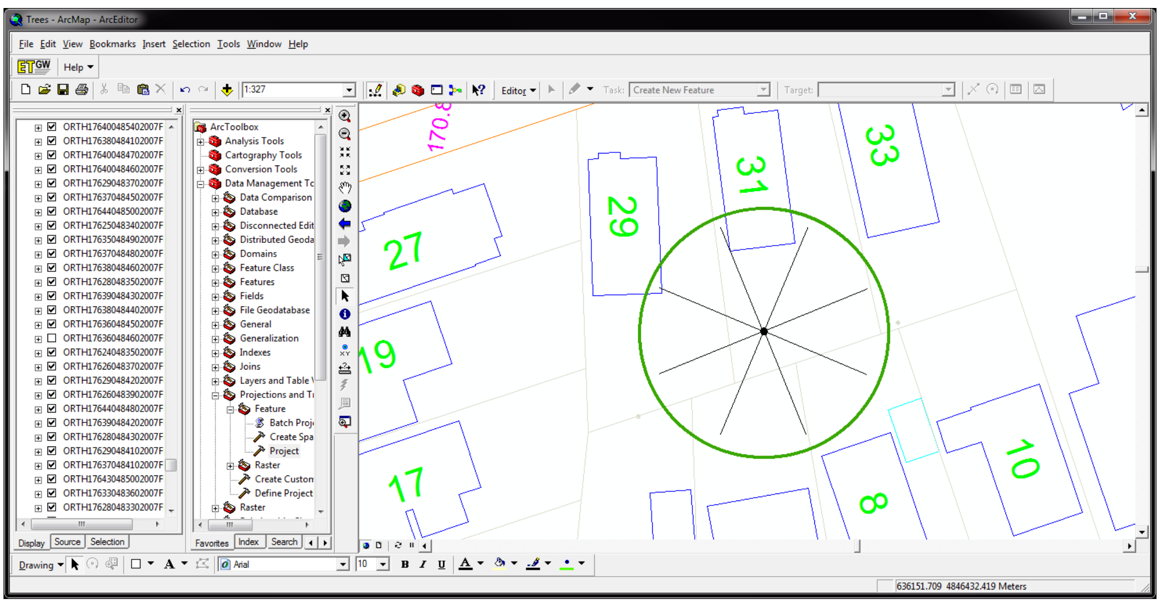

Figure 3.2: Screenshot of data collection procedure showing City of Toronto building and property boundary files. Black dot represents a LEAF tree, green circle represents 13.7m distance from tree.

The distance from a tree to a building was defined as spanning the distance from the tree base (centre of mainstem) to the nearest edge of the building. Orientation and distance data were only collected if the tree was located close enough to a building to provide some direct shade. Hildebrandt and Sarkovich (1998) suggest that beyond 15.2m a tree is considered too distant to directly shade buildings, while McPherson and Rowntree (1993) define potential energy-conserving growing space as a single-family residence with tree planting space no further than 12.2m from the building. Simpson and McPherson (1997) and the SMUD tree-siting guidelines both state that a distance of 10.7m or less is optimal for direct shading benefits. Both the SMUD Tree Benefits Estimator and the Toronto-specific model created for this research project consider trees planted up to 13.7m (45ft) away from a building to provide some shade. Trees farthest from a building (distance class: 9.2-13.7m) have the least energy conservation benefit. All LEAF trees were categorized into one of the eight azimuth classes of north, northeast, east, southeast, south, southwest, west, northwest, and one of three tree-building distance classes of 0-4.6m (0-15ft), 4.7-9.1m (16-30ft), and 9.2-13.7m (31-45ft) (Figure 3.3).

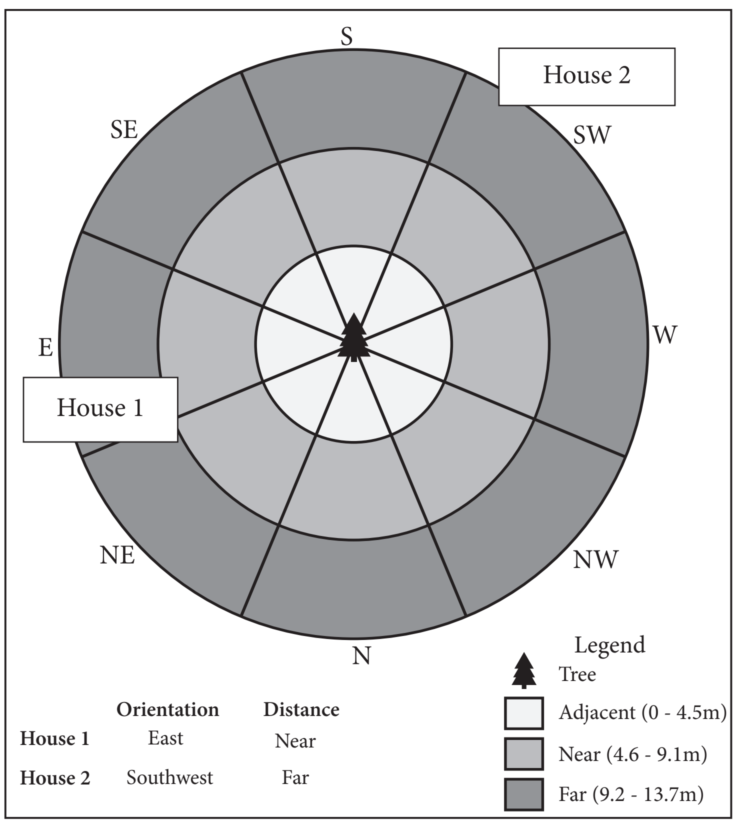

Figure 3.3: Classification guidelines for a tree's distance and orientation with respect to two houses (rectangle represents building footprint). Positions of cardinal directions are reversed because the classification is used to categorize the orientation of the tree with respect to the houses.

If a tree was within 13.7m of at least one house, its characteristics were entered into the Toronto-specific model to estimate its annual energy conservation benefits given its current age. In this project, the total energy conservation benefits of a tree are the sum of all benefits received by houses influenced by that tree.

3.3.6 Mature Tree Estimates

Using growth curves to determine the size of a tree at a given age permitted the prediction of the energy conservation benefits in the future. Such a future prediction required accounting for the potential mortality rate of trees. The average lifespan of an urban residential tree is three times as long as a sidewalk tree, but only half as long as a tree growing in a forest environment (Moll, 1989). Urban residential tree mortality rates have not been studied systematically. McPherson (1993) states that, based on interviews with landscape contractors, 15-30% of trees die during the first 5 years following planting, with 0.2-2% dying each year thereafter. A study by Nowak et al. (2004) confirmed that there is a significantly higher survival rate for larger trees. For a study of residential trees growing in Modesto, California, McPherson et al. (1999) used an annual mortality rate of 1.4%. A study conducted in Fresno, California used a mortality rate of 21% after 30 years, while in Sacramento a study used estimated mortality rates for the SMUD program of 30%, 36%, and 42% after 30 years (McPherson, 1993; Hildebrandt and Sarkovich, 1998). Due to the uncertainty associated with forecasting a mortality, this study determined the energy conservation benefits of residential trees by applying three separate rates of annual decline: (1) high - 1.5%; (2) moderate – 1.1%; and, (3) low - 0.7%.

Chapter 4

Growing energy conservation through residential tree planting

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First Author (**SAWKA**)
- conceived of and designed study
- performed research
- processed data for model adaptation
- analyzed data
- wrote paper

Co-Author (**MILLWARD**)
- contributed to design of study
- assisted with analyses
- assisted with data collection
- processed data for model adaptation
- provided editorial support

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4.1 Abstract

Energy conservation strategies are now at the forefront of electrical utility demand management planning. Residential shade trees extenuate the heating of buildings in the summertime by intercepting insolation and by evapotranspirative cooling of their immediate surroundings. By modifying location-specific climate data, and tree growth characteristics, we adapt the Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator for application in Toronto, Canada. We then use our tool to model the energy conservation savings delivered by 577 trees planted in Toronto backyards between 1997 and 2000. In urban residential neighbourhoods, where houses are closely spaced, the energy conservation benefits of planting a tree depend on species, pre-existing canopy, and on placement of the tree with respect to distance and orientation from buildings. Our study trees contributed 77,139 kWh of electricity savings as of 2009, 54.4% of which was due to shading of neighbouring houses. These findings indicate that urban residential tree planting programs should not focus exclusively on location-driven strategic planting to yield large energy conservation benefits. Instead, we argue that priority should be given to selecting planting locations that will maximize tree survival as neighbourhood energy conservation benefits of a tree that achieves mature stature often outweigh the homeowner-specific benefit of a strategically planted tree.

4.2 Introduction

Concern for climate change and energy conservation have led many urban municipalities to seek approaches to land use planning that integrate ecological sustainability by encouraging the preservation and creation of resilient natural systems within their cities (Grimm et al., 2008; Dwyer et al. 2003). These efforts emerge in contrast to a traditional North American perception of the urban environment as distinct from nature (Hough, 1989). Embracing nature in pursuit of energy conservation has the potential to both decrease electricity demand for air conditioning and expand the myriad of benefits urban vegetation provides (Nowak et al., 2008; McPherson, 2007).

Urban shade trees moderate temperature in their proximate environment and can assist with demand side management of electricity for indoor cooling (Donovan and Butry, 2009; Akbari, 1997; Heisler, 1986). Direct shading of buildings by trees inhibits incident solar radiation on roofs, walls and windows, thus reducing the amount of radiant energy absorbed, stored and reradiated as heat (Pandit and Laband, 2010; Chen and Jim, 2008). Beyond shade, trees influence temperatures and human comfort through two other processes. The first is by increasing evapotranspiration, which cools the air temperature by using solar energy to convert liquid water into vapour (Huang et al., 1987). Second, trees modify urban microclimates by altering airflow, thus affecting the diffusion and transport of thermal energy and water vapour (McPherson and Rowntree, 1993).

The effect of tree shade on cooling loads in residential buildings depends on factors that include meteorological conditions (primarily temperature and relative humidity), quality and quantity of shading, building construction, and occupant behaviour (Simpson and McPherson, 1996). The quality and quantity of shading is generally driven by tree species and foliar condition and includes canopy volume, crown shape, foliation period, leaf area, and tree location (i.e., distance from and orientation with respect to a building) (Simpson and McPherson, 1996; Clark and Berry, 1995). A tree can be planted strategically for the purpose of maximizing energy conservation benefits by considering the variables that influence the shading potential. Planting a large growing tree in a specific hierarchy of orientations will maximize the offset of summertime electricity demand (McPherson et al., 2006; Donovan and Butry, 2009).

Locating a tree on the west side of a residential building has been found to reduce demand for indoor cooling most significantly (Simpson and McPherson, 1996). A tree in a west position shades a further distance due to lengthening shadows, but is also optimal because it provides shade in the late afternoon when ambient air temperature is at a maximum, and electricity demand peaks as people typically return from work and turn on air conditioners (Donovan and Butry, 2009). Trees growing to the east of a building tend to have the second most significant impact on reducing energy demand; their influence results from shadows cast during the morning hours, a time when demand for air conditioning is typically lower than during the mid-afternoon (Simpson and McPherson 1996; Donovan and Butry, 2009). Compared with trees growing to the west and east of a building, those planted to the south have a reduced (and sometimes variable) influence on electricity demand for air conditioning. Shading benefits of a tree positioned to the south of a building can be limited because, while temperature climbs in the afternoon, shadows are shortened due to the sun's location overhead. Thus, trees planted (growing) to the south of a building are only effective if they are within close proximity of the structure (Heisler, 1986). Finally, trees planted to the north of a building do not significantly reduce demand for air conditioning (Akbari et al., 1997; Simpson and McPherson, 2003).

The effect of increased canopy cover on reducing demand for air conditioning in residential buildings has been shown in both controlled experiments and large model simulations. Using actual ratepayer data, a study by Pandit and Laband (2010a) produced specific estimates of the impact of tree shade conditions on electricity consumption in a suburban neighbourhood of Auburn, Alabama. These authors found that for every 10% increase in shade coverage, electricity demand for air conditioning decreased by 2.7% (1.3 kWh/day). Using a simulation approach with residential shade trees in Chicago, McPherson (1994) determined that three trees growing proximate to a building would minimize electricity use for indoor cooling by 7% annually (125 kWh). In a field experiment in Sacramento, California, Akbari et al. (1997) found that 16 trees growing on residential property decreased demand for cooling energy by between 26 and 47% (3.6 to 4.8 kWh/day). This study concluded that cooling energy use decreases by between 3-8% per addition of a large tree.

Comparing the energy conservation potential of residential shade trees in eleven California climate zones, Simpson and McPherson (1996) determined that for one 15 year old tree the most significant benefits (180 kWh/year or 12% of cooling energy) always occurred when the tree was growing to the west of a building. Donovan and Butry (2009) completed the first large-scale statistical regression study that used utility billing data to show that trees can reduce electric energy consumption. Their study found that, on average, trees oriented to the east, south or west of a residence reduced summertime electricity demand by 185 kWh annually (5.2% of cooling energy). Working in Toronto, Canada, Akbari and Konopacki (2004) found that four shade trees located 0.6 m from south and west walls of residential buildings reduced annual energy use by between 147 and 201 kWh, depending on the building vintage (greater conservation benefit with older buildings).

Historically, demand for electricity peaked in eastern North America during the winter months; however, a recent increase in demand for cooling (indoor air conditioning) has contributed to a system shift where peak demand now occurs in the summer. In Toronto, a city where the average annual air temperature has increased by 3°C over the last century (Environment Canada, 2006; Akbari and Konopacki, 2004), indoor climate control is becoming increasingly popular. Akbari et al. (2001) report that demand for air conditioning increases by about 3–4% for every 1°C increase in temperature above 18°C. Power consumption for residential air conditioning increased by greater than 100% in Toronto between 1990 and 2003, and recent data indicate that as many as 81% of households now have air conditioners (Ontario Power Authority, 2005; Statistics Canada, 2009). Air conditioner use places a substantial draw on the electrical grid, especially in transmission capacity constrained areas where installed capacity to deliver electricity may not be able to meet demand for electricity during the peak loads (which occur during mid- to late afternoon in July and August). Current levels of air conditioning use in cities like Toronto highlight the importance of residential shade trees as a viable demand-side management tool to assist with electricity conservation in urban areas (Hildebrant and Sarkovich, 1995).

A recent study by the City of Toronto estimated that its urban trees reduced residential energy costs for air conditioning by $9.7 million annually, based on 2008 electricity prices (City of Toronto, 2010). Recommendations stemming from this study indicate that this conservation benefit could be increased through more strategic planting that would maximize the shading effects of trees. The potential of new tree plantings to conserve energy depends on the amount of plantable space in a city. McPherson and Rowntree (1993) indicate that residential areas have the greatest tree planting potential in many American cities. This finding is paralleled in Toronto, where single family residential represents the largest land use category in terms of identifiable plantable space (City of Toronto, 2010). Growing proximity to buildings gives residential trees a distinct advantage over street or park trees concerning energy saving potential (McPherson, 1995).

In Toronto, voluntary participation in privately managed tree planting programs is one important approach to afforestation of residential property (Greene et al., 2011). Tree planting programs such as those offered by Local Enhancement and Appreciation of Forest (LEAF) plant trees on private residential property and prioritize tree survival; they have not typically planted trees in strategic locations that could maximize energy conservation. In urban residential neighbourhoods, where houses are closely spaced, the energy conservation benefits of one household planting a tree are likely to also be shared by neighbouring houses. Hildebrandt and Sarkovich (1998) considered both the participant and adjacent properties when analyzing the influence of the Sacramento Municipal Utility District residential tree-planting program on energy use. In their study, they determine that the shading of adjacent buildings contributes an additional electricity load reduction of 15%.

Another important consideration when evaluating the potential energy conservation benefits of a newly planted urban tree is the amount of existing canopy cover. In Southern Illinois, Carver et al. (2004) compared residential tree shading conditions for homes in two different aged neighbourhoods. They found that shade trees reduced demand for cooling energy in older neighbourhoods by 4.1% (66 kWh/year) while newer neighbourhoods saw a reduction of 15.5% (338 kWh/year). In this study, older neighbourhoods had a smaller reduction in energy demand, but they also had lower overall consumption of energy for air conditioning. This finding was indicative of older neighbourhoods having a greater number of large shade trees compared with less treed newly developed residential areas (Carver et al., 2004). Given that newer houses are generally constructed with more energy efficient materials (Simpson and McPherson, 1998), the results of Carver et al. (2004) highlight the importance of understanding the energy conservation benefits of adding an additional shade tree to a property with pre-existing canopy cover.

Studies typically skip forward in time and estimate the benefits of the trees once they reach maturity (usually at least 25 years post-planting), for example Donovan and Butry (2009) or Rosenfeld et al. (1998). While younger trees shade less building surface area than older trees, they still provide energy conservation benefits that increase in approximate proportion to their leaf area (Simpson and McPherson, 1996). Planners currently lack meaningful information on the benefits of trees in the short to medium term of 5 to 25 years following planting. Yet knowledge of expected near-term benefits could be important to a resident considering investing in a tree for their property or to an electrical utility considering shade tree planting as a viable strategy for demand-side electricity conservation.

The purpose of this research is to quantify the impact of a residential tree-planting program on demand-side conservation of electricity in urban residential neighbourhoods. Specifically, we were interested in understanding the impact on demand for air conditioning when tree survival is the first priority in identifying a planting location, and not strategic placement for shading. By modifying location-specific climate data and tree growth characteristics, we adapt the Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator for application in Toronto, Canada. We then use our tool to model the energy conservation savings delivered by 577 trees planted in urban Toronto backyards between 1997 and 2000. This study considers the augmented benefits of trees shading neighbouring houses, and also develops a method for discounting the shading benefits of a new tree in presence of existing tree canopy. Current year and cumulative energy conservation estimates are presented, as well as estimates of medium- and long-term benefits (25 and 40 years after planting).

4.3 Methods

4.3.1 Study Area

The City of Toronto is located on the north shore of Lake Ontario and covers an area of 630 km^2 (**Figure 4.1**). Home to 2.6 million people in 2010 (City of Toronto 2010a), Toronto is the most densely populated region in Canada. By 2031, the current population of Greater Toronto (5.7 million) is expected to increase by 2.7 million, with as much as 20% of this increase expected to occur within the City of Toronto (City of Toronto, 2010b). At present, tree cover is estimated to cover 20% of Toronto's land area (City of Toronto, 2010). Approximately 45% of Toronto's dwellings are classified as single-family residential (Statistics Canada, 2009), and 60% of the city's trees are growing on privately owned property (City of Toronto, 2010b).

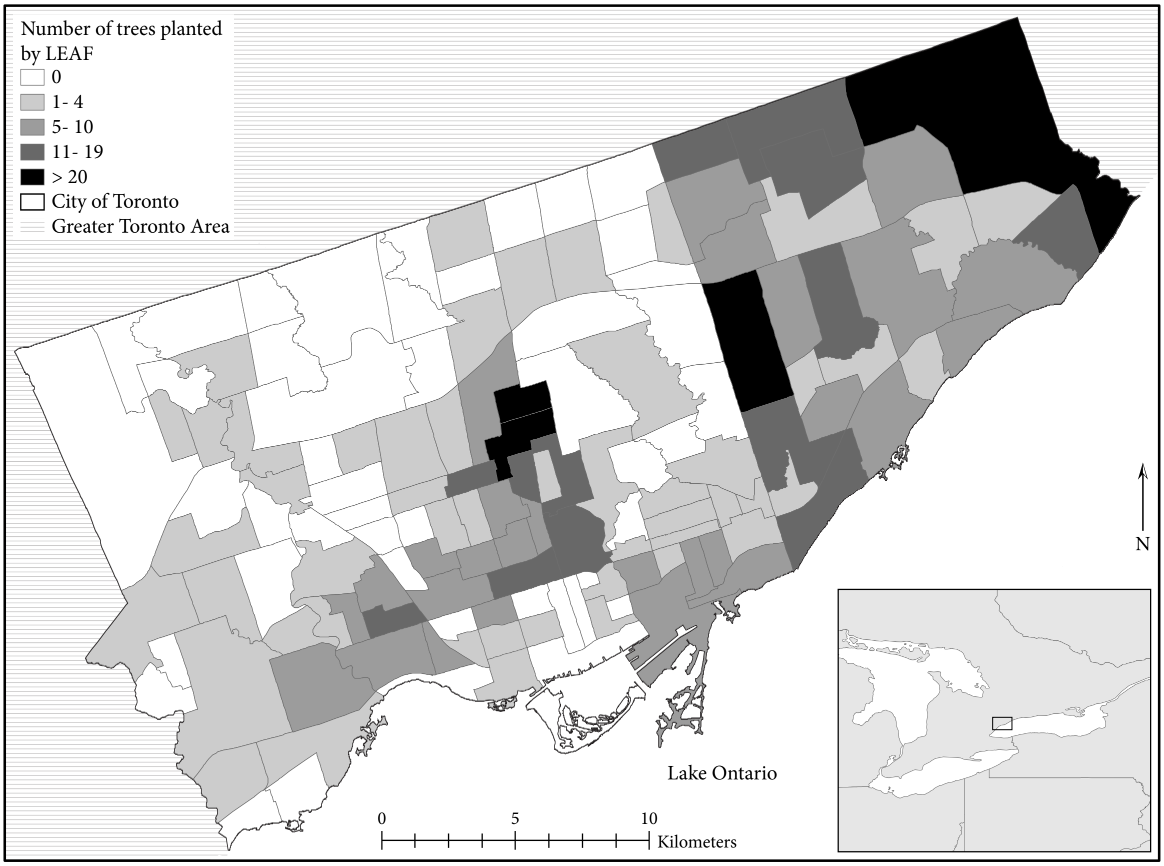

Figure 4.1: Location of Toronto and distribution of 577 trees planted by Local Enhancement and Appreciation of Forests between 1997 and 2000 in City of Toronto neighbourhoods.

4.3.2 Adaption of the Energy Conservation Estimation Model

We adapted the Sacramento Utility District (SMUD) Tree Benefits Estimator, originally designed to quantify the energy conservation benefits of a utility-sponsored shade tree planting program in California, for application to trees planted on urban residential properties in Toronto, Canada. SMUD developed its Tree Benefits Estimator using estimates of electricity load impact provided by 787 trees, planted on 254 residential properties, that participated in Sacramento's shade tree program (Simpson and McPherson, 1998). Electricity load impacts were estimated by Simpson and McPherson (1998) using building energy use and tree shading simulation models coupled with data collected by SMUD staff describing the actual planting location of trees

(Sarkovich, 2009). The USDA Forests Service's Shadow Pattern Simulator (SPS) provided data describing solar gain reduction resulting from tree shade (Simpson and McPherson, 1998). It was used by Simpson and McPherson (1998) to quantify the percentage of tree shade cast on each building wall and roof at hourly intervals for each month during an average year. The SPS shading estimations were then entered into Micropas (version 4.01) energy simulation software (Enercomp, 1992) along with specific building thermal characteristics and hourly weather data.

Consideration of the location-specific climatic difference was essential to our modification of SMUD's Tree Benefits Estimator for use in Toronto. We use Cooling Degree Days (CDD) to estimate the severity and duration of hot weather in the geographic location where the shading benefits of a tree are modeled. CDD is particularly useful for characterizing the potential impact of regional climate differences on energy demand for air conditioning (Sailor, 1998). A positive CDD value indicates the likelihood of electricity demand to cool indoor spaces. A daily CDD value is calculated based on mean temperature, which is estimated by taking the average of the minimum and maximum temperature over a 24-hour period. If the daily mean temperature is below the base temperature (typically 18°C), then the CDD value is set to zero. Where above the baseline measure, subtracting the base temperature from the daily mean temperature results in the daily CDD (Hor et al., 2005). An annual CDD value is calculated based on the following summation of daily CDD values for a year:

$$CDD = \sum_{i=1}^{i=365} (T_{mean} - T_{base})(\alpha) \tag{1}$$

where T_{base} represents the baseline temperature, T_{mean} represents the daily mean temperature, and α is 1 if the CDD value is greater than 0, and 0 if the CDD value is equal to or less than 0 (Sailor, 1999). In this research project an annual CDD value for Toronto of 358 was used, which was obtained from Environment Canada climate normals (1971 to 2000) (Environment Canada

2000).

The potential influence that a shade tree can have on mitigating energy demand for cooling also depends on the underlying relative humidity, which can be measured as Latent Enthalpy Hours (LEH). Hor et al (2005) describe a positive correlation between Latent Enthalpy Days (LEH divided by 24) and electricity demand. Increasing the water content in the air leads to latent heat gains. This hidden heat, called latent enthalpy (a measure of energy), has to be supplied or removed to change the relative humidity of air. LEH is defined as the amount of energy that must be removed from the air to lower it to 25°C and 60% relative humidity (Andersson, 1986). This means that in cities with humid climates (or with seasonal humidity), shade tree caused reductions in CDD will result in less offset of demand for air conditioning compared with less humid climates (Sailor, 1998). LEH is calculated in this research by summing enthalpy differences for every hour over the course of a year:

$$LEH = \sum_{i=1}^{i=365} \sum_{j=1}^{j=24} (E - E_0)(\alpha) \tag{2}$$

where E is the actual enthalpy and E_o is the enthalpy at 25°C and 60% relative humidity (Andersson, 1986). In this calculation, α is 1 if the LEH value is greater than 0, and 0 if the LEH value is equal to or less than 0. The LEH for Toronto, used in this research, is 1600 and was calculated as an average of a decade (2000-2009) of LEH values calculated from Environment Canada hourly temperature and humidity data (Environment Canada, 2000).

The magnitude of Toronto's CDD in relation to Sacramento's was determined by dividing its value by Sacramento's to obtain a correction factor. This CDD-factor of 0.56 was then used to adjust Sacramento's tree benefits to approximate those for Toronto. Because the actual cooling benefits of evapotranspiration are site-specific and difficult to quantify, the SMUD

Tree Benefits Estimator defines evapotranspirative benefits as contributing an additional 50% to energy conservation over and above direct shading. We model the evapotranspiration benefits of shade trees in this study using a LEH-factor. A simple linear equation that can predict LEH-factor values (dependent variable) from LEH values (independent variable) was developed based on known LEH and associated LEH-factor values for major US cities (generated by SMUD; M. Sarkovich, personal communication). The LEH value for Toronto was input into the model to determine the associated LEH-factor:

$$\text{LEH-factor} = -0.0069*\text{LEH}+42.265 \quad R^2= 0.96;\ p<0.01 \tag{3}$$

Toronto's LEH-factor value was determined to be 0.31.

The estimated energy conservation benefits of shade trees are modeled in the form of saved electricity (in kWh of energy not used for air conditioning) for full size trees growing in eight orientations with respect to a building (north, northeast, east, southeast, south, southwest, west, northwest), and at three distance classes of 0-4.6m (0-15ft), 4.7-9.1m (16-30ft), and 9.2-13.7m (31-45ft) from the edge of the closest building wall. To calculate climate-adjusted energy saving benefits of shade trees in our study, the Toronto CDD-factor was multiplied by SMUD data for trees of differing size classes (three in total), canopy structure (coniferous, broadleaf deciduous) and planting scenarios (orientation and distance with respect to building). Each of these resulting values was then multiplied by a factor of 1.31 (the LEH-factor), which served to add the energy conservation benefits of evapotranspiration.

Given that the energy conservation benefits of shade trees were simulated for full size trees by SMUD, an adjustment was needed to discount benefits for trees that have a lesser stature (smaller canopy volume). In this project, SMUD's data describing tree size according to species, and the corresponding proportion of total energy conservation benefits, were used to develop a linear regression model to predict the proportion benefits (dependent variable) at any DBH measurement (independent variable). The growth curves from New York City trees (geographically closest comprehensive collection of urban tree growth data) were used to determine the approximate size of our study trees, given knowledge of species and planting year (McPherson et al., 2007). Tree DBH (proxy for canopy size) was then estimated using the New York City growth curves, for every year of a tree's existence (up to 75), and entered into the regression model to predict the tree's energy conservation potential at each year of its life.

4.3.3 Planting Program Data Collection

This study used data describing the oldest and largest trees planted as part of the Toronto-based non-profit Local Enhancement and Appreciation of Forests' (LEAF) residential tree planting program, those planted between 1997 and 2000. The trees were selected because they reach large mature heights of 12m or greater. Data were collected for seven broadleaf deciduous and one coniferous tree species (577 trees total); all tree species are native to the geographic region. The species studied are Bur Oak (*Quercus macrocarpa)*, Hackberry (*Celtis occidentalis*), Kentucky Coffee Tree (*Gymnocladus dioicus*), Red Maple (*Acer rubrum*), Red Oak (*Quercus rubra*), Sugar Maple (*Acer sacchrum*), Tulip Tree (*Liriodendron tulipifera*), and White Pine (*Pinus strobus*).

LEAF collected data at the time of planting for each tree delivered as part of its residential tree-planting program. These data were analyzed in conjunction with 2007 City of Toronto colour leaf-off aerial images, Google Earth 2009 images, and City of Toronto GIS building and property boundary files to determine whether the tree was still present on the property. Where it was found alive, its exact position was mapped and the following data were collected: (1) species;

(2) age of tree from planting date; (3) orientation with respect to building(s); (4) distance from the building(s); and, (5) crown width.

The distance from a tree to a building was defined as spanning the distance from the tree base (centre of mainstem) to the nearest edge of the building. Orientation and distance data were only collected if the tree was located close enough to a building to provide some direct shade. We reviewed Hildebrandt and Sarkovich (1998) and McPherson and Rowntree (1993), who suggest that between 12m and 15m represents a distance threshold beyond which a tree no longer provides direct shade to a building. The SMUD Tree Benefits Estimator, the Toronto-specific model, and this data collection all consider trees planted up to 13.7m (45ft) away from a building to provide some shade. All LEAF trees were categorized into one of the eight azimuth classes of north, northeast, east, southeast, south, southwest, west, northwest, and one of three tree-building distance classes of 0-4.6m, 4.7-9.1m, and 9.2-13.7m, to reflect those included in the SMUD model (and our subsequent Toronto-specific adaptation of it). If, based on its planting location, a LEAF tree was determined to provide an electricity savings benefit to one or more houses, data corresponding to that tree were entered into our Toronto-specific model to estimate the energy conservation benefits. Where more than one house received shading benefits, the total energy conservation for a specific tree was calculated as the sum of the energy saving estimates for all the houses influenced by that tree.

4.3.4 Offset for Existing Canopy

The actual shade cast on a residential building from the planting of a tree is in part determined by the amount of shading the building already receives from existing trees. On a residential property with few pre-existing trees, shade from a newly planted tree will deliver the maximum estimated energy conservation benefits possible for its species, size and location (Simpson and McPherson, 1998). The energy conservation benefit of adding a tree to a property with pre-existing tree cover will diminish with the extent of coincident building shade (Simpson, 2002).

While there are no studies that specifically consider the influence of existing canopy on the shading potential of an additional tree, the work of Simpson and McPherson (1998) examines the shading impact of trees as a function of the number of trees planted (i.e., multiple simultaneous plantings). Their study investigated adding varying numbers of trees as part of SMUD's tree-planting program, and determined that the energy conservation benefits of additional trees started to decline after 3 or more trees were planted around a single residence. We used the findings of Simpson and McPherson (1998) as the basis for defining a discounting scheme for a newly planted tree in our study, where pre-existing tree canopy existed.

Using Simpson and McPherson's (1998) findings for 1 through 7 trees planted on a single residential property, we developed a regression model to estimate conserved energy (kWh) as a function of number of trees where:

$$\text{Conservation Benefit (kWh)} = 186+35*\ln(\text{Number of Trees}) \quad R^2=0.89;\ p=0.005 \tag{4}$$

To determine the proportion of energy conservation benefits (offset), the kWh difference between each number of trees was divided by the kWh value for 1 tree (**Table 4.1**).

Table 4.1: Proportion of energy conservation benefits provided by the LEAF tree based on the number of existing standard trees (10m canopy diameter) within 13.7m of the LEAF tree.

Number of existing 'standard' trees	0	1	2	3	4	5	6	7
Proportion of LEAF tree benefits	1	1	0.65	0.5	0.4	0.3	0.25	0.2

The average crown width of the trees considered by Simpson and McPherson was 10m. Therefore, in our study 10m was used as the crown width of a standard tree for the purpose of estimating the pre-existing canopy cover on the property for which LEAF had planted a tree. The total canopy cover provided by trees within 13.7m of each LEAF tree was measured from contemporary City of Toronto land cover data describing forest coverage (derived from classified Quickbird satellite imagery) (City of Toronto, 2010b). The canopy area provided by the LEAF tree was subtracted from the total canopy area to determine the additional non-LEAF tree canopy area. This additional non-LEAF tree canopy was then divided by the area covered by a standard tree ($78.5m^2$) to calculate the number of additional standard trees located in proximity to the LEAF tree. Once the number of additional standard trees was determined, the corresponding offset proportion was multiplied with the energy conservation benefit (kWh) for that same tree (at its full benefit potential), to determine the final energy conservation estimate for that tree. Where a tree was found to shade more than one house, this same offset proportion was applied to all homes for which energy conservation was estimated.

4.3.5 Air Conditioning

Not all the houses that receive shade from a LEAF tree are air-conditioned. In fact, only 81% of homes in Toronto report having air conditioning (Statistics Canada 2009). Additionally, our model does not differentiate between houses with central air conditioners and those with window/room air conditioning units. While window sized air conditioners are less common in residential homes, they only use approximately 25% of the energy of central air conditioners (Hildebrandt and Sarkovich, 1998). To account for variation in air conditioning use in Toronto, the total estimated energy conservation benefits provided by LEAF trees were multiplied by the percent of homes reporting central air conditioners (65%), to which was added one quarter of 16% of the energy conservation benefits (homes with window sized air conditioning; 25% of the electricity consumed by central air conditioning).

4.3.6 *Mature Tree Estimates*

Urban residential tree mortality rates have not been studied systematically. McPherson (1993) suggests, through interviews with landscape contractors, that 15-30% of trees may die during the first 5 years following planting, and 0.2-2% will die each year thereafter. In a paper that discusses trees in urban Modesto, California, McPherson et al. (1999) assume an annual mortality rate of 1.4%. A study conducted in Fresno, California used a mortality rate of 21% after 30 years, while in Sacramento a study used estimated mortality rates for the SMUD program of 30%, 36%, and 42% after 30 years (McPherson, 1993; Hilderbrandt and Sarkovich, 1998). Due to the uncertainty associated with forecasting a mortality, this study determined the energy conservation benefits of residential trees by applying three separate rates of annual decline: (1) high - 1.5%; (2) moderate – 1.1%; and, (3) low - 0.7%.

4.4 Results

Of the 577 LEAF trees evaluated, 461 were still alive at the time of this study, resulting in an average success rate of 79.6% after nine to twelve years (**Table 4.2**).

Table 4.2: Number of trees planted and success rate by species

Species	Red Maple	Sugar Maple	Red Oak	Burr Oak	White Pine	Tulip Tree	Kentucky Coffee Tree	Hackberry	Total
Number of trees	195	76	17	68	62	33	14	112	577
Success	77.4%	84.2%	58.8%	84.2%	72.6%	81.8%	92.9%	84.8%	79.6%

After discounting for existing canopy cover, and making adjustments to estimates for air conditioning, the total cumulative energy conservation benefit delivered by the 461 surviving trees as of 2009 was 77,140 kWh (167 kWh per tree). Between 2000 and 2009, the annual estimated energy conservation benefit increased from 4,518 to 9,283 kWh (9.8 to 20.1 kWh per tree). While the average annual energy benefit per tree was relatively low at the time of planting, after 10 years annual benefits doubled. Twenty-six percent of all LEAF trees studied provided no energy conservation benefit due to one or both of orientation and distance with respect to a house. During its first year following planting, the greatest energy conservation associated with a single tree was 112 kWh. This same tree was estimated to have provided 303 kWh in electricity savings during 2009 (the final evaluation year of this study). Projecting into the future, the total benefits provided by the LEAF trees after 25 and 40 years could range from 222,907-200,657kWh, and 424,269-338,280kWh, respectively, depending on the mortality rate (Table 4.3).

The average conservation benefits between 2000 and 2009 associated with homes receiving LEAF trees and neighbouring houses are shown in **Figure 4.2**. Comparatively, the average benefits per tree were significantly higher because a single tree was frequently found to shade multiple houses. At 9.0 kWh, the average estimated annual savings of a participant house (property on which the LEAF tree was planted) was higher than the 7.0 kWh for neighbouring houses. The maximum conservation benefit associated with a single house was 34 kWh in the first year of planting, growing to 92 kWh by year 12. In total, 8 houses experienced this benefit; all had Hackberry planted in an orientation to the west of the building.

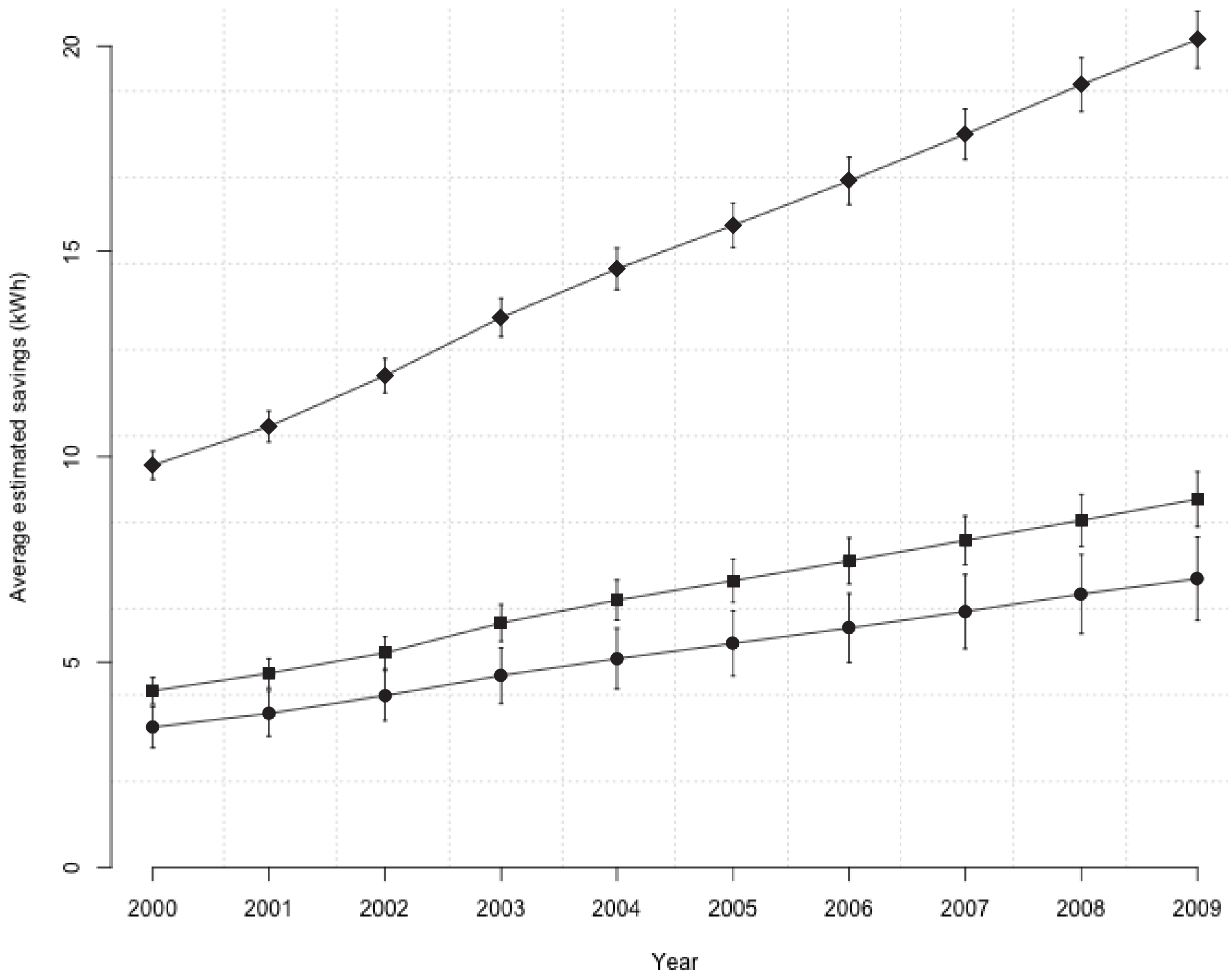

Figure 4.2: Average estimated annual energy conservation (2000 to 2009). Diamonds show per tree savings, squares represent per participant house savings, and circles symbolize per neighbouring house savings. Error bars depict 95% confidence intervals.

The percent of trees planted in each orientation (with respect to the house) is juxtaposed with the percent of total estimated energy conservation contributed by trees planted in that same orientation (**Figure 4.3**). Thirty-three percent of trees planted were located to the north, northeast, and northwest of a house. As a collective, these trees only accounted for 3.4% of the estimated energy conservation. The majority of the benefits were provided by trees located to the west of a house (53% of total energy conservation resulting from 16.7% of the trees). A similar percentage of the trees were planted to the east and southwest (12.8% and 12.5%, respectively);

however, those growing to the east contributed to 19.2% of the conserved energy, while those to the southwest only contributed 8.5%.

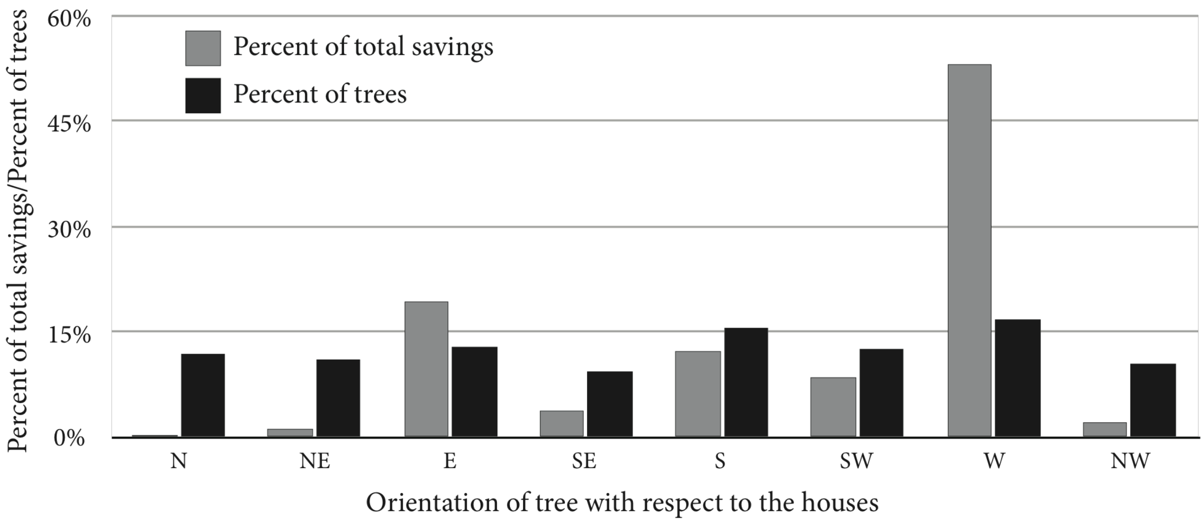

Figure 4.3: Percent of total energy conservation by planting orientation with respect to house and the proportion of trees planted in the corresponding orientation.

This study considered the energy conservation benefits received by neighbouring houses along with benefits delivered to the participant houses; taking neighbouring houses into account increased the estimated total energy savings by 119%. Of the trees planted by LEAF, 68% were near enough to provide some benefit of direct shading to neighbouring houses. The total energy conservation benefit of trees, by planting orientation, is provided in **Figure 4.4** for homes that planted LEAF trees and for neighbouring properties. In fact, the estimated conservation benefit to neighbouring houses was 54.4% of the total cumulative, which is slightly higher than for the participant homes (**Table 4.3**).

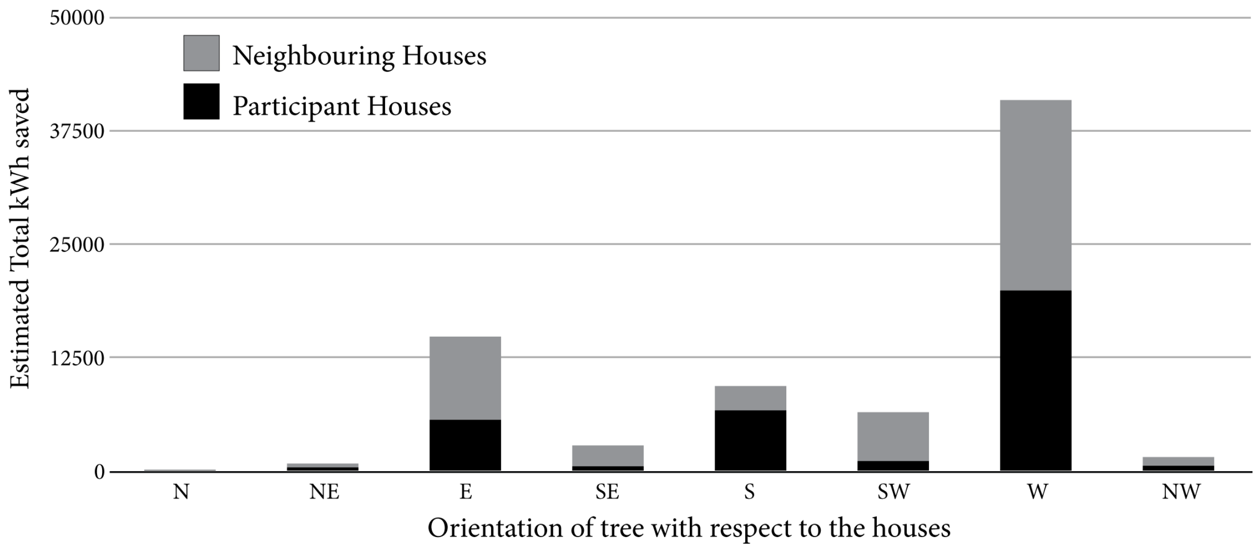

Figure 4.4: Total estimate kWh benefits for participant and neighbouring houses by orientation for trees that are 9 to 12 years old

Table 4.3: Summary of cumulative benefits (kWh) of trees planted in 1997-2000 after 12 years, and projected benefits after 25 and 40 years, considering different mortality rates.

	Participant Houses	Neighbouring Houses	Total
12 years	35,194	41,946	77,139
25 years (low mortality)	104,351	118,556	222,907
25 years (average mortality)	99,017	112,496	211,513
25 years (high mortality)	93,935	106,722	200,657
40 years (low mortality)	192, 050	232,219	424,269
40 years (average mortality)	171,526	207,403	378,929
40 years (high mortality)	153,126	185,154	338,280

Most of the LEAF trees (82%) were not planted to the west of the participant house. Yet, of those trees, 14.3% add west side shading to a neighbouring house. This resulted in shading from the west of 58 additional homes. The most common orientations on the tree-owned property to result in west shading of a neighbouring house were south and northwest (**Table 4.4**), but north, east, and southwest were all similarly likely.

Table 4.4: Percent of initial non-west orientations with respect to participant houses that result in west shading of a neighbouring house.

Orientation	Percent
North	15.3%
Northeast	10.2%
East	13.6%
Southeast	3.4%
South	18.6%
Southwest	15.3%
Northwest	18.6%
None	5.1%

With respect to the existing tree canopy, it was equally likely that a tree would be planted in an area with no existing trees as in an area with 7 existing trees (10% of trees in each category). The majority of LEAF trees were planted on properties with 1 to 6 existing trees; the most common numbers of existing trees were 2 or 3, which collectively accounted for 30% of all properties.

As was expected, LEAF trees were planted farther away from neighbouring houses compared with participant houses. We found that 18% of trees were considered adjacent (0-4.6m) to participant houses, compared to only 5% that were adjacent to neighbouring houses. The most common distance category for participant houses was near (4.7-9.1m), with 46% of the trees in this category. At 67%, far (9.2-13.7m) was the most common category for tree distance from neighbouring houses. This difference in distance had the largest impact on the energy conservation benefits of south-oriented trees. It decreased the contribution of this orientation to overall savings by neighbouring houses because trees located at a far distance from a home, and to its south, cast little shadow and therefore contribute negligible energy conservation benefit (**Figure 4.4**).

4.5 Discussion

The adapted model generated in this research allows for the estimation of the energy conservation levels of shade trees based on their age, species, orientation with respect to and distance from surrounding buildings in Toronto. Certain limitations exist within both the original model and the adaption process due to an inability to account for all potentially relevant variables. Specifically, assumptions were made about the physical characteristics of the trees, such that crown shape and leaf density (both of which influence tree shade) were not considered. The proportionate benefit of evapotranspiration is not clearly defined in the literature, and was thus conservatively estimated here. Finally, differences in building characteristics were not included even though construction materials, house size and heating and cooling systems vary among homes in Toronto and between Toronto and Sacramento. The model also does not consider the impact of Toronto's cold winters; this study only considers cooling energy savings and does not discount for heating penalties due to restricted incidence of solar radiation in the winter. While only 17% of homes in Toronto use electricity for heating, heating penalties will still have an environmental impact as heating in Toronto occurs mostly with natural gas (Statistics Canada, 2009). Despite these limitations, the model is an efficient tool that is unique in Ontario, and can be utilized by different groups to estimate the impact tree shade can have on energy savings. This information can be highly relevant when considering the benefits of urban afforestation programs. This research also outlines the model adaption methods and could be used to guide other researchers in adapting the SMUD model to their own location.

Results of this study demonstrate that a residential tree-planting program provides important energy conservation benefits in a dense urban environment. In urban residential neighbourhoods, where houses are closely spaced, energy conservation arising from shade trees goes beyond the property in which they are planted to the delivery of significant benefits to neighbouring homes. More than half of the trees in this study provided direct shading benefit to a neighbouring building, many of them delivered shading to multiple adjacent properties. Our results indicate that to fully appreciate the energy conservation benefits of tree planting in urban residential neighbourhoods, both the home receiving the tree and the adjacent properties must be considered.

Compared with Sacramento, where 23% of trees in the SMUD tree planting program provided some benefit from direct shading of neighbouring houses (Hildebrandt and Sarkovich, 1998), 68.3% of trees in our study shaded at least one neighbour. In fact, consideration of shade on neighbouring buildings is of such importance in our study that if these properties were not included the total energy conservation would be underestimated by greater than half. This result stems mainly from the large number of houses in the vicinity of the trees (715 neighbours close enough to receive shade from trees planted on the property of 461 participant homes).

In a study conducted in Toronto, Akbari and Konopacki (2004) analyzed the cooling energy benefits of fully-grown shade trees planted around residential buildings. They found 4 mature trees resulted in average annual cooling energy savings (not discounted for heating) of 165 kWh and 246 kWh, depending on the building vintage (greater conservation benefit with older buildings). By comparison, houses in our study were estimated to receive cooling energy benefits from a single tree that ranged from 0 to 172 kWh (at 25 years post-planting) and between 0 to 237 kWh (at 40 years post planting). We do not compare average conservation benefits from our trees to those of Akbari and Konopacki (2004) because these authors modeled trees that were strategically placed to the west and south, therefore, they had no trees contributing negligible benefits.

While trees provide their greatest energy conservation benefits when they have reached a mature stature, they do provide important shading as they grow, especially when considered cumulatively from one year to the next. McPherson (1993) simulated the shading benefits of trees at age 5 and 10 years old. He determined that energy conservation potential from shading increased by approximately 50% over this short time. In our study, between the fifth and tenth year post-planting, we estimate an increase in total conservation benefits of 48%. The yearly increase varied depending on whether the calculation considered benefits accrued to the tree-owning house, or the contribution of a tree to all houses it influences. In our study, both increase as a tree grows: per tree benefits increase at a rate of 1.1 kWh/year, while the tree-owning house saw benefits increase at 0.88 kWh/year.

Despite the general tendency for published studies to concentrate on the energy conservation benefits of mature trees, it is important to consider the benefits of trees over their entire lifetime. For example, in our study, in the first 10-12 years following planting, LEAF trees provided 26% of the estimated benefits contributed by these same trees (adjusting for mortality) 40 year after planting. While trees require large initial investments, and yield relatively modest conservation benefits at the outset, their contribution to demand-side management of electricity increases yearly. This circumstance is unique compared to other energy conservation options, which tend to provide immediate benefits that diminish over time as equipment ages (McPherson, 1993).

In general, the energy conservation benefits of young trees are especially high when they are strategically planted. Following 10 to 12 years of growth, the average annual energy saved per household was 9.8 kWh; where trees were planted in western orientations with respect to a home several houses received an estimated savings of 92 kWh/year. At only 12 years of age, a single

LEAF tree planted to the west of a house between 4.7 and 9.1m provided the homeowner with annual summertime energy savings of $11.87, and cumulative savings of $106.70, at current electricity prices, ($0.129/kWh). These short-term savings are likely to be of particular interest to homeowners who are not necessarily concerned with the benefits of the tree over its lifetime, but are more concerned with the timeframe in which they see themselves occupying a dwelling.

The average energy savings contributed per tree is often much higher than the conservation benefits received by the tree-owning house. After 12 years, the annual average savings per tree in our study was 20.1 kWh. Similar to per house benefits, values range greatly because the actual energy savings contributed by each tree are heavily dependent on the orientation of the tree. At 12 years old, individual trees contributed up to an estimated 303 kWh of summertime savings when influences on all houses (participant and neighbouring) are considered.

Over a quarter of the trees in this study provided no direct energy conservation benefit. This is attributable to 19.5% of trees planted too far to provide any shade on any house, and a further 6.5% of trees being located in northern or far south orientations. Energy conservation, however, is only one of many benefits provided by trees in urban areas. Trees planted in urban residential neighbourhoods provide a multitude of benefits to the community in which they grow. City trees improve air quality by removing pollution (gases and particulate), as well as by sequestering carbon, which reduces atmospheric carbon dioxide (McPherson, 2007). Where trees are growing, the potential for storm water runoff is mitigated and habitat for wildlife exists (Nowak 2004; Huang et al. 1992). Urban vegetation also has significant aesthetic value to the community; trees increase property values, create a sense of wellbeing, and foster an environment where people function (are capable of focusing) more effectively (Anderson and

Cordell, 1985; Kaplan et al., 1998).

Results of our study indicate that strategic planting for energy conservation benefits should not necessarily be the top priority in densely built urban residential areas. There can be obstacles that prevent trees from surviving in locations that would be deemed optimal from the perspective of shading benefit. Where houses are closely positioned, and generally high levels of canopy cover exist, tree planting guided by the potential to achieve shading benefit may in fact lead to higher tree mortality resulting from conflicts with existing or planned property features (e.g., pre-existing trees, overhead wires, proximity to patios and driveways). Furthermore, in dense residential neighbourhoods, planting a tree for survival first (as was the objective of LEAF's planting program) ensured a high success rate and provided shading benefits to neighbouring houses, some of which received optimal shade from a tree oriented to the west.

In urban areas with well-established tree cover, it is difficult to plant a tree in isolation. Prioritization of tree planting location based on potential energy conservation benefits and the strategy of locating trees to maximize survival may, in fact, be complementary in urban residential neighbourhoods. Establishing a large shade tree in a good location for survival involves planting it away from existing canopy cover, where existing canopy cover reduces the energy saving benefits of newly planted trees.

Tree canopy cover by neighbourhood varies across Toronto from between 2 and 62% (City of Toronto, 2010b). The neighbourhoods in which LEAF planted greater than 10 trees are among those with the highest canopy cover levels in the city. While, there are some exceptions, we found that most of the trees planted by LEAF, where survival was the first priority, still experienced competition for space and light from pre-existing trees. Our canopy cover offset results corroborate this circumstance; only 10% of trees were found to have no other canopy within 13.7m. The level of existing shade observed in this study can be partially explained by the age of the neighbourhoods. Generally, established downtown urban neighbourhoods tend to be older and, because trees are usually planted soon after homes are constructed, canopy levels generally increase with the median age of buildings in an area (McPherson, 1993).

The LEAF trees in our study were planted with no directional bias, yet the most common orientation ended up being west, which is optimal for energy conservation. This demonstrates that planting programs need not focus on strategic placement to provide conservation benefits. In dense urban environments, where the opportunity to plant trees in optimal locations is limited by the presence of utilities, narrow side yards, impervious surfaces, buildings, and existing vegetation, it may be more important to put trees in the ground than to orient them specifically for energy conservation.

Our findings serve as an important point of engagement with many stakeholder groups such as homeowners, community organizations, urban planners, and utility companies. By modifying location-specific climate data and tree growth characteristics, we adapted the Sacramento Municipal Utility District's (SMUD) Tree Benefits Estimator for application in Toronto. This research could be useful for members of the stakeholder groups, either as a tool for estimating conservation benefits in Toronto, or as a framework for adapting the SMUD model for use in other areas.

The second component of this research involved using the model to analyze and estimate energy savings of a tree planting program in a dense urban area. This study demonstrates that utility companies can use tree planting effectively in urban residential communities to influence demand-side management of electricity. With tightly packed houses and areas with extensive existing canopy, the conservation estimates were adjusted to factor in these characteristics of urban Toronto. As a result, it became evident that trees are providing benefits that extend beyond the houses of the participants in the program and contribute high levels of savings to neighbouring houses. The results of this analysis also indicate that many of the trees were planted in neighbourhoods with high levels of existing canopy cover, and their contribution to energy savings was constrained as a consequence. These findings indicate that urban residential tree planting programs should not focus exclusively on location-driven strategic planting to yield large energy conservation benefits. Instead, we argue that priority should be given to selecting planting locations that will maximize tree survival as neighbourhood energy conservation benefits of a tree that achieves mature stature often outweigh the homeowner-specific benefit of a strategically planted tree.

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Chapter 5

5.1 Model Uncertainty

In this project, certain assumptions were necessary to adapt the SMUD Tree Benefits Estimator for use in Toronto. In some cases we lacked measured data, relying instead on predictive tools (regression) to obtain model input, and in others there is a requirement for more detailed modeling of process (e.g., the conservation benefits of evapotranspiration). We identify two main categories of model critique, which include general weaknesses in SMUD's approach and criticism of our adaptation for general applicability in Toronto.

SMUD's Tree Benefit Estimator makes a broad assumption regarding physical characteristics of the trees. While growth rate and canopy size are considered, the shape of the crown and leaf density also influence the energy conservation potential, yet were not accounted for in the model (Parker, 1983; Carver et al., 2004). Benefits of direct shading are generally conclusive in the literature and were calculated using a well-established energy simulation model (Micropas). These benefits are also easier to simulate because they involve straightforward geometric calculations.

Evapotranspirative benefits, on the other hand, are less clearly defined in published studies and are much more complicated to simulate because they involve complex and variable (and often site-specific) meteorological conditions. Sailor et al. (1992) found the benefits of evapotranspiration to be comparable, or even greater in magnitude to those from direct shading. Others have estimated that evapotranspiration contributes to energy conservation in approximately a 1:1 relationship with direct shade (Simpson and McPherson, 1996). A study by Rosenfeld et al. (1998) indicates that evapotranspiration provided two thirds of the benefit of direct shading. With little agreement on exact methods for quantifying the contribution of evapotranspiration, we used a conservative estimation approach that relied on LEH and reference conditions for other US cities to establish this benefit for Toronto (31% of direct shading benefit).

The energy conservation benefits of evapotranspiration from residential trees peak when humidity is low. Additional research measuring the evapotranspirative contribution of trees to modification of temperature in an urban microclimate would assist in eliminating some uncertainty associated with this necessary component of the tree benefits estimator. Furthermore, knowing more detail about the evapotranspiration contribution to cooling would assist with creating a more refined offset method (i.e., when a property with a newly planted tree has pre-existing canopy). While a tree planted in the shade of an existing tree offers little direct shading of a building, it is likely to provide some evapotranspiration benefits (cooling of its immediate surroundings). In its current form the SMUD Tree Benefits Estimator, and our adaptation of it, defines such a tree as having a negligible energy conservation benefit.

The energy conservation potential of shade trees is likely to have been underestimated by the modeling approach outlined in this thesis because there is no accounting for the broader community wide benefit of a cooler urban microclimate. Given the format of our adapted model, this study only considered the benefits received by the tree owning, and neighbouring houses, that received direct shade. In so doing, we fail to incorporate the aggregate effect of trees on moderating temperature in the urban microclimate. These benefits are not well quantified in the literature, but generally involve the cooling benefits that can accrue for an entire neighbourhood as a result of trees (McPherson and Rowntree, 1993). Therefore, our study did not account for a general decrease in ambient air temperature that is likely to have moderated air conditioning use throughout the neighbourhood.

Trees may also influence energy use by creating their own microclimates, which have been shown to have intra-canopy temperature variability. The work of Parker (1993) reports that trees planted in close proximity to a house can create a cooler microclimate proximate to windows and walls, increasing the tree's cooling effect. The magnitude of this effect has only been quantified in one study, where, in Bloomington, Indiana, temperature reduction ranged from 0.7 to 1.3°C when measured midway between the tree trunk and dripline, compared to outside the tree canopy (Souch and Souch, 1993). This effect was not incorporated in our adaptation of the SMUD Tree Benefits Estimator due to the limited data and to uncertainty as to actual impact on air conditioning use (Sarkovich, 2009).

Our study focused on whether trees provide energy conservation benefits through shading of buildings and evapotranspirative cooling; it did not consider the effect of trees on winter heating. During cold weather (winter in Toronto), evergreen tree species and the trunks and bare limbs of deciduous trees block sunlight that would otherwise warm a building surface. While often much less, a leafless deciduous tree can block up to 50 percent of incoming solar radiation (Huang et al., 1992). In an electrically heated home, this shading during the cold weather will increase electric heating loads, especially when a tree is planted to the south, southwest, or southeast of a building (Hildebrandt and Sarkovich, 1998). Studies in mid-latitude cities indicate that the reductions in electricity use provided by shade trees during the summer can outweigh any increase in demand for winter heating energy, especially if the trees are not planted to the south of buildings (Arboit et al., 2008; McPherson, 1993).

Trees can also act as a windbreak. This effect reduces conductive heat loss from exterior building surfaces and infiltration of outside air into buildings. Wind reduction from trees can reduce heating energy requirements, especially in northern climates where there is significant heat loss due to cold winter winds (Heisler, 1986). Akbari and Taha (1992) report that in a cold climate, strategically increasing urban canopy cover by 30% can reduce winter heating energy use by 10%. They indicate that evergreen trees planted on the north, or northwest side of a house can effectively protect a building from heat loss due to cold north winds. Other research focusing on the benefits of trees to serve as a windbreak indicates that energy conservation can be equal to or greater than the increased heating loads due to blocked solar gains (Abarki and Konopacki, 2004; Huang, 1992).

An increase in demand for heating energy is due to the restricted incidence of solar radiation on south-facing walls resulting from trees positioned to the south of a building. Comparatively, energy conservation benefits of windbreak result from trees growing to the north and northwest of a home. Both these wintertime considerations are important to take into account when planting a tree. In Toronto, only 17% of homes use electricity as their principal heating fuel, while 76% rely on natural gas (Statistics Canada, 2009). Therefore, when considering demand for electricity the chance of trees in this study significantly increasing winter energy load is minimal. However, when the broader energy use implications (heating occurs mostly with natural gas) of planting a tree in Toronto are contemplated, we recommend where possible locating a tree to the south of a house as a last option.

In terms of the applicability of our adapted SMUD model to estimate the energy conservation benefits of trees in Toronto, there are a number of considerations that introduce some uncertainty. A consequence of the difference of latitude between Sacramento and Toronto is that, in Toronto, the sun is lower in the sky. This could result in the trees shading for a longer period of time, especially in the south orientation; therefore, our study may be underestimating the shading benefits. Another consideration is the difference in sun hours between the two cities. This study incorporated climatic differences in temperature and humidity, but did not account for the potential of additional summertime sun hours observed in Sacramento. More diffuse insolation results in less direct shading; therefore, this may have resulted in our study slightly overestimating energy conservation benefits for Toronto.

Additionally, our study was unable to adjust for building construction differences among houses in Toronto and between Toronto and Sacramento. Studies suggest that house size, heating and cooling systems, construction materials, and occupant behaviors significantly influence energy use (Donovan and Butry, 2009). All of these characteristics could potentially vary among Toronto homes and between Toronto and Sacramento. The SMUD computer simulations used as the base energy conservation estimates for our adapted model rely on building energy use characteristics (e.g., building vintage, air-conditioned floor area, window area), and physical solar obstructions (e.g., shade condition created by existing trees and buildings, tree size, tree orientation and distance from building) specific to Sacramento. SMUD's simulations relied on specific thermal characteristics of the buildings obtained through their general research; inputs not available, but required for Micropas simulation, were estimated based on the general characteristics of homes with a similar vintage located in Sacramento. Houses in our study are built to different standards than those used by SMUD in their simulation of the energy conservation potential of residential trees.

Building energy standards are dynamic; they evolve over time and can vary between countries and among neighbouring houses in the same city. The main differences in home construction practices that impact energy use include insulation levels, single versus double window glazing, and efficiency of air conditioning equipment. Different building vintages have different energy efficiency characteristics; newer homes are often more efficient (McPherson and Simpson, 1999). Not knowing the vintage of homes in our study was an additional uncertainty in our estimation of energy conservation benefits. Air-conditioned floor area (the average amount of floor area that is mechanically cooled), may also vary between Toronto and Sacramento (McPherson and Simpson, 1998). A final element of building construction that may have introduced error into our study is the type of residential building. Attached houses and row houses are common in Toronto's urban residential core. Akbari and Konopacki (2004) compared estimated energy saving impacts on single-family detached homes and row houses. They found small differences in the energy conservation benefits of trees, and even though their findings confirm variation was not drastic, it was not accounted for in our study.

5.2 Uncertainties in Data Collection and Offset Methodologies

In general, aerial-based tree inventories are defined as the gathering and analysis of aircraft or satellite data for the purpose of depicting canopy cover and the spatial distribution of tree characteristics across a defined area (Walton et al., 2008). The spatially contiguous nature of aerial imagery allows datasets to include trees located on public and private land. The ability to assess trees growing on private property was particularly advantageous to this research because all LEAF trees were planted on land classified as private residential. Use of aerial imagery in this study permitted a temporally distinct snapshot of tree cover, whereas site visits (asking owners permission to access their property) may have resulted in access refusal; therefore, requiring the omission of a tree based on owner partiality. Using aerial imagery also permitted us to work with a much larger sample size of trees, because the time associated with each tree assessment was dramatically lessened.

There are, however, disadvantages to using an aerial-based assessment. Our assessment could not include discrete information such as the physical condition of LEAF trees or the species makeup and condition of pre-existing canopy. While we had access to the species information provided in LEAF's planting maps, errors including mislabeling or planting the wrong species may have occurred, something that could not be evaluated using aerial imagery. Nowak (2008) recommends integrating aerial-based and ground-based assessments to provide a more comprehensive measurement of urban vegetation. Given more time, this integration would especially benefit a study such as ours because on certain properties, LEAF trees were difficult to discern given the dominance of existing canopy.

When applying our offsetting approach (under conditions with multiple trees on a property), the evaluation of canopy cover through direct observation on the ground would have been ideal for obtaining details of small area-specific canopy cover. Nevertheless, our use of remotely sensed data was especially useful for analyzing the existing canopy cover data because trees grow above other landscape features. However, classification of remotely sensed imagery does not easily pick up the fine-scale changes between features such as internal canopy edges in a contiguous patch of trees. At a micro spatial scale, such as around the LEAF trees assessed in this study, it is important to be able to measure the extent of canopy edge associated with individual trees. Some of the potential error introduced by difficulty in delineating canopy edge was minimized in our study by placing the offset values into categories instead of using the exact calculations. Nevertheless, a more accurate delineation of the boundaries of the existing canopy would improve the estimates for the small area sites examined in this study (Wu et al., 2008).

The temporal nature of the data used in the development of the offset methodology may have generated some additional uncertainty in our results. The offset values were calculated using 2009 remotely sensed data, yet they were used to estimate savings for all the study years since 1997. This approach assumes that the canopy around the LEAF tree was consistent in extent for all years, when in reality it likely showed some spatial variability across time. Assessing canopy cover using a standard tree size approach minimized some of the uncertainty. Because this study used categorized offsets, and generalized based on the number of trees, a slight increase or decrease in canopy would not necessarily change the calculated number of standard trees. Furthermore, in terms of increasing canopy, the main uncertainty would arise from existing trees growing larger, not new trees planted after the program tree.

In addition to existing canopy, it should be noted that neighbouring houses also provide shade. This shade was not accounted for in our offset calculations. While direct shade from nearby buildings can provide some energy conservation benefit, buildings do not moderate ambient air temperature through evapotranspiration. In fact, the presence of a building can often increase air temperature in its immediate vicinity (e.g., waste heat from an air conditioner, reradiated solar energy in the form of thermal radiation).

5.3 Group Perspectives and Future Research

As urban population densities increase, vegetation cover tends to decline as built-residential uses out compete non-built land uses (Nowak et al., 1993). Suburbs usually contain more planting space than downtown cores (Boone et al., 2010). This project focused on privately owned land in urban residential areas where, compared to peri-urban locations, there is generally less growing space and more stresses on trees. The results of our study are, therefore, specific to urban areas with a high density of homes and well established patterns of tree cover; they will not apply well to tree planting in less densely developed suburban areas.

Our findings serve as an important point of engagement with many key stakeholder groups (e.g., homeowners, community organizations, urban planners, and utility companies). These different groups, whether involved in the tree planting or not, will vary in their willingness to invest in the time it takes a tree to grow, the extent of the benefits estimated in this research, and the relative importance of different planting strategies. Individual homeowners will benefit from the information contained in this study concerning short and long-term reduction in demand for air conditioning that is possible through tree planting. Specifically, our results show that, for a single-family household, energy conservation benefits can be realized sooner and will grow to higher levels if a tree is planted strategically to the west of a building.

The motivations for planting a tree and the ideal planting position vary between homeowners. Aesthetics are often an important consideration (Lohr, 2004). Shade and cooling benefits are also cited as important considerations, but this importance is related more to the availability of shade for outdoor enjoyment, and thus the priority for shade location may not be on the building. Once planted, trees can take several decades to reach maturity, therefore, time is certainly a crucial element when choosing to invest in planting a tree for energy conservation. In fact, significant energy conservation benefits may only materialize after the length of the homeowner's residency. While this study demonstrated that there are short term energy saving benefits of planting a shade tree, a tree may take several years for it to provide enough shade to reach a level where most people would consider it a meaningful investment in energy conservation.

As a general tool for planning purposes, this study provides an analysis of the broad energy conservation benefits that a residential tree program can contribute over roughly a decade of time. Urban planners must think about medium to long-term time horizons. Planners are more likely to recognize the societal energy conservation benefits that go beyond those experienced by a participant house, and are, therefore, interested in how a tree benefits all the houses in its vicinity. Thus, the high levels of savings attributed to a single tree shading multiple houses in this study are likely to be of significant interest.

This study demonstrates that utility companies can use tree planting effectively in urban residential communities to influence demand-side management of electricity. SMUD reports that their tree-planting program effectively lowered demand for electricity in Sacramento (Sarkovich and Hildebrandt, 1998; McPherson, 1993). It has also provided them with a notable marketing and public relations tool. Our study findings indicate that a tree-planting program in an urban residential neighbourhood that does not prioritize shading benefits when planting trees still yields significant demand-side energy conservation. This illustrates that a utility company does not necessarily have to implement a tree-planting program targeted specifically at energy conservation to realize energy conservation benefits. Investing in an already established program, even if it does not plant specifically for shade, may still be a worthwhile endeavour in urban residential areas.

From the utility's perspective, another important component of electricity use is instantaneous demand, measured in kilowatts (kW). Instantaneous demand management is crucial during periods of maximum energy use (e.g., hot and humid summer afternoons) (Clark and Berry, 1995). In Toronto, electric utilities typically peak in the mid- to late afternoon during July and August (OPA, 2005). To serve this peak demand, utilities often run their least efficient and most costly generation units (sometimes those that are the largest environmental polluters).

When homeowners decrease demand for power during peak periods, they help reduce capital investment in peak electric generating capacity and/or reduce costly power purchases from other jurisdictions (McPherson and Rowntree, 1993). As utilities increasingly transition toward time-of-use (TOU) metering, the role of shade tress in reducing instantaneous demand for energy during peak periods will translate into more savings for consumers. A tree planted to the west of a house not only provides the greatest aggregate shading benefit, it also delivers this benefit during a peak power demand on an electricity grid. Thus, an important avenue for further research would be to analyze the influence of shade trees on peak electricity demand.

An important area of future research that could improve the estimates of this study would be access to tree growth curves that are geographically specific to the Greater Toronto Area. This study relied on the growth curves of trees growing in New York City, but there are two potential research directions that could improve on this method. The simpler method would be to collect data on a small sample of trees in Toronto and compare the growth characteristics to the New York City trees. This would help validate the use of New York trees by providing a statistical analysis of their applicability. A second, more ideal option, would be to collect long-term data on a large, stratified sample of species growing in Toronto. This method would negate the need to use New York City trees by providing Toronto specific growth curves.

Another aspect of this study that is worth noting is its focus on tree benefits without assessing the drawbacks. Many of the costs and risks associated with tree planting are being taken on by the homeowner, while neighbours can reap many of the benefits. Trees can incur costs for a homeowner through planting, pruning, disposal of green waste, water use, removal and replacement of those dead or dying (McPherson, 1993). Further research consisting of a cost-benefit analysis of the LEAF tree-planting program could be completed from the homeowner's perspective. From an economic standpoint, this analysis would be especially useful for considering the net benefits of a tree.

Finally, focusing solely on the impact of trees to moderate air conditioner use may interfere with the potential environmental benefit of rooftop solar thermal and photovoltaic systems. Rooftop solar installations and shade trees do not necessarily have to be adversarial conservation methods because avoiding planting a tree to the south of a house could be a compromise that would allow both approaches to exist in complement. Further research on amalgamating the two approaches could result in a very successful conservation strategy, whether from the perspective of homeowner, planner or utility.

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