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THE POTENTIAL FOR PERENNIAL VINES TO MITIGATE SUMMER WARMING OF AN URBAN MICROCLIMATE

By

Michelle Blake,

Honours Bachelor of Science,

McMaster University, 2011

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Environmental Applied Science and Management

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The Potential for Perennial Vines to Mitigate Summer Warming of an Urban Microclimate

Master of Applied Science, 2013

Michelle Blake

Environmental Applied Science and Management, Ryerson University

Abstract

Shading and evapotranspirative cooling by vegetation are important controls on moderating rise in city temperatures and mitigating urban heat islands. The purpose of this research is to evaluate the potential of Boston ivy (*Parthenocissus tricuspidata*) to mitigate warming of building surface temperature in an urban core. Temperature loggers were placed on vine-shaded and non-shaded walls in Toronto, Canada to collect surface temperatures over a six-month period. During peak solar access periods, average vine-shaded and non-shaded temperature differentials of up to 6.5 °C and 7.0 °C for the south and west-facing walls were measured, respectively. Predictive models were developed to estimate daily degree hour difference (DHD), a metric for capturing the temperature moderating potential of vines. At ambient air temperatures exceeding 22 °C, ambient air temperature and solar radiation were significant positive drivers of DHD. Results are important to further understanding urban plant-microclimate interactions and strategies for heat island management.

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CHAPTER 1

1.1 Introduction

Urban forests are a principal component of city environments, delivering important ecological, social and economic services. They function to provide habitats for wildlife, improve air quality, reduce noise, conserve energy, moderate climate conditions and offer psychological benefits (Dwyer et al., 1992). The term urban forestry was first coined by Jorgensen in 1974 as "… a specialized branch of forestry and has as its objectives the cultivation and management of trees for their present and potential contribution to the physiological, sociological and economic well-being of urban society. These contributions include the over-all ameliorating effect of trees on their environment, as well as their recreational and general amenity value" (Jorgensen, 1974). This basic definition underlines the extensive influence of urban forests and the significance of the urban forestry discipline.

The prospective increase in global rates of urbanization presents challenges for urban forest sustainability and advancement efforts (Dwyer et al., 2003). It is predicted that by 2030 the number of people living in urban areas worldwide will rise from approximately 3.5 billion to 5 billion (UNFPA, 2011). Land use changes resulting from the process of urbanization include the advancing substitution of vegetated land cover by built surfaces, such as asphalt and concrete (Synnefa et al., 2008). This type of land use change in urban centres gives rise to an effect known as the urban heat island effect, a phenomenon whereby the ambient air temperature of urban centres is distinctly greater than that of surrounding rural locations (Rosenfeld et al., 1995). Vegetated surfaces release moisture into the air via evapotranspiration, shade built surfaces and reflect incoming solar radiation; collectively acting to minimize urban heat islands (Synnefa et al., 2008). In contrast, built surfaces enhance urban heat islands by absorbing incoming solar radiation and storing it as heat (Synnefa et al., 2008). The occurrence and enhancement of urban heat islands present substantial consequences for local energy demands concerning air conditioning use, air quality, (Akbari et al., 2001) and heat and pollution-related health issues (Patz et al., 2005). With the rate of urbanization increasing worldwide, the potential increase of the impacts associated with urban heat islands is of great concern (Grimm et al., 2008).

There is a considerable amount of empirical evidence demonstrating the particular success of urban trees and large vegetation to mitigate urban microclimatic air temperature (Akbari et al., 2001; Akbari et al., 2002; Hoyano, 1988; Parker, 1989; Rosenfeld et al., 1995). An urban microclimate can be defined as the climate of a discrete urban area that may differ from the adjacent regional climate (Camuffo, 1998; Steane & Steemers, 2005). Increasing vegetation at the micro-scale level can help to mitigate the negative impacts of the urban heat island effect, thereby benefiting sustainable design and urban planning efforts on a larger scale. Cook (1989) states: "In modern construction the various means of heat avoidance are by far the most economical energy conservation methods in spite of the availability of many technical or mechanical solutions." The space constraints of most urban centres and resources required for many vegetation-associated mitigation strategies, such as planting trees and green roofs, can render these strategies difficult for planners and policy-makers to implement. Therefore, given the copious amounts of vertical wall space in urban centres and the quick and vast growth of perennial vines, greening the external walls of buildings with perennial vines prospectively presents a far-reaching opportunity to moderate urban microclimate conditions by means of vegetation. Their use as a technique to moderate microclimatic temperatures of building environments, however, has not been comprehensively investigated. Having quantified data indicating that the presence of perennial vines on the walls of an urban building can significantly mitigate microclimatic temperatures substantiates the use of vines in pursuits to reduce warming of urban environments.

1.2 Thesis Objectives

The purpose of this thesis is to assess the potential for perennial vines to mitigate warming of the urban microclimate. Particularly, the potential for the perennial vine Boston ivy (*Parthenocissus tricuspidata*) to mitigate summer rise in surface temperatures of a building in Toronto, Canada was evaluated during peak solar access periods. Temperature loggers placed on vine-covered and bare walls recorded shaded and non-shaded surface temperatures over a six month period (May through October, 2012). The specific objectives of this study are: (1) To quantify the difference in surface temperature between vine-shaded and non-shaded south and west-facing building walls; (2) If there is a difference, to determine the magnitude of the difference and assess during what time it is greatest; (3) To determine how results vary between south and west-facing wall exposures; (4) To evaluate how much variability exists among the values recorded by vine-shaded and non-shaded loggers; (5) To produce a statistical model for the prediction of the effectiveness of vine mitigation under particular meteorological conditions; and, (6) To evaluate the possible implications of this research for environmental management in urban centres.

1.3 Thesis Outline

This thesis is presented in manuscript format and is organized into four chapters. Chapter One provides an introduction to the thesis context and objectives of our research. Chapter Two contains a literature review that provides a survey of the current research relevant to the thesis topic and identifies gaps in knowledge in the field of study. Chapter Three presents a standalone manuscript to be submitted to the scientific journal *Landscape and Urban Planning*. The manuscript is organized into associated journal sections, which include an abstract, introduction, methods, results, discussion and conclusion. Lastly, Chapter Four discusses the limitations of the thesis research, presents additional conclusions, offers recommendations for future research and provides supplementary research details. The Appendices include figures and tables that detail supplementary data.

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CHAPTER 2

2.1 The Urban Heat Island Effect

Amidst the many pressing issues surrounding the topic of climate change, one prominent concern of urban areas is the urban heat island effect. The urban heat island effect is a phenomenon whereby the ambient air temperature of urban centres is distinctly greater than that of surrounding rural locations (Figure 2.1). First coined the urban heat island by Manley (1958), the effect has been thoroughly researched for many years (Chandler, 1960; Oke, 1988; Rosenfeld et al., 1995; Rosenzweig et al., 2005; Sobrino et al., 2012). The first comprehensive study of the urban heat island dates back to 1833 when chemist Luke Howard measured the urban heat island of the city of London by analyzing and comparing thermometers placed in the city centre and in the adjacent countryside (Howard, 1833). He found that the temperature of the city was warmer than the countryside. Until the 1970s and 1980s, much urban heat island research was descriptive in nature (Brazel & Quatrocchi, 2005). After this period, research conducted by Tim Oke moved the attention toward investigating the mechanisms driving the urban heat island effect and pioneered much of the modern urban heat island research that we see today (Brazel & Quatrocchi, 2005; Oke, 1988).

Heat islands can occur at a number of different scales, from the micro-scale of one city building (Parker, 1983) to the large scale of an entire city (Taha, 1997). The specific impacts of urban heat islands are governed by the distinctiveness of the locale (Taha, 1997). On average, many urban centres display a warming effect of approximately 2.5 °C on a cloudless afternoon during the summer (Bretz et al., 1997). In large metropolises, such as New York City, temperature differences can be greater than 4 °C (Rosenzweig et al., 2006). These differences in temperature are greatest in the summer season (Oke, 1978).

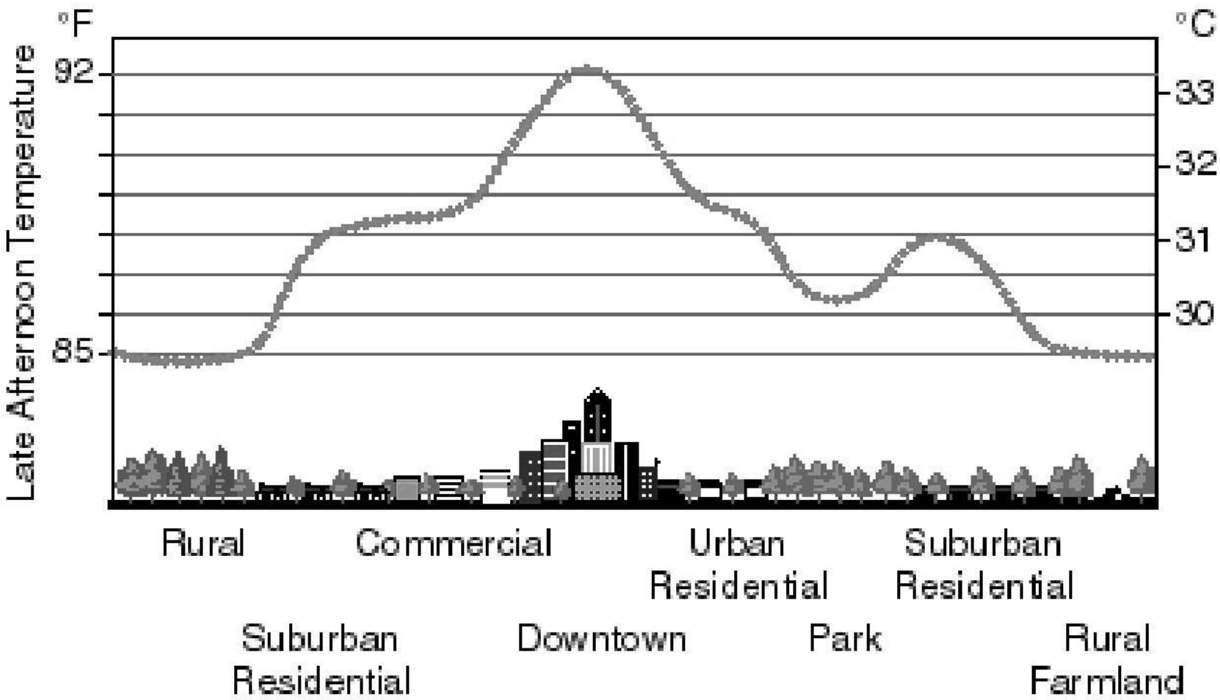

Figure 2.1: Sketch of an urban heat island profile. The ambient air temperature of the downtown core is distinctly greater than that of surrounding rural locations (University of Hong Kong, 2000).

With the rate of urbanization surging globally, the potential increase of the impacts associated with the urban heat island effect is of great concern as the causes of urban heat islands are exacerbated by the alteration of natural landscapes through the process of urbanization (Grimm et al., 2008). It has been recognized that with increased urbanization, the temperature differential between urban and rural areas has increased (Akbari et al., 2001). The population of urban areas is growing three times faster than that of rural areas (Wong, 2008). With an exponentially growing population, by 2030 the number of people living in urban areas worldwide is expected to rise from approximately 3.5 billion to 5 billion (UNFPA, 2011).

2.1.1 Causes

Heat islands occur due to a combination of different factors. The primary causes of urban heat islands can be summarized as follows:

a) Built Surfaces

The land surface of cities is composed largely of built material, such as asphalt and concrete. This type of built material has low reflectivity and a large heat capacity, allowing these materials to absorb a significant amount of incoming solar radiation during the day and store it as heat (Oke, 1978; Streutker, 2003).

b) Decreased Vegetative Cooling

With the substitution of natural land cover by built material, cities lose the natural cooling effects of vegetation. Vegetation release moisture into the air via evapotranspiration, shade built surfaces and reflect incoming solar radiation; collectively acting to minimize urban heat islands (Synnefa et al., 2008).

c) Urban Canyons

The confined organization of buildings in cities can create urban canyons that prevent both short-wave and long-wave radiation from escaping from the lower city atmosphere into the atmosphere above (Johnson et al., 1991). This trapped radiation is absorbed by built surfaces, stored as heat and subsequently emitted back into the environment.

d) Anthropogenic Heat

The generation of waste heat from industrial activities, vehicular traffic, air conditioning systems and other anthropogenic sources can contribute to the occurrence of urban heat islands (Rosenzweig et al., 2006).

e) Pollution

The high concentration of atmospheric pollution in cities can act to trap long-wave radiation inside the urban environment (Rosenzweig et al., 2006). These pollutants include carbon dioxide, nitrogen dioxide and aerosols (Phalen & Phalen, 2012).

f) Reduced Air Flow

The high-reaching and built-up structures in cities impede the flow of air that can help to reduce warming (Johnson et al., 1991).

2.1.2 Consequences

The occurrence and enhancement of urban heat islands present substantial consequences for urban areas. The primary consequences of urban heat islands can be summarized as follows:

a) Energy Demands

When temperatures are warm, many people rely on the use of air conditioning systems, especially in urban areas affected by the high heat of urban heat islands. Akbari et al. (1992) have found that above a temperature threshold of 15 to 20 °C, the demand for electricity increases by 2 – 4% for every 1 °C increase in the daily maximum temperature. The increased temperatures of urban areas were deemed to account for 5 – 10% of the peak electricity demand.

b) Air Quality

Urban heat islands can lower the air quality of urban regions. Higher air temperatures enhance the production of ground-level ozone, which is commonly known as smog. In the presence of heat, volatile organic compounds (VOCs) and nitrous oxides (NOx) react to form this ground-level ozone (Cardelino and Chameides, 1990). The greater the heat, the greater the production of ground-level ozone.

c) Heat-related Illnesses

The increased temperatures caused by urban heat islands can have a direct impact on heat-related illnesses and deaths, particularly for children and the elderly. Research shows that heat-related deaths are more common in urban regions (McGeehin, 2001). High air temperatures can cause heatstroke, fainting, heat exhaustion and heat cramps (McGeehin, 2001).

2.2 Vegetation and Temperature Mitigation

Urban forests and vegetation have far-reaching impacts in urban areas. Urban vegetation can act to provide habitat for wildlife, filter air, conserve energy, enhance aesthetics and contribute to psychological enjoyment (Dwyer et al., 1992). In addition to these benefits, one particular service of urban forests and vegetation that is at the forefront of urban forestry management efforts today is the use of vegetation for climate change mitigation purposes.

There is extensive literature on the effective use of vegetation as a heat island mitigation strategy. Dating back to the 1980s, studies have demonstrated that the strategic placement of trees and large plants around buildings can considerably reduce the microclimatic temperatures of built environments (Akbari et al., 2001; Akbari et al., 2002; Hoyano, 1988; Parker, 1989; Rosenfeld et al., 1995). For example, measurements of air temperatures in areas under the shade of trees in Miami, Florida were an average of 3.6 ◦C lower than air temperatures measured in adjacent, non-shaded areas (Parker, 1989). An urban microclimate is the climate of a distinct urban area that may deviate greatly from the regional climate that is proximate (Camuffo, 1998; Steane & Steemers, 2005). Urban microclimates are caused by a combination of natural and anthropogenic influences, including the presence or absence of vegetation. Changes in microclimatic conditions can have a significant impact on climatic conditions of urban areas on a large scale. These impacts can further influence energy budgets and human wellness (Miller, 1997).

The effective moderation of temperatures by vegetation is accomplished through the processes of shading, evapotranspiration and the urban breeze cycle *(*Miller, 1997; Pérez et al., 2011; Spronken-Smith & Oke, 1999). The degree of temperature mitigation is determined by the size, species, health and location of the vegetation, including the orientation of vegetation to a building as well as soil and water conditions (Donovan & Butry, 2009; McPherson & Rowntree, 1993; Sawka et al., 2013). Plant structure, leaf area and leaf density change greatly with the size and species of vegetation (Köhler, 2008; Millward & Sabir, 2010; Nowak, 1996). The larger these particular vegetation characteristics are, the greater the effectiveness of temperature moderation that can be delivered.

2.2.1 Shading

The shading property of vegetation inhibits the warming of shaded surfaces by blocking the heating effects of solar radiation (Miller, 1997). Specifically, the leafy structure of vegetation acts to prevent solar radiation from accessing the region beneath the shade of the vegetation (Huang et al., 1990). Surfaces shaded by vegetation can be 11–25 °C cooler than the maximum temperatures of non-shaded surfaces (Akbari et al., 1997). The lowered surface temperatures decrease the amount of heat that would normally be emitted to adjacent environments. Shashua-Bar & Hoffman (2000) studied the impact of shade trees in urban areas. Considering the various cooling properties of vegetation, they discovered that 80% of the cooling impact of the trees was due to the shading property of the tree (i.e., the tree's ability, through shading, to prevent rise in temperature).

2.2.2 Evapotranspiration

Evapotranspiration is characterized by the release of water into the air through the leaves of vegetation (Barry & Charley, 1992). Water is absorbed by vegetation from the ground through their root system and transported to the leaves of the plant. The water found in the leaves of vegetation will evaporate through pores of the leaves into the air. The process of the water evaporating from the leaves utilizes energy from the heat in air. This acts to reduce the heat energy produced by the urban heat island. On a summer day, approximately 960 MJ (910 kBTU) of heat energy is extracted from the surrounding environment by a well-watered tree for the process of evapotranspiration (Gartland, 2008). Climate conditions can have a large impact on the evapotranspiration process. Evapotranspiration can increase with wind and in dry conditions (Pérez et al., 2011). Research indicates that evapotranspiration alone can mitigate the warming of air temperatures (Huang, 1990; Kurn, 1994). Air temperatures above fields of grass were found to be 1-2 °C cooler than air above parking lots with no vegetation (Kurn, 1994).

2.2.3 Urban Breeze Cycle

Vegetation can increase the cooling impact of wind in urban regions via the urban breeze cycle concept (Figure 2.2). Urban areas are warmer than rural areas, reaching higher temperatures more quickly and to greater degrees during the day (Ahrens, 2006). The warm air in urban areas generated by the urban heat island effect rises over denser, cooler air and extends out to rural areas where it cools and sinks. The cool air in the rural region has a greater atmospheric pressure than the incoming warm air and thus, moves from this high pressure condition back to the low pressure area of the urban region as wind. The cool, rural wind supersedes the warmer urban air, the warm air rises and the cycle continues (Spronken-Smith & Oke, 1999). On a microscale level, vegetation can mimic the rural area conditions within an urban environment and produce a "park breeze" cycle (Spronken-Smith & Oke, 1999). The lower temperatures of parks and areas of vegetation compared to surrounding urban environments create the same type of pressure differential observed between the rural and urban regions in the urban breeze cycle. Thus, a breeze is produced from within the vegetated area to the built areas of the urban centre, helping to alleviate the urban heat island effect.

2.3 Green Walls

Climbing plants have long been aesthetic attributes of structural designs. The earliest indication of vertical gardens dates back 2000 years in the Mediterranean (Köhler, 2008). In comparison to green roofs, green walls can cover a larger surface area in built environments

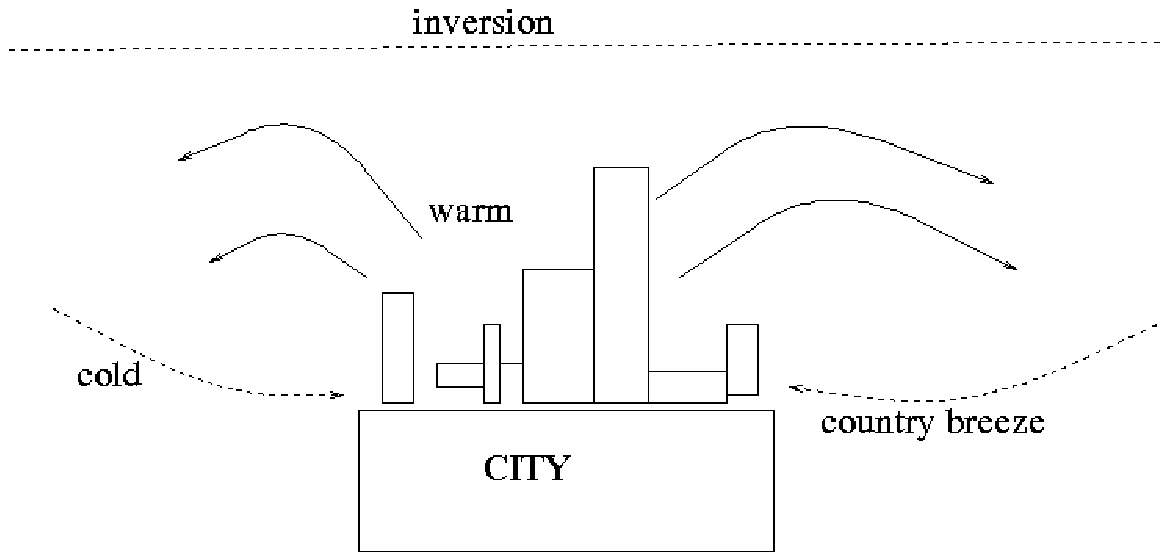

Figure 2.2: The urban breeze cycle. The warm air in urban areas rises over denser, cooler air in rural areas, moving cool, rural winds to the urban centre (The Electronic Universe Project, 2013).

(Jonathan, 2003). The terms green wall, vertical garden and plant wall are typically used interchangeably to refer to the general concept of vegetated wall surfaces. Here, the term green wall will be used. In urban regions green walls have been present for centuries, however, the use of green walls in urban regions for all of the environmental, economic and social benefits they provide, including urban heat island mitigation, improving air quality and aesthetic enhancement, has only been a recent occurrence (Perini et al., 2013).

With the large amount of vertical building space in urban areas, there is great potential for capitalizing on the benefits of vegetation by implementing green walls into cities. There have been a wide variety of approaches to introducing green walls into cities. Generally, green walls can be categorized into three main groups: traditional, green façades and living walls (Figure 2.3). For each category, different plant types are used that are best suited for the system and location. The type of plant selected in combination with the type of green wall and materials used will impact the aesthetics and environmental performance of the system (Dunnett & Kingsbury, 2004; Ottelé et al., 2011). Maintenance of the system is dependent on the type of system and the associated plant types.

2.3.1 Traditional Green Walls

Traditional green walls are those that feature plants grown directly on the wall surface without any assistance from external support structures (Pérez et al., 2011). Plants that grow vertically are commonly seen in nature, for instance vines. Traditional green walls can occur in natural areas, such as on the side of cliffs or on trees, and can also be found in urban areas, naturally or purposefully, on the sides of buildings and houses. Certain species of traditional

Figure 2.3: Categories of green walls: a) green façades (Pérez et al., 2011), b) traditional (PNW Plant Disease Management Handbook, 2013) and c) living walls (Perini et al., 2013).

green wall plants are thought to cause damage to particular wall surfaces, such as stone (Mishra et al., 1995; Mouga & Almeida, 1997; Lisci et al., 2003), while others are considered to act as a protective agent that prevents the weathering of such surfaces and valued for their aesthetics (Darwin, 1846; Holm, 1989; Ottelé et al., 2010).

2.3.2 Green Façades

Green façades are considered a type of green wall system in which climbing plants grow onto structures that are specifically constructed for a particular surface (Pérez et al., 2011; Perini et al., 2013). These plants are typically rooted in the ground, in raised planter boxes or on the roof of the building. The structure used to support the growth of the plants can be an independent structure, including fences and pillars, or integrated with existing building walls. The modular trellis system and cable systems are popular green façades that use trellises, panels and cables to support the growth of climbing plants in a manner that keeps the plants from contacting wall surfaces (Pérez et al., 2011; Perini et al., 2013).

2.3.3 Living Walls

Living walls are green wall systems that feature pre-vegetated wall panels, geotextile felts or planter boxes that are attached to the surface of a wall or an independent wall frame (Pérez et al., 2011; Perini et al., 2013). In comparison to green façades, living walls are able to utilize and sustain a larger variety of plant types since they do not have to rely on the sole use of climbing plants (Lambertini, 2007). These plants root into and obtain nutrients and water directly from the support structure as opposed to the ground. The panels are constructed in such a way that allows water to move within and between panels (Perini et al., 2013). Overall, designs of living walls are often more complex than those of green façades due to increased material use and the aboveground nutrient and water control. This increases the cost of this type of system (Ottelé et al., 2011).

2.4 Green Walls and Temperature Mitigation

The use of vegetation as a temperature mitigation strategy has proven to be very productive. This strategy is especially relevant today, at a time where society is embracing more sustainable urban living. Given the vast amount of unexploited external wall space in urban centres, greening the external walls of buildings with climbing plants prospectively presents a far-reaching opportunity to mitigate urban microclimate conditions by means of vegetation. In addition to its general contribution to sustainability and the greening of urban environments, the use of green walls for its temperature mitigation benefits has become a novel and emergent field. There has been much investigation on the concept of using green walls for moderating the warming of urban climates, with research dating back to 1988 (Hoyano, 1988). In spite of this, the topic has been underutilized in practice and in comparison to research on using trees and green roofs for temperature mitigation, has not been studied to a great extent. Moreover, the majority of scholarly literature available on this subject primarily derives from European and Asian studies.

One of the first studies describing the use of climbing plants for the mitigation of microclimatic temperatures was conducted by Hoyano (1988). In this study, the premise that the strategic placement of plants around buildings is able to mitigate energy cooling loads and adjust indoor and outdoor thermal conditions was quantitatively assessed. Results supported the effectiveness of plants for solar control. Most notably, results demonstrated the effectiveness of ivy and vine sunscreens to moderate microclimate temperatures around buildings. For the vine sunscreen experiment, results indicated that the sunscreen prevented warming of the west-facing wall by 18 °C in comparison to a non-shaded west-facing wall.

According to Kingsbury & Dunnett (2008), standard walls of buildings can reach maximum temperatures of up to 60 °C in comparison to green walls, which contrastingly reach maximum temperatures of up to 30 °C. Of the research available on the use of green walls for the mitigation of microclimatic temperatures, green façades and living walls are the focus of the literature, with minimal scholarly research on the impact of traditional green walls. In a study conducted by Sandifer & Givoni (2002), a traditional green wall featuring the climbing plant Virginia creeper prevented a temperature rise of up to 20 °C in contrast to a bare wall. Köhler (2008) indicates that for traditional green walls, ivy is a climbing plant that produces maximum temperature mitigation due to its dense foliage. Di & Wang (1999) also indicate that ivy is an effective climbing plant for temperature mitigation and that the temperature reduction they offer is comparable to that of the shade of trees, however, covering a much smaller area (i.e., immediately proximate to a building). Eumorfopoulou & Kontoleon (2009); Kontoleon & Eumorfopoulou (2010) also report that climbing plants can offer a cooling effect on the surface of building walls, stressing that the cooling is most impactful during the hottest times of the year. In these studies, maximum temperatures of building surfaces during these warm periods were effectively lowered by climbing plants.

Studies assessing the temperature mitigation potential of green façades and living walls are quite prevalent due to the complex ways in which these systems can be manipulated and designed for strategic environmental uses. Like traditional green walls, studies indicate favourable results for the mitigation of urban temperatures by green façades and living walls. Stec et al. (2005) examined the thermal impact of placing plants within the cavity of a doubleglaze façade using both a computer simulation model and experimental study. Results demonstrated up to a 20% reduction in wall surface temperatures with the use of a green façade. Using both green façades and living walls in their experiment, Wong et al. (2009) found a definite prevention in the warming of wall surface temperatures from all systems used, with the prevention of a maximum temperature warming of 11.6 °C in comparison to a bare wall. Performing an experiment evaluating the thermal behaviour of a turf-based living wall system, Cheng et al. (2010) exhibited that the moisture in the growth substrate as well as the plants of the system were closely correlated with a surface cooling effect. Perini et al. (2011) denote the various attributes of green façades and living walls that contribute to their ability to effectively mitigate temperatures of building walls, including the thickness of plant foliage, shade of foliage, moisture content, composition of structure materials and air cavities.

Most studies assessing the potential for green wall mitigation, whether traditional, green façade or living wall systems, have used similar experimental designs. The majority of this research has been based on short-term and small-scale experiments. Generally, temperature measurements are taken over the summer season, as this is when temperatures are warmest and temperature mitigation strategies are of most value. To capture wall surface temperatures, temperature sensors are typically used and placed on areas of a wall surface that feature a green wall system and on an adjacent area of the wall or separate wall surface with no green wall system present. Measurements of the surface temperature of the substrate material or vegetation are also taken in various studies using temperature sensors. South and west-facing walls are typically the walls of focus. During the growing season, the south and west-facing walls of buildings receive significant and the greatest amount of net heat gains (McPherson, 1984; Simpson & McPherson, 1996; Solecki, 2005). North and east-facing walls do not receive a large enough heat gain to benefit substantially from the cooling effect of green walls. Variations in the outcome of studies indicate that additional research is needed to establish the most successful plants, settings and systems to obtain the greatest green wall temperature mitigation benefits. Studies call for further supportive research and applications in different climate environments. Furthermore, in light of current sustainable urban planning initiatives, there is a lack of discussion and consideration of the environmental management implications of these types of analyses.

Overall, it is evident that green walls can contribute to the offset of microclimatic warming. Bass & Baskaran (2003); Wilmers (1990) report that a combination of green walls with other vegetation cover, such as green roofs, can offer effective temperature mitigation of building microclimates. Moreover, Bass & Baskaran (2003) suggest that if the combination of these vegetation systems were employed on a widespread basis, considerable reductions in urban temperatures could be seen.

2.5 Boston Ivy

Boston ivy (*Parthenocissus tricuspidata*) is a perennial climbing vine in the plant family Vitaceae (Tenenbaum, 2003). Native to eastern Asia, it can be found in many temperate locations and is recognized for its large, abundant and lobed foliage. It has a strong adhesion to wall surfaces, using branched tendrils coated with adhesive discs (Critchfield, 1970; Tenenbaum, 2003). This adhesion method allows it to grow on surfaces without the need of growth supports and without indication of significant damage to common building materials, such as brick or stone, or to the mortar binding these materials together (He et al., 2010). The leaves of Boston ivy grow to 25 cm (Tenenbaum, 2003) with growth climaxing in the summer season (Critchfield, 1970). Boston ivy has a long lifespan in comparison to most plants, spanning many years. Grown across North America, it is the customary ivy of the "Ivy League" schools in the eastern United States (Critchfield, 1970). Propagation of Boston ivy can occur by bare root, cuttings and seed in full sunlight to light shade and in fertile to loamy soil. Further, it has a steadfast resistance to drought, heat, cold, insects, and disease (Critchfield, 1970). For maintenance of Boston ivy, pruning in the summer season may be required in areas where extensive growth is unwanted.

2.6 Local Distinctiveness of the City of Toronto

The City of Toronto is the largest city in Canada with a population of over 2.7 million people reported in 2013 (City of Toronto, 2013b). The hub of the Greater Toronto Area, the City of Toronto is located on the shore of Lake Ontario. The city is diverse in people, culture and landscape. Coinciding with global trends of increased urbanization, the City of Toronto is continually expanding.

2.6.1 Climate

Toronto's weather is one of the mildest in all of Canada, with spring and summer temperatures fluctuating between 15–25 °C (Table 2.1). In the winter season, the daytime temperature remains slightly below freezing, exclusive of the month of January (City of Toronto, 2013a). These moderate temperatures are a result of the close vicinity of Lake Ontario and the high rate of urbanization. Temperatures in Toronto are becoming warmer and extreme weather events are becoming more prevalent (Penney, 2008). In the summer of 2005, temperatures remained above 30˚C for 41 days, a record for the city (Environment Canada, 2005). These types of climate and weather changes are expected to ensue with the prospective proliferation and

Table 2.1: Toronto Climate Normals, 1961-2000. The characteristically moderate temperatures of the City of Toronto, a highly urbanized metropolitan area (Environment Canada, 2013).

	Jan	**Apr**	**Jul**	**Oct**
Temperature				
Daily Maximum (°C)	-2.1	11.5	23.7	13.9
Daily Minimum (°C)	-10.5	1	14.8	3.9
Daily Mean (°C)	-6.3	6.3	20.8	8.9
Extreme Maximum (°C)	16.7	31.1	37.6	30.6
Extreme Minimum (°C)	-31.3	-17.2	3.9	-8.3
Precipitation				
Rainfall (mm)	24.9	62.4	74.4	63.4
Snowfall (cm)	31.1	5.7	0.0	0.5
Precipitation (mm)	52.2	68.4	74.4	64.1
Extreme Daily Rainfall (mm)	58.7	55.8	118.5	121.4
Extreme Daily Snowfall (mm)	36.8	26.7	0.0	7.4
Extreme Daily Pcpn. (mm)	58.7	55.8	118.5	121.4
Extreme Snow Depth (cm)	67	13	0.0	13
Days With				
Maximum Temperature > 0 °C	12.3	29.4	31.0	31.0
Measurable Rainfall	5.1	10.7	10.1	11.5
Measureable Snowfall	12.6	2.6	0.0	0.40
Measureable Precipitation	14.9	12.1	10.1	11.5

impacts of climate change.

2.6.2 Urban Heat Island Mitigation and Adaptation

In response to the current and impending climate change in Toronto, the City of Toronto has developed a number of climate change adaption strategies, including programs to manage storm water and flooding, strengthening energy supply systems and increasing urban forest cover (Penney, 2008). It is one of the first cities to establish a detailed climate adaptation scheme (Penney, 2008). In 2010, the Clean Air Partnership (CAP) held the 2010 Urban Heat Island Summit to address the particular concern of the negative impacts of the urban heat island effect. Local government, researchers and industry members came together to discuss and devise strategies for heat island mitigation. The major strategies that were proposed were cool roof technology, the use of green roofs, innovative paving options, the strategic planting of trees around homes and buildings and proposals for new policy and planning initiatives and standards (Clean Air Partnership, 2010). Overall, the main recommendations made for effective heat island mitigation in Toronto were for greater partnership, discussion, research and awareness.

The main strategies for heat island mitigation in Toronto regarding increased vegetation cover include sustainable building standards, tree protection and green roof bylaws and increased canopy cover. The Toronto Green Standard (TGS) is a standard that requires the urban heat island effect to be accounted for by new corporate and private developments. The TGS is a "two-tiered set of performance measures with supporting guidelines related to sustainable site and building design for new public and private development. The standards are designed to work with the regular development approvals and inspections process" (City of Toronto, 2012). To fulfil the urban heat island development feature, under Tier 1, some requirements or options include the use of high-albedo surface materials, providing adequate shade (built or vegetated) and the installation of green roofs (City of Toronto, 2012).

The province of Ontario has established the Ontario's Trees Conservation Act, 1946, Trees Act, 1950, Forestry Act, 1998 and Municipal Act, 2001 to ensure the maintenance of healthy forest systems in the province (FitzGibbon & Summers, 2002). These Acts grant municipalities with the power to legislate by-laws and policies that manage the protection of city trees. Accordingly, urban forest by-laws and policies in Toronto have been put in place to protect against the damage to trees and to sustain urban forestry management practices and objectives (City of Toronto Urban Forestry, 2005). The Private Tree By-law states that if the diameter of a tree is 30 centimetres or greater, it cannot be removed from city or private property without a valid permit. The Green Roof Bylaw requires that new developments of private and public buildings with a minimum Gross Floor Area of 2000 m^2 must install a green roof and adhere to a set of standards for green roof design and production. Toronto is the first city in North America to instate a bylaw of this manner.

Toronto's urban forest is comprised of 10.2 million trees and encompasses about 20 percent of city land, a much greater urban forest cover than most regions in Ontario (City of Toronto Urban Forestry, 2005). Preceding this coverage, the City observed a 0.7 percent decline in canopy cover over an extent of six years, from 1999 and 2005 (City of Toronto Urban Forestry, 2005). Current tree coverage is highly disproportioned throughout the city, with the majority of trees clustered on natural or park land. The sustenance and expansion of Toronto's urban forest has been gaining increased public and government concern over the past few years and is a pressing issue for today's policymakers and planners. Based on research evaluating the state and performance of urban forests in various locations across the United States, American

Forests propose that to maintain a maximally serviceable and sustainable urban forest, tree cover should comprise an average of 40 percent of land, comparable to about 50 trees per hectare (City of Toronto Urban Forestry, 2005). Facilitated by this proposal, in 2005 the City of Toronto set a target to increase tree cover from 20 to between 30 and 40 per cent in the next 50 years. Bass et al. (2002) states that potential land use and zoning restrictions in the City of Toronto can significantly impact the potential for expanding tree canopy cover. He suggests that other space in the city, such as private residential property, needs to be exploited to increase vegetation in Toronto.

2.7 Summary

The urban heat island phenomenon is a major threat to the well-being of urban centres. In the face of prospective increases in temperatures due to climate change and with the rate of urbanization rising worldwide, there is an urgent need for heat island mitigation strategies in order to combat the current adverse effects of urban heat islands and prevent their intensification. The loss of urban vegetation due to its replacement with built surfaces and the re-introduction of vegetation in urban centres are key aspects of heat island formation and prevention, respectively. The strategic arrangement of trees and large plants around buildings has been shown to significantly reduce temperatures of building microclimates through shading, evapotranspiration and air circulation processes. Using green walls to reduce microclimatic temperature in cities is a novel concept with significant potential, notably if used in combination with additional vegetation-based temperature mitigation strategies (e.g., strategic planting of trees). Moreover, this vegetation strategy can make use of the vast and unexploited wall space of urban centres. In addition to the prospective climate moderating influences of this study, covering the exterior walls of urban buildings may offer energy-saving, aesthetic and psychological values that are also widely associated with increased vegetation in urban areas.

The evaluation of the potential for green walls to mitigate microclimatic warming is an ongoing area of research. Of the limited research available on the use of green walls for the mitigation of microclimatic temperatures, new green façade and living wall green wall systems are the focus of the literature, as opposed to studies on traditional green wall systems, though all systems demonstrate good temperature mitigation performances. There is a need for further research on the execution of traditional green wall systems. Most research in the field of green wall systems has been based on short-term and small-scale studies. Variations in the outcome of studies indicate that additional research is needed to establish the most successful species of plants, systems and settings. Studies also call for further supportive research and applications in other climate environments. The majority of published literature on this subject comes from European and Asian studies. With regard to the selection of plant species for traditional green wall systems, the vine species Boston ivy is a noteworthy selection as it is easy to propagate, has large, dense foliage that can offer enhanced shading and evapotranspiration effects, its growth climaxes in the summer when its temperature mitigating potential is most needed, it has good adhesion to surfaces without causing significant damage to building materials, it grows quickly, has a long life span and is robust and able to endure harsh environmental conditions.

At present, there is a lack of commentary, discussion and consideration of the environmental management implications of the use of green walls for urban temperature mitigation. The City of Toronto has established a variety of strategies to mitigate its urban heat island, one being the increase of vegetation. Green walls are recognized under the TGS for their mitigation of the urban heat island effect, however, unlike trees and green walls, there is no valid municipal management plan for green walls in the City of Toronto and the discussion and support for its use for heat island mitigation is not prevalent. Green walls may have a compelling place within heat island mitigation and the associated urban forestry expansion efforts in the City of Toronto. Moreover, the conception of a predictive model to evaluate the effectiveness of perennial vines to mitigate rise in built surface temperatures (an important driver of microclimatic temperature) under specified climatic variables, is not present in the literature. This type of model could be useful for management of the use of perennial vines for heat island mitigation in cities.

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CHAPTER 3

3.1 Abstract

Shading and evapotranspirative cooling by urban vegetation are important controls on the rise of summer temperatures in cities. Increased plant cover in cities can play an important role in moderating rise in temperature and mitigating the adverse effects of urban heat islands. The purpose of this research is to evaluate the potential of Boston ivy (*Parthenocissus tricuspidata*) to mitigate warming of building surface temperature in an urban core, where vine use for this purpose has not been comprehensively investigated. Temperature loggers were placed on vine-shaded and non-shaded walls in downtown Toronto, Canada to collect surface temperatures over a six-month period (coincident with perennial leaf coverage). During peak solar access periods, average vine-shaded and non-shaded temperature differentials of up to 6.5 °C and 7.0 °C for the south and west-facing walls were measured, respectively. Predictive models were developed to estimate daily degree hour difference (DHD), a metric for capturing the magnitude and duration of the temperature moderating potential of vines. At ambient air temperatures exceeding 22 °C, ambient air temperature and solar radiation were determined to be significant positive drivers of vine effectiveness to mitigate rise in built surface temperature. Results are important to further understanding the significance of urban plant-microclimate interactions and strategies for heat island management in cities.

Keywords: urban heat island; microclimate; perennial vines; temperature mitigation

3.2 Introduction

In cities, the process of urbanization is habitually accompanied by the replacement of vegetated land cover with impervious, built surfaces. Natural surfaces typically consist of vegetation, which release moisture into the air via evapotranspiration, shade built surfaces and reflect incoming solar radiation; collectively acting to minimize urban heat islands (Synnefa et al., 2008). In contrast, built surfaces enhance urban heat islands by absorbing incoming solar radiation and storing it as heat (Synnefa et al., 2008). The high heat absorption of these urban surfaces and loss of the natural cooling effect of vegetated land cover give rise to higher air temperatures relative to surrounding rural regions, a phenomenon known as the urban heat island effect (Rosenfeld et al., 2005). Heat islands can occur at the micro-scale of one city building (Parker, 1983) or at the large scale of a big city (Taha, 1997). During the summer, the average urban centre can produce a warming effect of roughly 2.5 °C on a cloudless afternoon (Rosenfeld et al., 2005).

The urban heat island effect has significant implications for the environmental stability of cities, causing major ecological, social and economic concerns (Akbari et al., 2001; Patz et al., 2005). The occurrence and enhancement of urban heat islands present substantial consequences for local energy demands, air quality, (Akbari et al., 2001) and heat and pollution related-health issues (Patz et al., 2005). Akbari et al. (2001) report that when ambient temperatures reach 18 °C, there is a 3 – 4% increase in air conditioning use for every 1 °C increase thereafter. McGeehin (2001) indicate that heat-related deaths are more common in urban regions. High ambient temperatures can cause heatstroke, fainting, heat exhaustion and heat cramps. With impending climate change and the rate of urbanization rising globally, the frequency and severity of urban heat islands and their associated adverse effects may intensify, accelerating the need for urban heat island mitigation strategies (Akbari et al., 2001). Accordingly, the mitigation of urban heat islands has become a prominent objective of many environmentally-conscious urban policy regimes (Papadopoulos et al., 2003; Solecki et al., 2005; Yamamoto, 2006).

Increasing vegetation cover in urban centres has proven to be an effective urban heat island mitigation strategy (Akbari et al., 2001; Rosenfeld et al., 1995; Solecki et al., 2005). Vegetation acts to mitigate rise in summer ambient air temperatures by providing shade and through the process of evapotranspiration (Akbari et al., 2002). There is a considerable amount of empirical evidence demonstrating the particular success of urban trees to moderate air temperature in urban microclimates. Urban microclimates arise due to the intricate interactions of natural and anthropogenic factors, resulting in climates of discrete urban areas that may deviate from the proximate regional climate. Studies demonstrate that the strategic placement of trees and large plants around buildings can considerably mitigate the microclimatic temperatures of building environments (Akbari et al., 2001; Akbari et al., 2002; Parker, 1989; Rosenfeld et al., 1995). Measurements of air temperatures in areas under the shade of trees in Miami, Florida were an average of 3.6 ◦C lower than air temperatures measured in adjacent, non-shaded areas (Parker, 1989). Vegetation-induced microclimate modifications can influence energy budgets, climate conditions and human wellness (Miller, 1997).

Climbing plants and green walls have the potential to offer urban environments similar thermal microclimatic improvements to that of trees and large plants. In view of the space constraints of most urban centres, greening the external walls of buildings with climbing plants prospectively presents a far-reaching approach to mitigating warming of urban microclimates by means of vegetation. The terms green wall, vertical garden and plant wall are used interchangeably by the public and in academic research to refer to vegetated wall surfaces. Green walls can generally be categorized into three main groups: traditional, green façades and living walls. Traditional green walls are those that feature plants that grow directly on the wall surface without any assistance from external support structures, such as vines (Pérez et al. 2011). Green façades and living walls are green walls that incorporate vegetation with wall frames or other built material on or around a building surface (Pérez et al. 2011; Perini et al. 2013). While current literature proposes that green walls have significant temperature moderating capabilities (Hoyano, 1988; Sandifer & Givoni, 2002; Stec et al., 2005; Wong et al., 2009), few have undertaken a comprehensive assessment of the summer temperature moderating potential of these vegetated surfaces in cities.

The purpose of this research is to evaluate the potential of Boston ivy (*Parthenocissus tricuspidata*) to mitigate warming of building surface temperature in an urban core. Traditional green walls have long been aesthetic attributes of structural designs. Their use as a technique to moderate microclimatic temperatures of urban building environments, however, has not been comprehensively investigated. Specifically, there is a lack of research that investigates and captures the time of day and particular temperature thresholds at which this cooling potential would be most relevant and impactful. The notion of using green walls for environmental improvement is particularly unstudied in North American settings. Additionally, there is little discussion of the environmental management implications of perennial vines to moderate summer temperature rise in urban areas.

Tools to assess how green walls influence the thermal microclimate of buildings are needed so that planners may have information necessary to consider the potential for this form of greening to be included in urban heat island mitigation strategies. The use of statistical models to predict the outcome of environmental phenomena is rapidly becoming an important tool in environmental planning and management sectors (Herrera et al., 2010; OECD Global Science

Forum, 2011). To date, a model has not been published that can predict the effectiveness of green walls at mitigating rise in built surface temperatures under specified climatic conditions.

The main objective of this research will be to evaluate the ability of perennial vines to mitigate rise in built surface summer temperatures during peak solar access periods and at peak temperatures. At these particular time periods and temperatures, this temperature moderating effect would be most beneficial at alleviating human thermal discomfort and, accordingly, temper demand for air conditioning. Specifically, this study aims to: (1) quantify the degree to which perennial vines can moderate rise in built surface temperature by comparing temperatures recorded on vine-shaded and non-shaded south and west-facing urban walls; (2) if there is a significant temperature difference, to determine the magnitude of the difference and assess during what time it is greatest; (3) determine how results vary between south and west-facing wall exposures; (4) evaluate how much variability exists among the values recorded by shaded and non-shaded temperature loggers; (5) produce a statistical model for the prediction of the effectiveness of vine mitigation under particular climatic conditions; and, (6) evaluate the possible implications of this research for environmental management in urban centres.

3.3 Methods

3.3.1 Study Site

The study site was located at the University of Toronto, 27 King's College Circle, Toronto, Ontario, Canada. This setting was an ideal location for the purpose of this study as it is situated in a highly urbanized region of Toronto that features buildings with exterior walls covered in part by perennial vines. Specifically, this study examined Hart House, a stone masonry constructed building with good coverage of Boston ivy (*Parthenocissus tricuspidata*), a perennial climbing vine, on the approximately south and west-oriented walls (Figure 3.1). Built in 1919, it is a two and a half-storey building located in an area of the campus that largely keeps it free from the shading effects of surrounding features.

3.3.2 Boston Ivy

Boston ivy is an ideal vine to grow on walls for mitigating temperatures. Originating from eastern Asia, Boston ivy can be found in many temperate locations and is characterized by its large, abundant and lobed foliage. The leaf layer and leaf size of Boston ivy is thickest in the summer season when its potential to mitigate warming is most needed, with leaf size reaching 25 cm (Critchfield, 1970; Tenenbaum, 2003). It is easy to grow, adheres well to surfaces, has a long life span and can withstand harsh environmental conditions (Critchfield, 1970; Tenenbaum, 2003). Adhesive discs from the tendrils of the vines allow the vine to attach to substrate material. This adhesion method allows the growth of Boston ivy on common building materials, such as brick or stone, without significant damage to surfaces or to the mortar binding these materials together (He et al., 2010). Where vines are found in Toronto, Boston ivy is a common species.

3.3.3 Instruments

To monitor the surface temperatures of vine-shaded and non-shaded wall environments and temperatures of the ambient environment, HOBO® Pendant® Temperature Data Loggers were used (Onset Computer Corporation). This type of logger was chosen for its high accuracy, small size and large memory capacity. These temperature data loggers are weather-resistant, transportable devices that measure and record temperature readings over a specified range of time. Temperature readings are recorded in digital format, enabling temperature information to

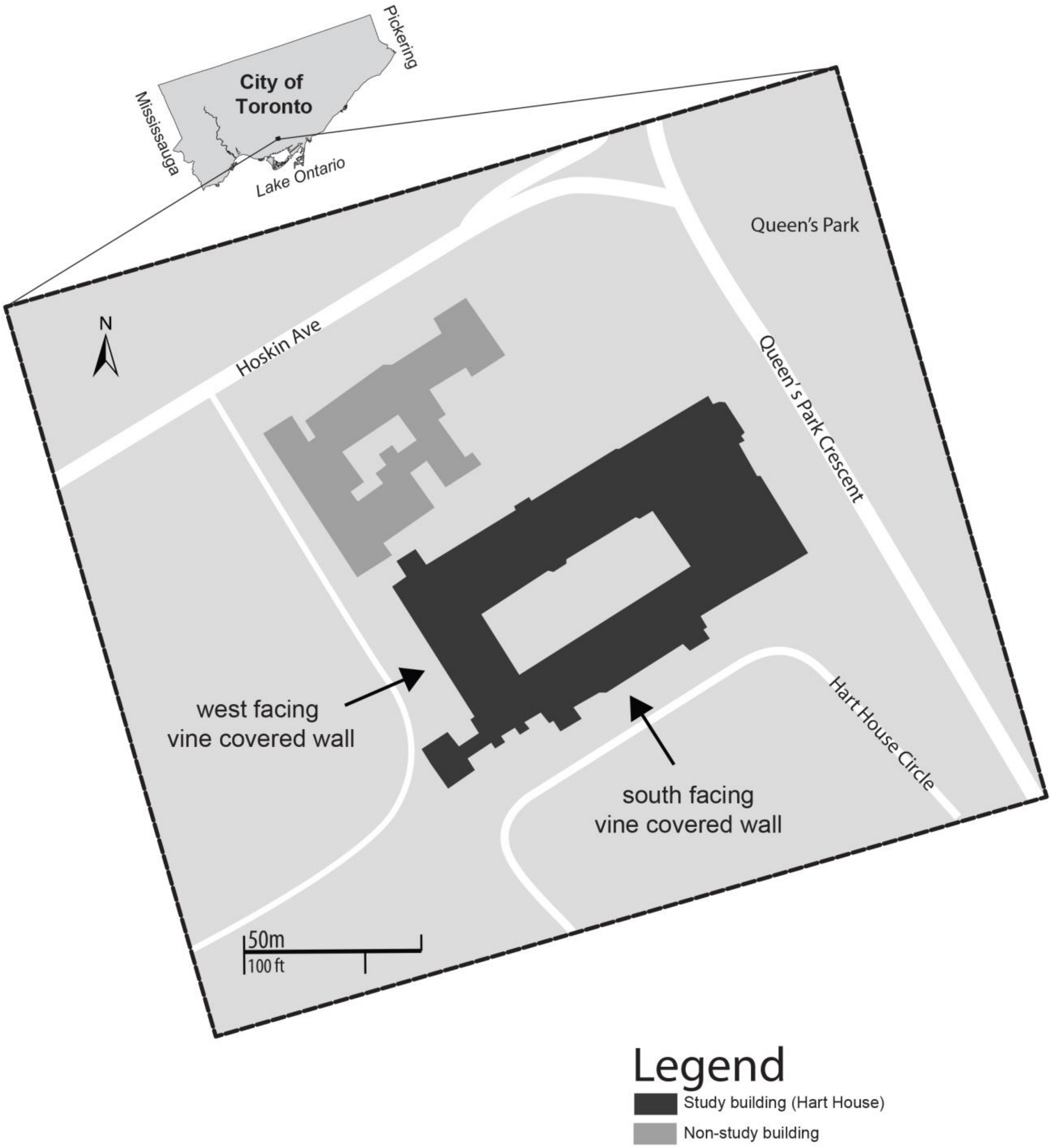

Figure 3.1: Location of the study site (University of Toronto, 27 King's College Circle, Toronto, Ontario), featuring the study building and indication of the south and west-facing walls (approximate directions) under investigation.

be digitally accessed and reviewed. As loggers were exposed to direct solar radiation, each logger was placed in individual solar radiation shields to ensure accurate temperature measurements. Loggers were tested in laboratory settings prior to the start of the study to ensure that they were functioning optimally and concurrently, although loggers were calibrated by the manufacturer to record temperatures within 0.5 °C of each other. To test loggers, all loggers were set to collect data every 15 minutes over a one week period in temperature conditions that ranged from 2.5 °C to 26 °C. Subsequently, a multivariate correlation analysis was used to assess the similarity between loggers. All loggers used in this study were deemed statistically similar.

3.3.4 Data Collection

For each of the exterior walls of the building that were monitored, the south and west-facing walls, 12 vine-shaded loggers, 6 non-shaded loggers and 2 ambient loggers were sited, labelled by location and mapped. The vine-shaded and non-shaded loggers measured wall surface temperatures, while ambient loggers measured the temperature of the ambient environment. To ensure objectivity, the location and positioning of vine-shaded and non-shaded loggers were determined using a randomized sampling approach. For each wall, a photo of the wall was taken and a grid was superimposed on top of the photo. The grid cells were used to select for proportionate strata of vine-covered and non-shaded wall areas. Sample locations within each strata were randomly selected for using a random number generator, where the cell corresponding with the randomly generated number represented a temperature logger location. This sampling method captured the entire spatial extent of each wall between 2 and 5 m in elevation on the building, allowing for consistent measurements and representative of the first and second storey of the study building. This height situated the loggers away from the reach of people and ground-level activity around the building. To further ensure consistency and accuracy, all vine-shaded logger sites were selected to provide a high degree of leaf coverage, which was determined using a visual assessment of leaf density. All areas where vine-shaded loggers were located had good vine coverage. Over the study period, the amount of coverage was qualitatively accounted for. Using a ladder, vine-shaded temperature loggers were situated on each wall under the shade of the vine canopy to obtain vine-shaded temperatures and non-shaded temperature loggers were placed on vine-free exposed areas of each wall. Loggers were secured inside radiation shields and attached to the walls using VELCRO® Brand extreme strength fasteners, allowing them to be simply and non-invasively fixed to and easily removed from the walls. Ambient microclimatic temperatures in the vicinity of each wall were measured using temperature loggers fitted in radiation shields and affixed to lamp posts situated within 5 m of the building walls and at between 1.5 and 2 m above the ground.

Only the west and south-facing walls of the building were monitored as the literature indicates that during the growing season, the west and south-facing walls of buildings receive the greatest amount of net solar gain (McPherson, 1984; Simpson and McPherson, 1996; Solecki, 2005). The solar gain received by north and east-facing walls are not usually deemed to be large enough to significantly benefit from the temperature moderating effects of vegetation (Givoni, 1998; McPherson, 1984; Simpson and McPherson, 1996; Solecki, 2005). The number of loggers and their sampling frequency were deemed appropriate to capture sufficient variation in recorded temperatures and are valid for conducting robust statistical analyses; they also mirror sampling techniques used in similar research (Pérez et al., 2011; Sandifer & Givoni, 2002; Wong et al., 2009).

Over the time period of May 9 to October 31, 2012, simultaneous temperature readings were measured and recorded by all loggers every 15 minutes. This timeframe captured the general growing season of Boston ivy (May to mid-late October) and the periods of highest temperatures in Toronto (generally June through August). The collection of data every 15 minutes allowed for the desired temporal resolution for prospective analyses. Data from loggers had to be periodically downloaded as the memory storage of the device had a limited capacity. Loggers were removed to download data on the following dates: June 27, July 12, July 30, August 30 and November 1, 2012; with the exception of November 1, all temperature loggers were returned to their individual locations on the walls following data download. Loggers never remained off-line for more than two hours when taken down for downloading data. Other than ambient temperature, which was obtained using temperature loggers within 5 m of the study walls, as previously discussed, all other meteorological data used in the study were acquired from a weather station within 1 km of the study site that collected data on wind speed, precipitation, relative humidity and solar radiation every 15 minutes.

3.3.5 Data Processing

Data were digitally downloaded onto a computer using HOBOware Pro (Onset Computer Corporation), a software tool for accessing data logger information and for graphing and analyzing data. Using this software, the data were exported into Microsoft Excel spreadsheets, one spreadsheet of data for each logger. Spreadsheets were combined to encompass all data from the duration of the study period for both the south and west wall data sets. All data loggers for each temperature measurement category (ambient, vine-shaded or non-shaded) were averaged to obtain 15-minute measurements for each category over the 6 months of the study period for both the south and west wall environments.

For the purpose of this study, only temperatures recorded during the peak solar access periods, where ambient temperature exceeded a threshold temperature, were used in subsequent analyses. Generally, these threshold ambient temperatures are at 18 to 22 °C and occur at a time of the day when walls experienced direct exposure to the sun (Akbari et al. 1997; Akbari et al., 2001; Fountain et al. 1996). To determine the peak solar access period for each wall, the average ambient, vined-shaded and non-shaded wall temperatures over the course of a day for the warmest months of the study period (July and August) were graphed and visually compared. The time period for each wall that most accurately captured any mitigation activity (greatest difference between sun and shade temperatures) and at which the largest ambient temperatures appeared, were deemed suitable solar access periods. Time windows were selected to be 10:00 to 18:00 for the south wall and 12:00 to 20:00 for the west wall. The variation between the time windows is dictated by the movement of the sun during the day and the amount of solar radiation reaching each orientation, as the sun moves from east-to-west in the sky.

To analyse daily temperatures over the course of each month, ambient, vined-shaded and non-shaded temperatures recorded at times that occurred within the 8-hour, peak solar access periods were averaged on a daily basis for each wall. Median temperatures that were recorded by the ambient loggers were subtracted from each of the median vine-shaded and median non-shaded logger recordings for each day. These differences permitted an evaluation of how the different wall temperature environments deviated from the proximate ambient microclimatic temperatures. Additionally, temperatures that were recorded by the vine-shaded loggers were subtracted from those measured by non-shaded loggers for each day. These differences (differentials) permitted an evaluation of the effect of vines to mitigate rise in building surface temperature. The average of these daily differences, for each month, permitted the assessment of the general ability of vines to mitigate temperature rise.

To analyze temperatures over the course of an average day, ambient, vined-shaded and non-shaded temperatures recorded at times that occurred within the 8-hour peak solar access periods for each wall were averaged for each 15-minute time point obtained by the loggers (starting at time 10:00 and ending at time 17:45 for the south wall and starting at time 12:00 and ending at time 19:45 for the west wall). Temperatures that were recorded by the vine-shaded and non-shaded loggers were both subtracted from measurements received by the ambient temperature loggers that corresponded with the appropriate wall orientation. These differences allowed for a review of how the various wall environments differed from the ambient environment for a "typical day" temperature pattern.

Degree hour difference (DHD) values were calculated over the course of each month, and for each building aspect, by taking the difference between the hourly average of vine shaded and non-shaded temperature loggers and summing them over the course of each day to determine temperature differential x duration of the differential. DHD was developed to provide information on total daily thermal energy differences between vine-shaded and non-shaded microenvironments. It is a metric that allows for an evaluation of variables that may provide an explanation of the energy differential encountered between vine-shaded and non-shaded walls, such as climatic conditions (i.e., solar radiation, ambient temperature, wind speed, relative humidity, precipitation).

For each of the building aspects (south and west) in this study, DHD was calculated at time points where ambient temperature exceeded a 22 °C threshold, subsequently referred to as

South-DHD22 and West-DHD22. This threshold was selected because at ambient temperatures of between 18 to 22 °C, the thermal comfort of humans is compromised (Akbari et al. 1997; Akbari et al., 2001; Fountain et al. 1996), resulting in rising demand for indoor air conditioning.

To evaluate daily meteorological data over the course of each month, ambient temperature, relative humidity, wind speed, solar radiation and precipitation data recorded at times that occurred within the 8-hour, peak solar access periods for each wall were averaged on a daily basis. This overview of data allowed for the general meteorological occurrences and trends over the period of the study to be evaluated in the context of the effectiveness of the temperature mitigating impact of the vines.

3.3.6 Statistical Analyses

All descriptive statistical analyses and tests of difference were conducted using IBM SPSS software. General descriptive statistics (mean, standard deviation, minimum, maximum, median, skew and variance) for the three temperature categories collected over the 6-month period of the study (ambient, vine-shaded and non-shaded) were calculated for the 15-minute interval data, and for the daily average temperature data, for both the south and west wall data sets.

Comparisons of the difference between average daily vine-shaded and non-shaded building surface temperatures were conducted for each wall across the 6-month study period, as well as the difference between the average vine-shaded and non-shaded temperature differentials between the south and west walls across the 6-month study period. To evaluate whether the daily average vine-shaded and non-shaded temperature samples followed an approximate normal distribution, an assumption necessary for the use of prospective statistical methods, a Shapiro-

Wilk test was run. Data were determined to be negatively skewed and thus, a square root reflection transformation was applied. Two-sample t-tests were performed using the transformed data to determine whether the difference between samples was statistically significant.

Similarly, two-sample t-tests were performed to evaluate the difference in temperature between average daily vine-shaded and non-shaded building locations, for each month and for the south and west walls, respectively. All data were evaluated to ensure that the assumption of an approximate normal distribution was present. Comparisons between the average daily temperature differentials recorded on the south versus west walls were also conducted for each month.

3.3.7 Predictive Modelling

Multiple regression analysis is an inferential statistical technique that can produce a model from samples of data in order to predict the response of a dependent variable based on a set of predictor variables (Allison, 1999). To predict how effective the summer temperature mitigating potential of perennial vines may be under particular meteorological conditions, two predictive models (one for each of south and west-facing building walls) were produced using multiple regression analysis in the R computing environment. The temperature moderating effectiveness of vines was based on DHD values, where higher DHD values indicate a greater daily impact of vine-shade on mitigating rise in wall temperatures.

Multiple regression analysis was used to determine the importance of climatic variables as drivers of DHD. Daily average ambient temperature, solar radiation, wind speed, precipitation and relative humidity constituted the suite of independent variables for potential inclusion in each model. The multiple regression was a generalized least squares model that included a moving average correlation structure to account for first-order autocorrelation. Initial model construction involved all independent variables. Where context appropriate, interaction terms were added to the model. A balance of the following factors were considered during model development: (1) model complexity (simpler models were given priority); (2) statistical significance of model coefficients; and, (3) consistency among the two models. R^2 values were calculated to assess how well each model was able to predict DHD. Associated p-values for each model and for each variable and interaction term were also calculated to assess the significance of the relationship between DHD and the associated meteorological predictors.

3.4 Results

3.4.1 Vine Characteristics

The leaf layer at this site was qualitatively evaluated for each season over the course of the study period. Overall, the leaf coverage was consistently denser (i.e., greater leaf area index) on the south wall than the west for the entire duration of the study period. The peak leaf depth for both walls was in the summer season (late-June through August) and was lowest in the spring season (May through early-June). In the fall season (September and October), as leaves started to senesce, the leaves began to fall from the wall, reducing the leaf-generated vine shade. Leaf size at this site was also evaluated for each season over the course of the study period. Peak leaf size occurred in the summer season at approximately 20 cm +/- 1.35 (SD) and was lowest in the spring season at approximately 17 cm +/- 1.9 (SD). Leaf size was determined by measuring the average length of leaves at vine-shaded logger sites for the south and west walls. Generally, conditions of healthy vine coverage were found. Redundancy in the number of vine-shaded sensors used in the study (12 per shaded wall) allowed the microsite variation in leaf characteristics to be captured. Thus, vine-shaded temperature values reflect microsite variation in temperature behind a healthy vine-covered wall.

3.4.2 Meteorological Data

Average daily meteorological data (i.e., ambient temperature, relative humidity, wind speed, and solar radiation) for the study area during peak solar access periods are presented in Figure 3.2 and 3.3 for the south and west-facing walls, respectively. These figures also include precipitation, which was summed daily. These meteorological trends correspond with standard weather conditions in Toronto, Canada, and reflect a dryer than average growing season.

3.4.3 Sun and Shade Temperature Differentials

Overall, descriptive statistics show variability between daily average vine-shaded and non-shaded temperatures for each of the south and west walls during their corresponding 8-hour peak solar access periods. Vine-covered walls were found to have less overall variance in temperature than non-shaded walls. Daily variance in temperatures recorded in vine-shaded locations were lower than those in non-shaded locations. Standard deviation values were +/- 4.86 and +/- 5.67 for the south and west vine-shaded walls, respectively. In contrast, standard deviation values were +/- 6.57 and +/- 7.73 for the south and west non-shaded walls, respectively. Moreover, non-shaded walls had higher daily maximum temperatures and lower daily minimum temperatures. The average maximum and minimum daily temperatures for the vine-covered walls were 34.4 °C and 11.5 °C, respectively, for the south wall and 34.4 °C and 8.3 °C, respectively, for the west wall. The average maximum and minimum daily temperatures

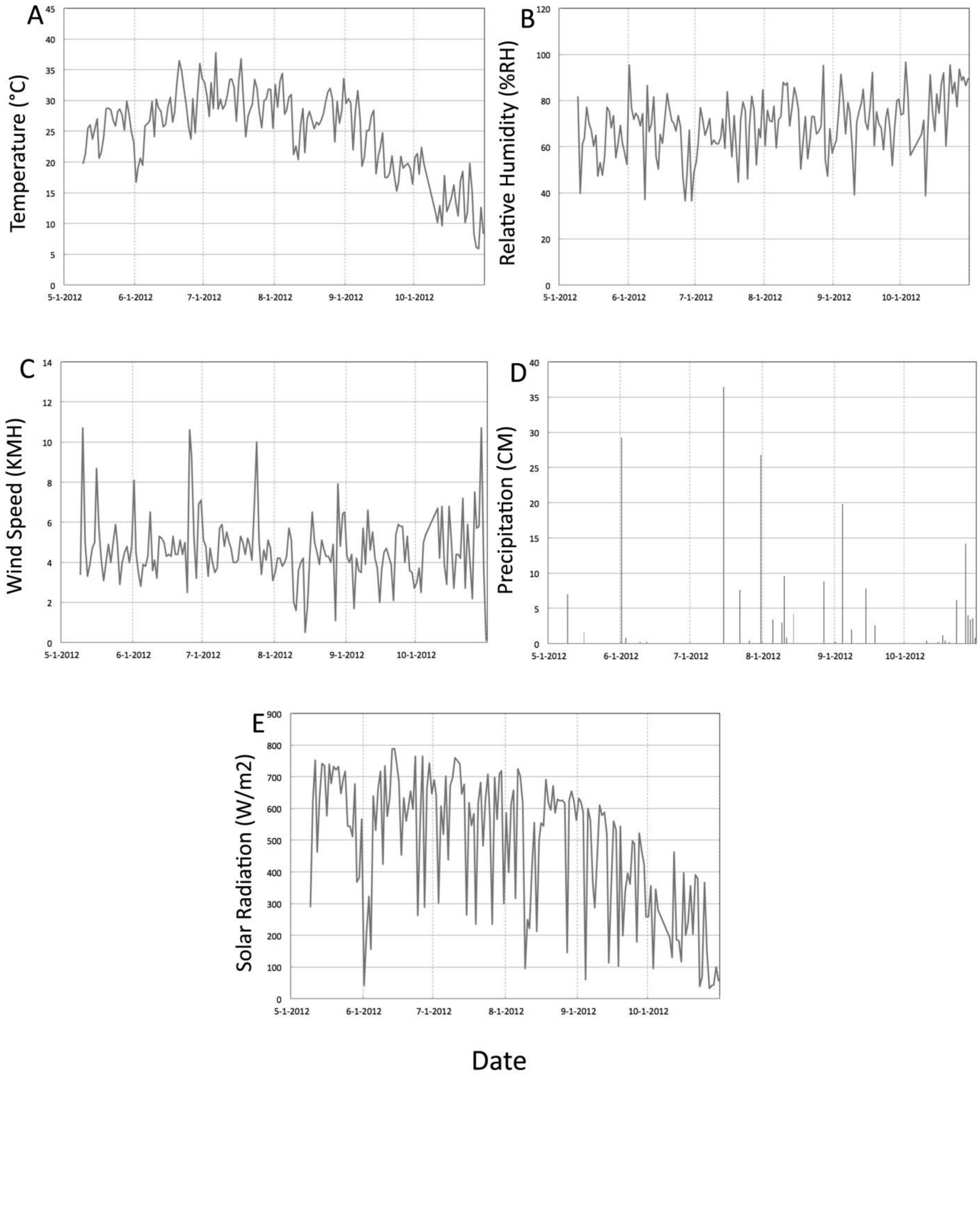

Figure 3.2: Daily meteorological data during the peak solar access period of the south wall (10:00 to 18:00): a) ambient temperature, b) relative humidity, c) wind speed, d) precipitation and e) solar radiation.

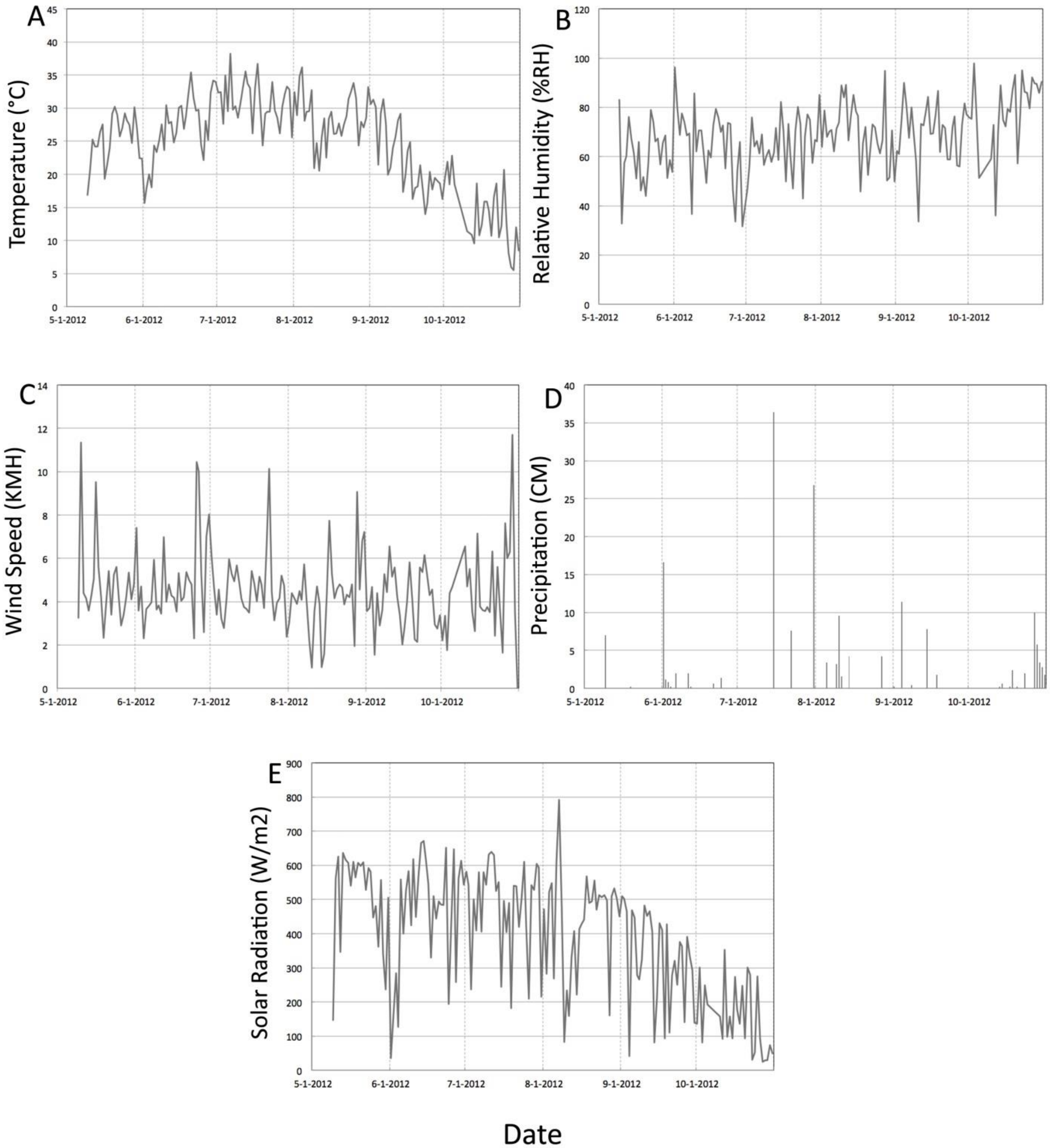

Figure 3.3: Daily meteorological data during the peak solar access period of the west wall (12:00 to 20:00): a) ambient temperature, b) relative humidity, c) wind speed, d) precipitation and e) solar radiation.

for the non-shaded walls were 39 °C and 8.3 °C, respectively, for the south wall and 39.9 °C and 6.3 °C, respectively, for the west wall.

The daily median ambient temperature subtracted from each of the daily median vine-shaded wall temperatures and the daily median non-shaded wall temperatures for the south wall during the 8-hour peak solar access period (10:00 to 18:00) across the study period is shown in Figure 3.4a. With the exception of the months of September and October, the vine-shaded temperatures were largely lower than ambient temperatures, resulting in a large proportion of negative values. Prior to September, the difference between vine-shaded wall temperatures and ambient air temperatures ranged from much cooler (-5.9 °C) to slightly warmer (2.4 °C). In September and October, the vine-shaded wall temperatures were typically greater than the corresponding ambient air temperature, reflected as a large proportion of positive values. The temperature differential ranged from the wall being slightly cooler (-1.2°C) to quite a bit warmer (7 °C). In general, non-shaded wall temperatures were greater than corresponding ambient air temperature, displaying a large majority of positive values. The non-shaded temperature differential ranged from the wall being slightly cooler (-3.2 °C) to quite a bit warmer (10.9 °C) than the ambient air temperature. Overall, the vine-shaded to ambient temperature differential remained lower than the non-shaded to ambient temperature differential across the study period, although the magnitude of the difference between the two differentials appeared to decrease in October.

Figure 3.4b shows the daily median ambient temperature subtracted from each of the daily median vine-shaded wall temperatures and the daily median non-shaded wall temperatures for the south wall during the 8-hour peak solar access period (12:00 to 20:00) across the study period. With the exception of mid-September and October, the vine-shaded wall temperatures

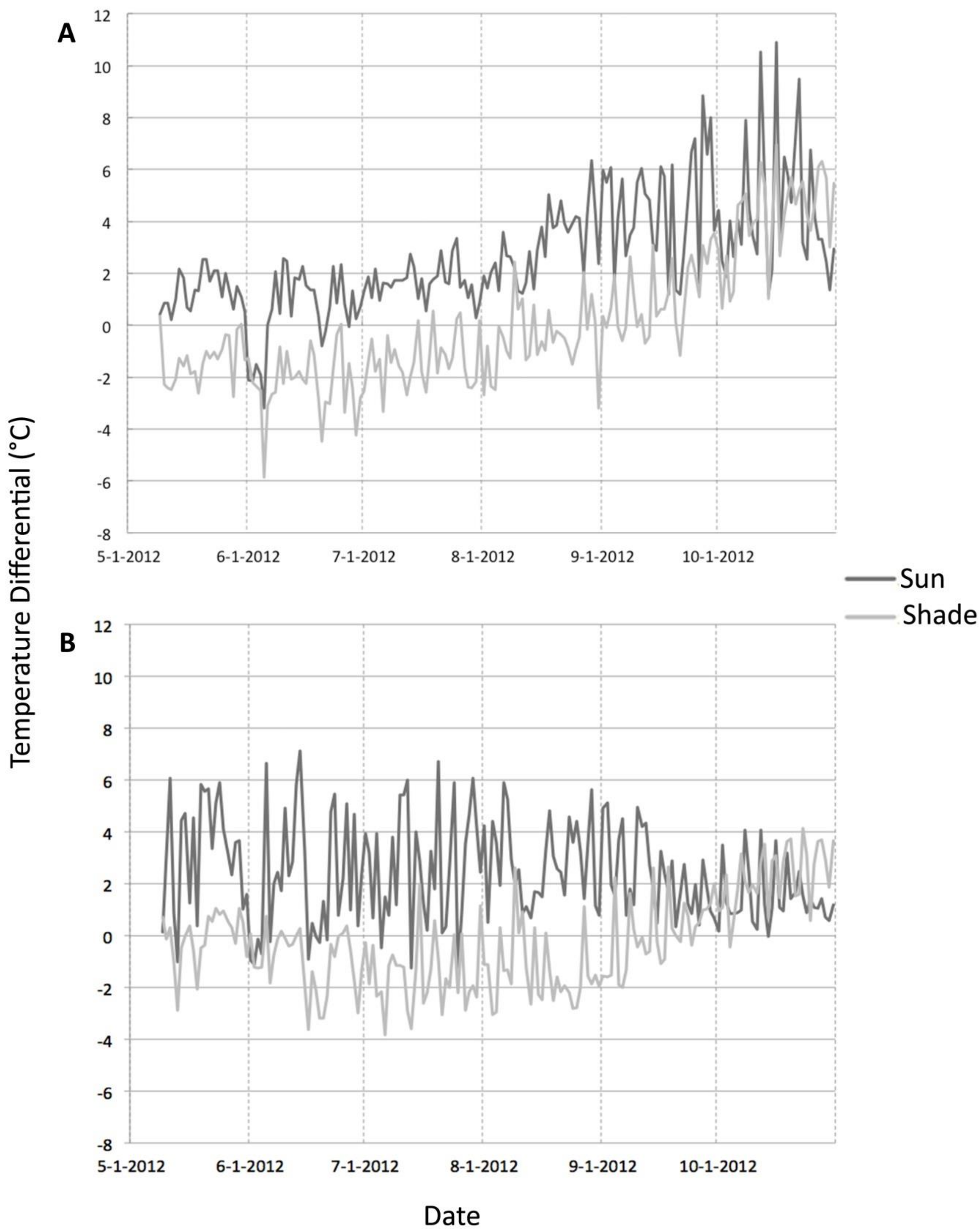

Figure 3.4: Difference of daily median ambient temperatures from non-shaded (sun) and vine-shaded (shade) wall temperatures: a) south wall during south peak solar access period (10:00 to 18:00) and b) west wall during west peak solar access period (12:00 to 20:00).

were lower than ambient temperatures, with a majority of negative values for the length of the study period. Prior to mid-September, shade differential temperatures ranged from modestly cooler (-3.8 °C) to slightly warmer (2.6 °C). In September and October, the vine-shaded temperatures were generally greater than ambient temperatures, represented as a large proportion of positive values. The differential ranged from little difference (-0.42°C) to moderately warmer (4.1 °C). As with the south-facing wall, non-shaded wall temperatures were mostly greater than ambient temperatures, displaying predominantly positive values. The non-shaded wall temperature differential ranged from -1.2 to 7.1 °C. Overall, the vine-shaded differential remained lower than the non-shaded differential for the duration of the study period, with the magnitude of the difference between the two differentials decreasing in late September.

The median ambient air temperature subtracted from the corresponding median shaded and non-shaded wall temperatures for the south-facing wall and during the peak solar access period 10:00 to 18:00 was also evaluated at a 15-minute sampling interval (Figure 3.5). Daily values for each month were averaged to provide a "typical day" temperature pattern for each of the six months investigated. Overall, it can be seen that the fluctuation in temperatures is greater for the non-shaded wall than for the vine-shaded wall. For the months of May, June, July and August, vine-shaded temperatures were mostly lower than ambient temperatures, with predominantly negative values. In contrast, non-shaded temperatures were generally higher than ambient temperatures, and represented by mostly positive values. For each of these months, the vine-shaded differential temperatures ranged from -2.4 to 0.19 °C (May), -2.6 to -1 °C (June), -2.8 to -0.34 °C (July) and -1.5 to -0.45 °C (August). The non-shaded temperature differentials ranged from -1.2 to 3.7 °C (May), -0.83 to 4.1 °C (June), -1.3 to 6.3 °C (July) and 0.3 to 9.1 °C (August). For the months of September and October, both vine-shaded and non-shaded wall

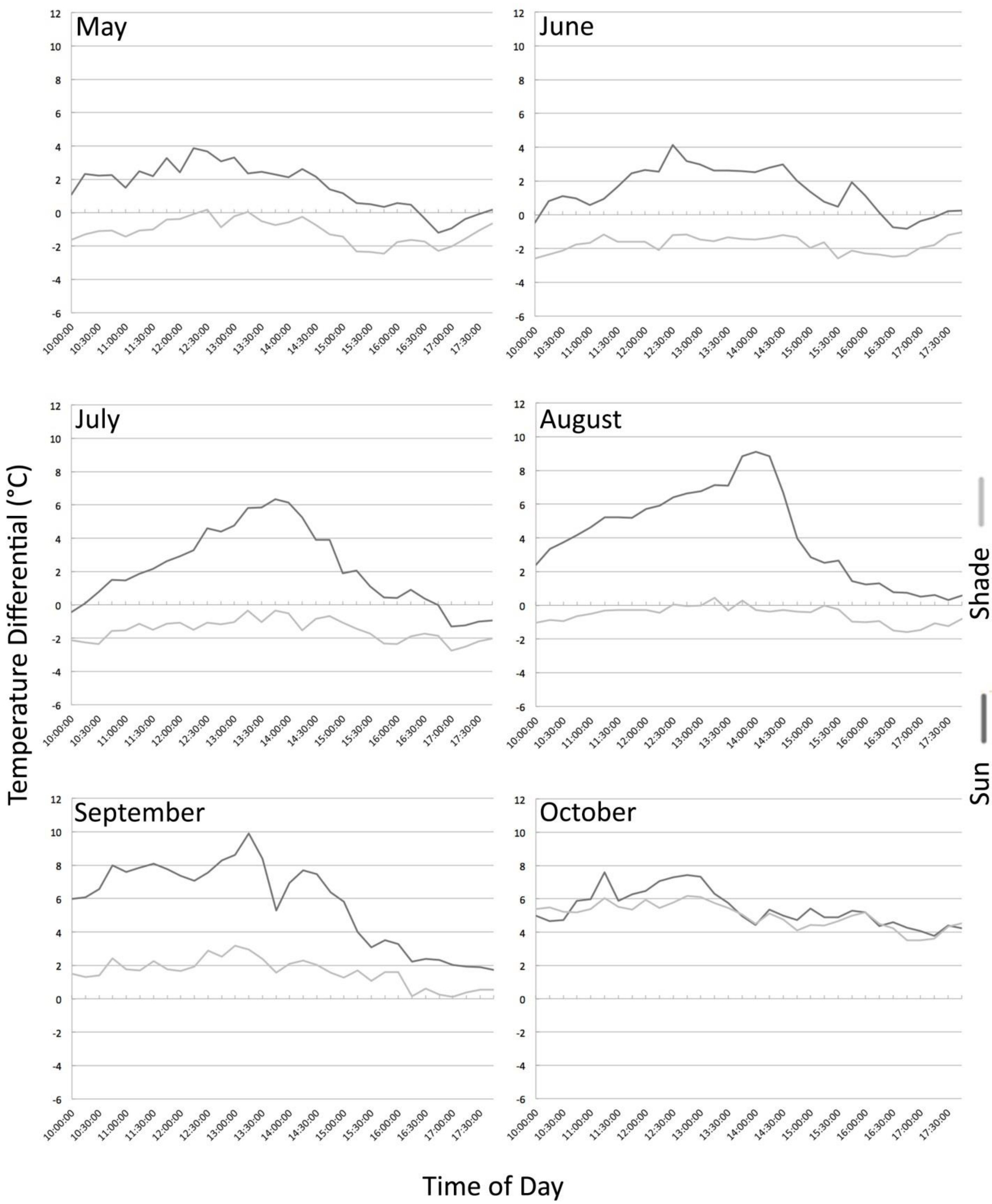

Figure 3.5: Difference of daily median ambient temperatures from non-shaded (sun) and vine-shaded (shade) south wall temperatures for 15-minute sampling interval. Differential measured during the south peak solar access period (10:00 to 18:00) for each month.

temperatures where higher than ambient air temperatures, represented by positive values. Vine-shaded temperature differentials for these months ranged from 0.11 to 3.2 °C (September) and 3.5 to 6.2 °C (October). Non-shaded temperature differentials for these months ranged from 1.7 to 9.9 °C (September) and 3.8 to 7.6 °C (October). The vine-shaded temperature differential remained smaller in magnitude than the non-shaded differential for each month; however, the magnitude of the difference between the two differentials decreased appreciably in October.

The median variation in ambient temperature (15-minute sampling interval) subtracted from each of the median non-shaded and vine-shaded west wall temperatures for all months in the study period and during the 8-hour peak solar access period (12:00 to 20:00) is displayed in Figure 3.6. Overall, fluctuations in temperature were greater for the non-shaded wall than the vine-covered wall. For the months of June, July and August, shade temperatures were mostly lower than ambient temperatures, evidenced by negative values. Vine-shaded wall temperatures were mostly higher than ambient temperatures. For each of these months, the vine-shaded differential temperatures ranged from -2.3 to 1.9 °C (June), -4.1 to 1.7 °C (July) and -4.3 to 1°C (August). The non-shaded differential temperatures ranged from -0.79 to 6.5 °C (June), -3 to 6.1 °C (July) and -3.4 to 6 °C (August). During the months of May, September and October, both vine-shaded and non-shaded wall temperatures were mostly higher than ambient temperatures. Shade temperatures for these months ranged from -2.8 to -1.7 °C, -2.3 to 3.1 °C and 0.91 to 5.6 °C, respectively. Non-shaded temperature differentials for these same months ranged from -1.3 to 5.9 °C, -2.1 to 5.8 °C and 0.23 to 5 °C, respectively. With the exception of October, the vine-shaded temperature differential remained mostly lower than the non-shaded differential.

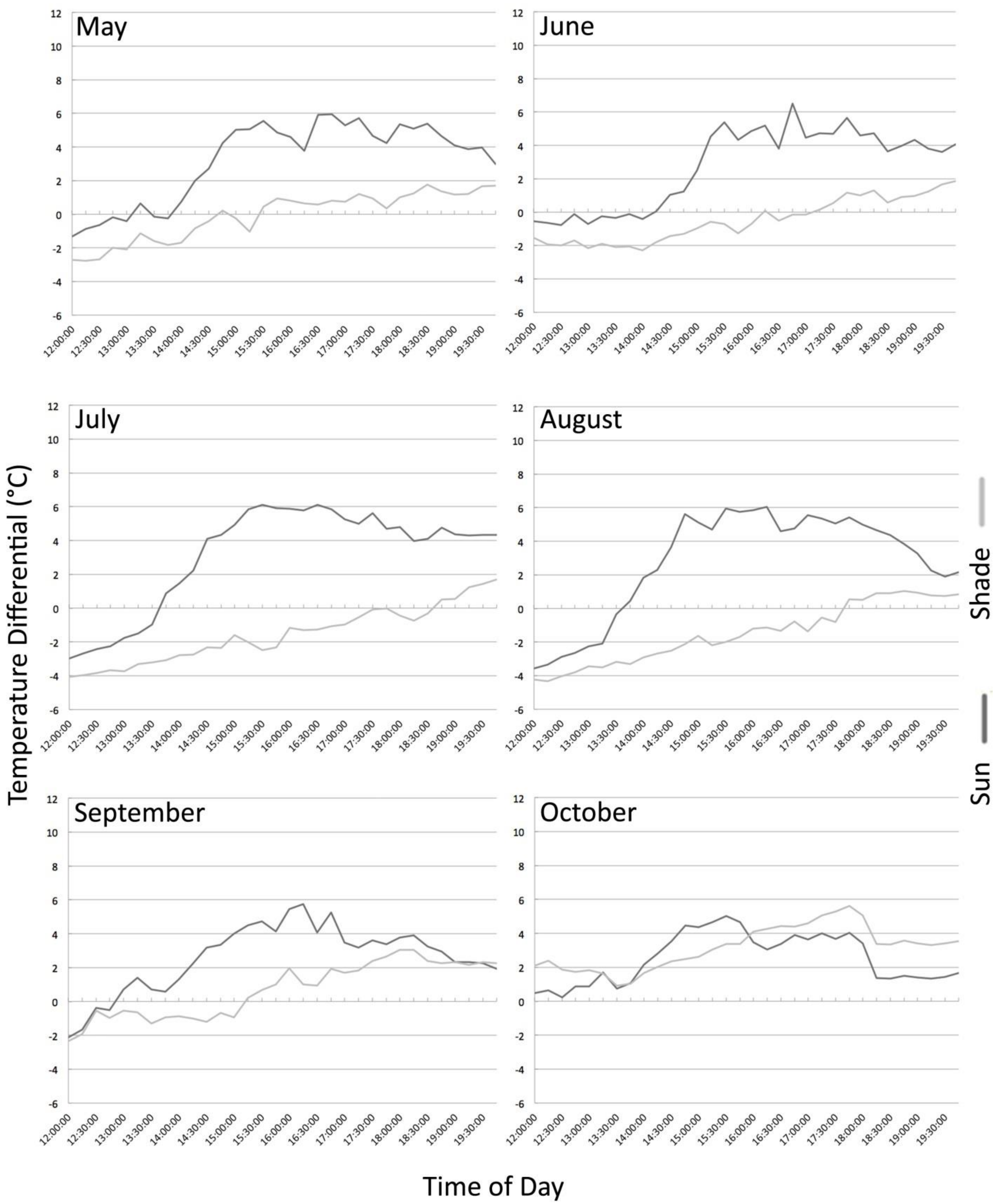

Figure 3.6: Difference of daily median ambient temperatures from non-shaded (sun) and vine-shaded (shade) west wall temperatures for 15-minute sampling interval. Differential measured during the west peak solar access period (12:00 to 20:00) for each month.

The average daily non-shaded and vine-shaded temperature differentials for the south wall and for each month in the study period during the 8-hour peak solar access period (10:00 to 18:00) were assessed (Figure 3.7a). The average temperature of the vine-covered wall was lower than that recorded on the non-shaded wall for all months. The greatest average temperature differential was in August (mean differential = 3.9 °C, SE [Standard Error] = 0.34) and the lowest differential was in October (mean differential = 0.33 °C, SE = 0.40). With the exception of the month of October, temperature differences between vine-covered and non-shaded environments for all months were statistically significant (Table 3.1). Overall, across the six month study period, the vine-covered wall was significantly cooler (mean = 24.7 °C) than the non-shaded wall (mean = 27.5 °C), $t(335)=5.658$, $p<0.001$.

Figure 3.7b displays the average daily non-shaded and shaded temperature differential for each month of the study period for the west wall during the 8-hour peak solar access period (12:00 to 20:00). With the exception of October, the average temperature of the vine-covered wall was lower than the non-shaded wall for all months. For October, the average temperature of the vine-covered wall was higher than the non-shaded wall. The greatest average temperature differential was in July (mean differential = 4.0 °C, SE [Standard Error] = 0.31) and the lowest differential was in October (mean differential = -0.87 °C, SE = 0.24). With the exception of September and October, temperature differences between vine-shaded and non-shaded environments for all months were statistically different (Table 3.1). Overall, across the six month study period, the vine-covered wall was significantly cooler (mean = 24.4 °C) than the non-shaded wall (mean = 27.1 °C), $t(338)=2.769$, $p=0.006$.

South-facing versus west-facing wall:

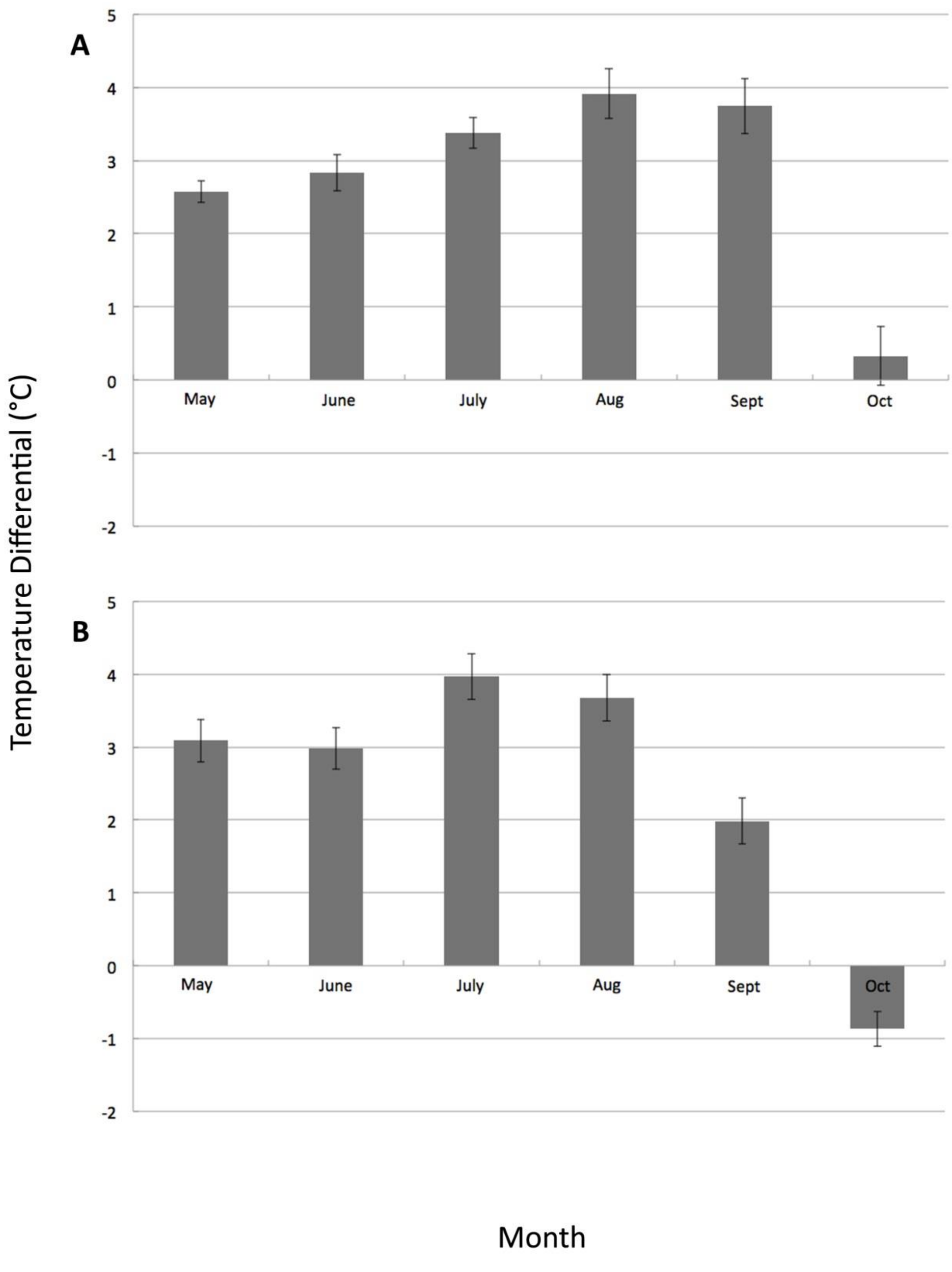

Figure 3.7: Average non-shaded and vine-shaded temperature differential for each month: a) south wall during south peak solar access period (10:00 to 18:00) and b) west wall during west peak solar access period (12:00 to 20:00).

Table 3.1: Building orientation and the effect of vine shade on monthly mean temperature difference (°C) for daily peak solar access periods.

	May	**June**	**July**	**August**	**September**	**October**
South (Shade to Sun)	(-) 2.6**	(-) 2.8*	(-) 3.4***	(-) 3.9***	(-) 3.7**	ns
West (Shade to Sun)	(-) 3.1*	(-) 3.0*	(-) 4.0***	(-) 3.5***	ns	ns
Differential (South to West)	ns	ns	ns	ns	(-) 1.8***	(-) 1.2*

Non-significant (ns), * p<0.5, ** p<0.01, *** p<0.001.

For the majority of the months studied, the difference between the monthly average non-shaded and vine-shaded temperature differential for the south and west wall orientations (during their corresponding 8-hour peak solar access periods) was not significantly different, with the exception of September and October. Across the entire six month study period, vine-shading on the south-facing wall was more effective at preventing the average rise in built surface temperature than was shading of the west-facing wall, $t(350)=3.827$, $p<0.001$. The six-month average difference in temperature between vine-covered and non-shaded walls for south and west was 2.8 °C and 2.4 °C, respectively.

3.4.4 Degree Hour Difference (DHD)

The daily average DHD values for each month of the study period for the south and west walls during their respective 8-hour peak solar access periods, where ambient temperatures exceeded the 22 °C temperature threshold were evaluated (Figure 3.8). The greatest average daily DHD value for the south wall was in August (mean DHD = 29, SE [Standard Error] = 3), and in July (mean DHD = 31.8, SE = 2.4) for the west wall. The lowest daily average DHD value was in October for both the south and west walls (mean DHD = 2, SE = 0.94 and mean DHD = 1.3, SE = 0.7, respectively).

3.4.5 Climatic Drivers of DHD

A multiple regression was developed to predict South-DHD22 from day difference, ambient temperature, solar radiation, wind speed and three interaction terms (day difference * solar radiation, ambient temperature * wind speed, day difference * wind speed). All independent variables added statistical significance to the prediction ($p<0.01$). Ambient

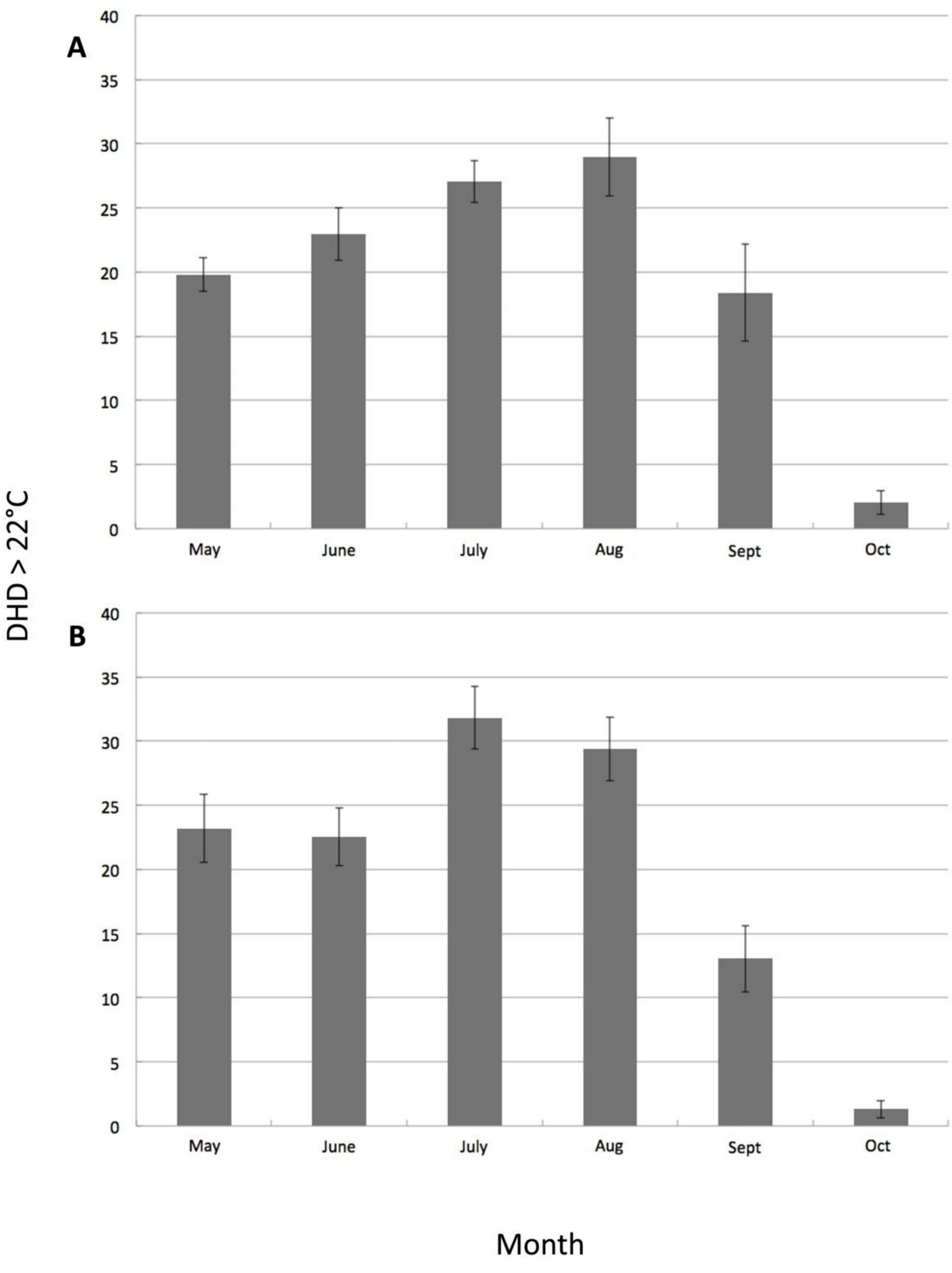

Figure 3.8: Average daily DHD for each month at ambient temperatures > 22 °C: a) south wall at during south peak solar access period (10:00 am to 18:00) and b) west wall during west peak solar access period (12:00 to 20:00).

temperature and solar radiation were the most significant climatic variables for explaining South-DHD22.

The final regression model for South-DHD22 can be written:

$$\text{South-DHD22} = -19.462 - 3.936*D - 0.031*I + 2.522*AT + 0.706*W - 0.158*RH + 0.009*(D*I) - 0.197*(AT*W) + 0.621*(D*W) \quad (1)$$

$r^2 = 0.736$, $p<0.001$

where D is the numeric variable day difference (date – 01/01)/(365/12), I is insolation (incoming solar radiation, W/m^2), AT is ambient air temperature (°C), RH is relative humidity (%RH) and W is wind speed (m/s). Each of I, AT, RH and W were calculated as a daily average for the south orientation peak solar access period (10:00 to 18:00).

Similar to South-DHD22, a multiple regression model was developed to predict daily West-DHD22 from meteorological variables. Specifically, West-DHD22 was predicted from day difference, ambient temperature, solar radiation, wind speed and two interaction terms (day difference * solar radiation, solar radiation * ambient temperature). Each of these independent variables added statistical significance to the prediction ($p<0.01$). As with South-DHD22, ambient temperature and solar radiation were the most important climatic variables for explaining West-DHD22.

The final multiple West-DHD22 regression model can be written:

$$\text{West-DHD22} = -0.591 - 2.011*D - 0.043*I + 0.600*AT - 1.418*W + 0.008(D*I) + 0.002(AT*I) \quad (2)$$

$r^2 = 0.852$, $p<0.001$

Each of I, AT, and W were calculated as a daily average for the west orientation peak solar access period (12:00 to 20:00). Given that both models (South-DHD22 and West-DHD22) were generated using data from May to October, their application outside of this time frame is not recommended.

3.5 Discussion

When considering the continued escalation of global temperatures and the urban heat island effect (under prospects of increased urbanization), exploitation of the temperature mitigating capabilities of vegetation can offer cities important temperature moderating benefits. Attenuating summer rise in temperature of built surfaces can make an important contribution toward reducing heat-related discomfort and illness, as well as lessening demand for air conditioning (Akbari et al. 2001; McPherson, 1984). Therefore, management of vegetation in cities is increasingly important to urban sustainability. This research demonstrates that the shading and evapotranspiration processes of perennial vines can provide important temperature mitigation benefits for built surfaces (and their proximate microclimate) in the downtown core of a large urban centre. Specifically, vine-covered surfaces on building walls were found to be significantly cooler than their non-shaded counterparts during peak solar access periods. These differentials reached 6.5 °C in early September for the south-facing wall and 7.0 °C in July for the west-facing wall.

Overall, vine-covered surface temperatures were generally significantly cooler than non-shaded surfaces, suggesting that vines can successfully mitigate microclimatic warming of urban building environments. Vines were able to lower fluxes and extremes in surface temperatures. Plots of monthly average differentials for solar access periods effectively showcase the greater variance in non-shaded temperatures, with higher maximum and lower minimum values, particularly in the summer months of June, July and August. This effect is explained by the direct impact of solar radiation heating non-shaded wall environments. Vine-covered environments receive the cooling effects of shading and evapotranspiration, which act to intercept incoming solar radiation and absorb heat, respectively. Vines can serve as a barrier that allows the moisture from their evapotranspiration properties to be held in the microclimate environment for a longer period of time and shelters the wall surface from the wind. Thus, fluctuations in temperatures are decreased. The open, non-shaded wall surface absorbs incident solar radiation and maintains heat throughout the day; it is also likely to be more easily affected by wind that can serve to strip heat rapidly from a built surface resulting in greater variation in wall surface temperature throughout the day.

Median daily and 15-minute interval shade temperatures were largely lower than median daily and 15-minute interval ambient temperatures through the months of May to August for the south-facing wall and from June to August for the west-facing wall during their respective peak solar access periods. This finding demonstrates that built surfaces with lower temperatures than proximate ambient air temperatures can have an important influence on their immediate microclimate during June through August, the warmest months of the year. Moreover, the fact that the vine-shaded differential remained lower than the non-shaded differential across the length of the study period indicates reduced heat at the wall surface for all months. Altogether, this decreases the heat at the wall surface that may re-radiate into the ambient environment. The prevention of this re-radiation of heat by perennial vines can help to reduce the warming of ambient temperatures that contribute to and intensify the urban heat island effect.

Generally, the largest vine-shaded temperature differentials compared with non-shaded temperature differentials occurred during the mid to late-afternoon, at the time of day when ambient temperatures were greatest. Human thermal discomfort is typically experienced in the late afternoon to early evenings during conditions of extreme heat, after lengthy exposures to high temperatures during the daytime (Kershaw and Millward, 2012). Thermal discomfort drives increased use of indoor air conditioning, which has an appreciable impact on energy demand in cities during the summer months. Research indicates that air conditioning systems are most used in the late afternoon and early evening (Donovan & Butry, 2009). Increased demand for air conditioning at this time of day can place appreciable strain on energy delivery infrastructure in urban areas (Sawka et al., 2013). Therefore, the temperature mitigating effects of the perennial vines under study are most impactful at a time of day when they are most needed to ease demands for indoor air conditioning. For many large North American cities, demand for cooling energy is the single largest draw on the electrical grid during the summer months. In Toronto, for example, from 1990 to 2003, the energy demand for air conditioning use increased by more than 100% (Ontario Power Authority, 2005). During this time there was a 16% decrease in electricity intensity (amount of electricity used in relation to activity levels) per household, a 5% increase in electricity consumption, a population growth of 19% and a 26% increase in the number of households (single family and multi-unit buildings) (Ontario Power Authority, 2005).

The average daily non-shaded and vine-shaded temperature differentials for each month during the study period reveal that the vine-covered walls were significantly cooler than non-shaded walls for the months of May to September (south-facing orientation) and May to August (west-facing orientation) during their respective peak solar access periods. Additionally, the threshold temperature of >22 °C to calculate DHD was met for each wall orientation and for all months across the entire study period. This finding suggests that there was a prolonged stretch of time in which ambient air temperature was warm enough to benefit from the temperature moderating capabilities of vine-shaded surfaces. The greatest average temperature differential values and daily average DHD were found in August for the south-facing wall and in July for the west-facing wall, supporting the argument that vines “work harder” when they are needed most to moderate rise in built surface temperature; this finding is similar to what is reported for the temperature moderating benefits of trees in Sawka et al. (2013).

In contrast with all other months of the study period (and for both south and west orientations), the average temperature of the vine-covered wall was higher than the non-shaded wall for the month of October. This break from the pattern observed in temperature across the other months may be explained by the drop in ambient temperatures observed in the month of October. In October, the vines may begin to shift from a temperature mitigation role to one of insulating (i.e., acting as a windbreak and shielding the wall surface from the cooler winds). Oke (1978) states that the dampening effect of wind around vegetation can act to insulate vegetation and prevent the loss of surface heat from the building walls. Furthermore, the change in leaf colour that was observed during late September and October may also contribute to this deviation in temperature pattern when compared with earlier season findings, especially in June through August. In perennial plants, leaves begin to fall in the autumn season in preparation for dormancy in the winter. At the end of the growing season when the length of day shortens and temperatures decrease, leaves undergo senescence. Senescence is characterized by the loss of chlorophyll in the leaves, the green pigment in vegetation (Sinha, 2004). Consequent to this loss of green pigmentation, the carotenoids, the yellow, orange and anthocyanin pigments, become prominent. The dark, auburn colours of perennial leaves are less reflective than the green colour displayed during the growing season, reducing the amount of solar radiation reflected away from the wall surface. Moreover, when leaf senescence begins, transpiration decreases, which may contribute to a further lessening of potential cooling at the wall surface (International Rice Research Institute, 1982).

In general, it was determined that vines growing on the south of the building surface were more effective at preventing average rise in built surface temperature than was shading of the west-facing wall. McPherson et al. (2006) indicate that the mitigation of temperature rise in the morning, as seen by vines during the south peak solar access period of 10:00 to 18:00, can extend to reducing the heating of surfaces that occurs throughout the day. Based on the orientation of the sun, west-facing wall orientations receive the largest gains for solar radiation during the summer season (Givoni, 1998). Our results suggest that at higher ambient temperatures, the temperature mitigating potential of vines should be more pronounced. One explanation concerning the effectiveness of vines to shade built surfaces of differing wall orientations is the angle of the sun in relation to the orientation of leaves. Boston ivy leaves have a tendency to grow perpendicular to the sky, meaning that they are more effective at intercepting and reflecting solar radiation when the sun angle is greatest, and they are less effective as sun angle drops. This leaf characteristic may result in the plant's greater effectiveness at mitigating temperature rise in the peak solar access period specified for the south wall orientation.

The vine density and leaf size may be an additional factor influencing the effectiveness of the temperature moderating potential of vines when comparing the two wall orientations. Vine characteristics in this study suggest that leaf cover was somewhat more dense on the south wall in comparison to the west wall. This points to the importance of proper vine management so as to ensure healthy and maximal growth of vine density and leaf size. Denser foliage and more extensive vine cover will provide greater temperature mitigation benefits. Moreover, the leaf density and size are typically greatest in the summer season when compared with spring and fall, contributing to a larger temperature mitigation impact.

Meteorological conditions at the time of the study were found to influence the effectiveness of perennial vines to mitigate temperature rise on built surfaces of south and west orientations, as indicated by daily DHD values. The predictive models for DHD can offer valuable information about the effectiveness of the vine mitigation under specified meteorological conditions. The variables (ambient temperature, relative humidity, wind speed, solar radiation) used in the predictive models (Equations 1 and 2) were found to be important predictors of the variation in DHD when ambient temperatures exceeded a 22 °C threshold during peak solar access periods.

Both DHD models (south and west) indicate that there is a positive relationship between DHD and ambient temperature and DHD and solar radiation; in other words, holding all other variables constant, as these independent variables increase in value so does daily DHD. Therefore, vine-shade is more effective at mitigating rise in built surface temperatures at higher ambient temperatures and on days with more solar radiation.

Moreover, significant interactions between independent variables (D*I, AT*W, D*W and AT*I) also impact daily DHD. For example, in both the south and west models, as the day difference variable (D) increases there is a greater impact of solar radiation on DHD (e.g., the effect of solar radiation on DHD was greater in July and August compared with May). This suggests that one or both of sun elevation and leaf characteristics are changing throughout the course of the study and may be influencing vine-shading properties. For the south-facing wall, at higher wind speeds, the impact of ambient temperature on DHD decreased, confirming that wind played an important role in stripping heat from the built surface. The influence of wind on DHD was also found to increase with increases in D, suggesting that later in the study period, wind played a greater role in limiting the effectiveness of vine shade on the south wall. Finally, for the west wall, it was found that with higher solar radiation values, the influence of ambient temperature on DHD increased.

The majority of published literature on the temperature mitigation benefits of vegetation focuses on the impact of trees and large shrubs (Akbari et al., 2001; Akbari et al., 2002; Di and Wang, 1999; Parker, 1989; Rosenfeld et al., 1995). The work of Bass and Baskaran (2003) as well as Wilmers (1990) suggests that a combination of green walls with other vegetation types, such as green roofs, can offer effective mitigation of temperature rise in urban microclimates proximate to buildings. Bass & Baskaran (2003) also report that the combination of these vegetation systems, when implemented into urban regions on a widespread basis, could provide considerable reductions in urban temperatures. The present study confirms that perennial vines are also an effective approach to mitigating rise in building surface temperature, a finding that when scaled to the geography of a city could make an important contribution to moderating summer temperatures in cities. Scaling the use of vines for heat island prevention to a city-level may be a challenging task. Engaging urban municipalities in new city practices requires the collective participation of industry, government and public bodies and general preferences for vine aesthetics and natural surroundings can vary from person to person. Furthering the education and awareness about the value of vines for enhancing the sustainability of urban areas is needed to drive mainstream promotion of the use of vines as a strategy for heat island management.

The temperature mitigating ability of vines can be of particular use as a vegetation-based strategy for offsetting increased temperatures in urban regions where it is difficult or not possible to grow trees. Competition for land in the downtown core of many cities can be fierce and severely limits adequate growing space for large growing shade trees. However, where there is a high density of buildings, there is a concentration of walls. Absent of cover, such as vines, these walls considered collectively are a massive heat sink and can have a huge impact on elevating ambient temperature in cities. Furthermore, soil quality and volume is very important for the growth of trees; urban soil is often poor or inadequate (De Kimpe & Jean-Louis, 2000; Millward et al., 2011). In contrast, vines are a very robust vegetation type and can successfully propagate and thrive in most soil conditions. Moreover, vines grow much faster than trees, enabling them to offer more immediate temperature mitigation benefits (Gartland, 2008). Specifically, Boston ivy can grow by as much as 2 m in one growing season and can reach a length of approximately 18 m at maturity (Musgrave, 2005). The particularly large, dense summer foliage and strong, non-invasive growth of Boston ivy make it an ideal species to use to mitigate the warming of building surface temperatures in comparison to other vine species, such as the native-growing Climbing Bittersweet (*Celastrus scadens*) and Virginia Creeper (*Parthenocissus quinquefolia*). These other vine species, however, also possess the potential to adequately contribute to reducing the rise of building surface temperatures.

3.6 Conclusion

Perennial vines were evaluated to assess their ability to mitigate rise in summer built surface temperatures (building walls). Specifically, this potential was assessed during peak solar access periods, time ranges during the day when solar radiation and ambient temperature are typically greatest. Results of this study indicate that perennial vines can be an effective approach toward mitigating rise in built surface temperatures; when scaled to the geography of a city, such benefits can serve to reduce the magnitude of the urban heat island phenomenon. Mitigation of temperature rise was most prevalent in the summer months (June through August), when temperature moderation strategies are most needed. Similarly, perennial vines growing on urban buildings may serve to contribute to a reduction of energy demand from air conditioning and a decrease in heat-related illnesses by lessening human thermal discomfort resulting from high summer ambient temperatures.

Space constraints and poor soil quality found in many urban centres, as well as the resources required to implement other vegetation-centred heat island mitigation strategies (e.g., planting and maintaining trees, green roof design and construction) can make these strategies difficult for planners and policy-makers to implement. Given the large amount of vertical wall space in urban centres, and the rapid growth of perennial vines, greening the external walls of buildings with perennial vines presents a cost effective and comparatively easy opportunity to quickly begin to moderate summer temperatures within urban microclimates. This research may also present a practical temperature mitigation and energy conservation strategy for residents of low-income localities, who do not have the space or financial means to grow and maintain trees.

Through planning, policies and by-laws, and education efforts, the planting, maintenance and protection of vines for their temperature mitigation benefits could be promoted and implemented in urban centres as a part of urban heat island mitigation strategies. The predictive models for DHD developed in this study provide planners with some basic tools with which the temperature moderating benefits of Boston ivy can be projected from May to October, under two different building orientations, and under different meteorological conditions. While it is not recommended that the models be applied outside of the southern Ontario region, they serve as an important starting place for quantifying temperature-moderating benefits of vines. Many site-specific factors, such as the vine species, vine coverage, building substrate, building height and building location, are likely to influence the performance of vines to moderate built surface temperatures.

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CHAPTER 4

4.1 Limitations of Research

Several major limitations to this study included restricted access to the building wall surfaces, public access to equipment, and equipment and site-related constraints. The range of wall heights on which vines were investigated was limited to between 2 and 5 m above ground; a height higher than 5 m being unsafe to install temperature loggers, and a height lower than 2 m putting loggers at risk to interference from ground-level disturbances (such as people passing by). Ideally, measurements across the entire wall surface of the building would have been accounted for in the data collection if not limited by these constraints. Further, the study building was public property and thus, subject to interactions from those outside of the research group. Vandalism of one vine-shaded logger on the west wall occurred in June, resulting in the loss of data from that logger thereafter. The equipment and site conditions of the building presented some minor interference. During two major rain storm events in the month of August, the adhesive from two loggers was compromised and the loggers fell off of the building wall. These loggers were down for less than a week and were placed back onto the wall surface during routine site monitoring. The data recorded by loggers while they were on the ground were removed from analyses. Fortunately, our study setup was designed in anticipation of such losses in data, ensuring that we included a high degree of replication in our measurements.

4.2 Additional Conclusions

Unlike trees, there is no current management plan for vines in the City of Toronto. Urban forest by-laws and policies in Toronto have been established to protect against the damage to trees and to maintain urban forestry management goals (City of Toronto Urban Forestry, 2005).

In addition to trees, vines can be seen as a valuable part of the urban forest. The results of this project could influence Toronto's Urban Forestry Branch to manage for the planting, maintenance and protection of vines for their temperature mitigation benefits. Currently, Toronto Urban Forestry Services offer the planting of free trees for Toronto residents who own property with a city-owned street allowance (City of Toronto, 2012b). Moreover, the Government of Ontario offers financial incentives for planting trees as part of Ontario’s 50 Million Tree Program (Trees Ontario, 2009). Former Minister of Natural Resources Donna Cansfield said: "Landowners see the value in the Ontario government's tree planting incentives and are working with us to green up the province and reduce the effects of climate change while saving a significant amount of money" (Trees Ontario, 2009). Conceivably, these types of programs could also be adopted for the promotion of perennial vines in Ontario cities as an approach to moderating summer urban temperatures. Based on these existing planting programs and incentives and the response from residents, there appears to be a government and public interest in the environmental protection of urban areas in Ontario through increasing the presence of vegetation. The addition of perennial vines to these types of programs, and other municipal and provincial investments into growing vines on urban buildings, could provide an additional strategy for protecting and enhancing the natural environment in cities.

To fulfil the development feature of “Urban Heat Island Reduction” under the Toronto Green Standard (TGS) for new infrastructure construction in the city, one option is to include green walls into design plans for shading purposes (City of Toronto, 2012a). The results of this project could advocate for the growth of vines on the walls of suitable new developments as an option for urban heat island reduction in the TGS, as results of this study indicate that perennial vines are an effective temperature mitigation strategy.

4.3 Future Research

Further investigations might be conducted subsequent to this study. For example, vine species, vine coverage, building substrate, building height and building location, may influence the temperature mitigation performance of vines on the surface of a building wall. Therefore, future studies could be conducted that test for different combinations of these elements. These types of investigations could lead to better planning for the implementation of vines in urban areas as they could provide further insight into the most optimal combination of site elements for the most effective temperature mitigation results. Scenario-based application of the statistical models developed in this study is encouraged. For example, the temperature mitigating benefits of vines could be evaluated under altered climate scenarios. Furthermore, each predictor variable can be analyzed on its own to observe its individual effect on vine temperature mitigation.

To further examine the role of vines in mitigating microclimatic temperatures, investigations that addressed the impact that vines have in addition to other landscape features in a building environment could be studied. For example, an investigation of the combined temperature mitigating potential of vines and trees within the immediate environment of an urban building, would be useful.

To assess the density of vine coverage, qualitative assessments were made due to time and resource constraints and because we deemed this approach appropriate for the type of analyses we sought to conduct. For a more detailed evaluation of vine density or coverage, future studies of this type may choose to make quantitative assessments of vine density. To achieve this, remote sensing technology such as an NDVI camera could be used to quantify the leaf density and condition of the perennial vines.

. The present study does not assess the impact vines may have on mitigating air pollution in built environments. In addition to their ability to cool ambient air temperatures through shading and evapotranspiration effects, vegetation can have a significant impact on air quality. The large surface area and roughness of vegetation intercepts the movement of pollution and dust particles, acting as a sink for air pollutants (Beckett et al., 1998; Hill, 1971). Additionally, the temperature mitigating effects of vegetation indirectly reduce air pollution concentrations by decreasing air conditioning demands, thereby decreasing the emissions produced from the power plants meeting increased energy demand (Heisler, 1986). High concentrations of air pollutants such as nitrogen oxide (NO_2) and particulate matter (PM) can be found in urban areas and are dangerous to human health (Mayer, 1999). Research suggests that urban trees and other plants can offer protection against these harmful air pollutants (Nowak et al., 2006; MacDonald, 2007; Yang et al., 2008), however, the specific benefit of vines for urban pollution control has not been studied comprehensively. Future research should examine, as an additional environmental service, the impact vines have on urban air quality.

4.4 References

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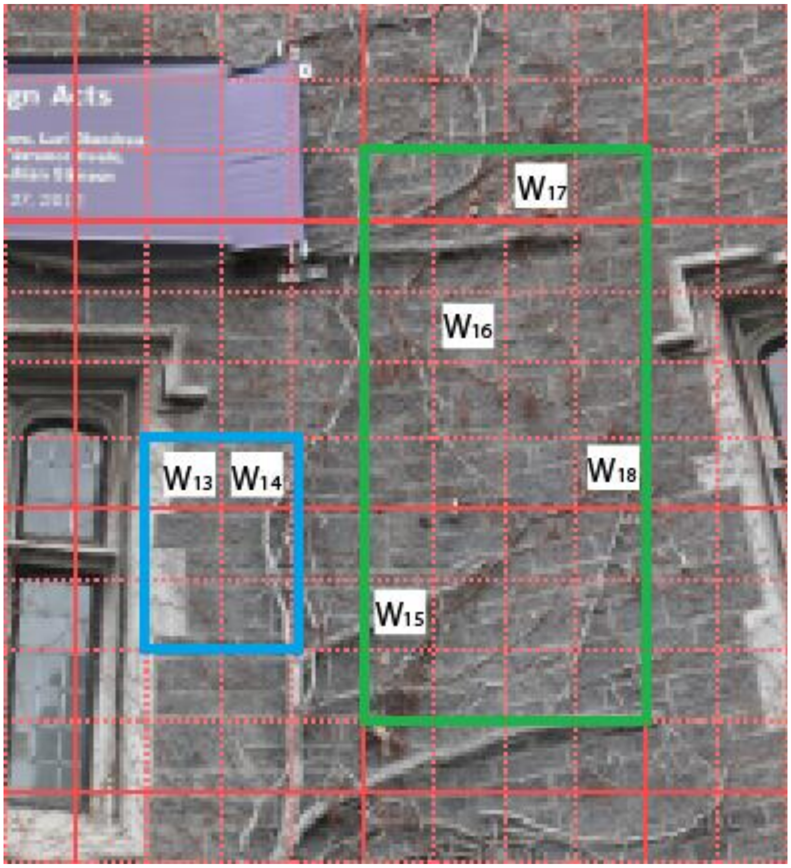
Appendix A: Stratified random sampling approach. Layout for the selection of temperature loggers within a non-covered wall stratum (blue rectangle) and a vine-covered stratum (green rectangle) for a section of the west-facing wall.



The photograph of the wall was taken when there was no vine cover; however, the stratified random sampling approach was conducted when vine cover was present. Stratified random sampling was used in this project to determine the location and positioning of vine-shaded and non-shaded loggers to ensure that the sample result was objective. This sampling approach was selected due to the nature of the population being studied. Within the overall population of each the south and west-facing walls exist the subpopulations of vine-covered and non-shaded environments. When interested in specific subpopulations (strata) within a total population, it is useful to independently sample each subpopulation (stratum) so that when generating the sample, an equal probability of selection from each stratum is established (Fink, 2009). To apply the stratified random sampling approach, the population must first be divided into the homogeneous strata of interest (Fink, 2009). In this project, for each wall, a photo was taken and a grid was superimposed on top of the photo. The grid cells were then used to proportionately divide the population into strata of vine-covered and non-shaded wall areas. The next step in the stratified random sampling approach was to employ a simple random sampling within each stratum (Fink, 2009). In this project, grid cells within each stratum were numbered and a random number generator was used to select for sample locations, where the cell corresponding with the randomly generated number represented a temperature logger location.

The number of samples selected from each stratum was taken in proportion to the stratum's size weighted against the population.

Appendix B: Logger specifications (HOBO® Pendant® Temperature Data Loggers – Part # UA-001-XX).

Measurement Range	-20° to 70°C (-4° to 158°F)
Alarms	High and low alarms can be configured for total amount of contiguous or non-contiguous time outside of user-defined limits between -20° and 70°C (-4° to 158°F)
Accuracy	±0.53°C from 0° to 50°C (±0.95°F from 32° to 122°F), see Plot A
Resolution	0.14°C at 25°C (0.25°F at 77°F), see Plot A
Drift	Less than 0.1°C/year (0.2°F/year)
Response Time	Airflow of 2 m/s (4.4 mph): 10 minutes, typical to 90% Water: 5 minutes, typical to 90%
Time Accuracy	±1 minute per month at 25°C (77°F), see Plot B
Operating Range	In water/ice: -20° to 50°C (-4° to 122°F) In air: -20° to 70°C (-4° to 158°F)
Water Depth Rating	30 m from -20° to 20°C (100 ft from -4° to 68°F), see Plot C
NIST Traceable Certification	Available for temperature only at additional charge; temperature range -20° to 70°C (-4° to 158°F)
Battery Life	1 year typical use
Memory	UA-001-08: 8K bytes (approximately 6.5K sample and event readings) UA-001-64: 64K bytes (approximately 52K sample and event readings)
Materials	Polypropylene case; stainless steel screws; Buna-N o-ring
Weight	15.0 g (5.3 oz)
Dimensions	58 x 33 x 23 mm (2.3 x 1.3 x 0.9 inches)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU).

Appendix C: Descriptive statistics.

Descriptives

			Statistic	Std. Error
South_Sun	Mean		27.481	.4956
	95% Confidence Interval for Mean	Lower Bound	26.503	
		Upper Bound	28.459	
	5% Trimmed Mean		27.809	
	Median		28.851	
	Variance		43.224	
	Std. Deviation		6.5745	
	Minimum		8.3	
	Maximum		39.0	
	Range		30.7	
	Interquartile Range		9.3	
	Skewness		-.700	.183
	Kurtosis		-.033	.364
South_Shade	Mean		24.681	.3661
	95% Confidence Interval for Mean	Lower Bound	23.959	
		Upper Bound	25.404	
	5% Trimmed Mean		24.845	
	Median		25.574	
	Variance		23.593	
	Std. Deviation		4.8573	
	Minimum		11.5	
	Maximum		34.4	
	Range		22.9	
	Interquartile Range		6.8	
	Skewness		-.513	.183
	Kurtosis		-.471	.364
West_Sun	Mean		26.770	.5826
	95% Confidence Interval for Mean	Lower Bound	25.620	
		Upper Bound	27.920	
	5% Trimmed Mean		27.091	
	Median		28.373	
	Variance		59.739	
	Std. Deviation		7.7291	

Descriptives

			Statistic	Std. Error
West_Sun	Minimum		6.3	
	Maximum		39.9	
	Range		33.6	
	Interquartile Range		11.6	
	Skewness		-.617	.183
	Kurtosis		-.476	.364
	Mean		24.354	.4275
	95% Confidence Interval for	Lower Bound	23.511	
	Mean	Upper Bound	25.198	
	5% Trimmed Mean		24.578	
	Median		25.737	
	Variance		32.170	
West_Shade	Std. Deviation		5.6719	
	Minimum		8.3	
	Maximum		34.4	
	Range		26.1	
	Interquartile Range		8.8	
	Skewness		-.627	.183
	Kurtosis		-.417	.364
	Mean		2.7991	.15653
	95% Confidence Interval for	Lower Bound	2.4902	
	Mean	Upper Bound	3.1080	
	5% Trimmed Mean		2.9059	
	Median		3.2072	
	Variance		4.312	
SouthDif	Std. Deviation		2.07665	
	Minimum		-3.21	
	Maximum		6.54	
	Range		9.75	
	Interquartile Range		2.85	
	Skewness		-.741	.183
	Kurtosis		.213	.364
WestDif	Mean		2.4157	.17280

Descriptives

	Statistic	Std. Error

WestDif	95% Confidence Interval for Mean	Lower Bound	2.0746	
		Upper Bound	2.7567	
	5% Trimmed Mean		2.4734	
	Median		2.8244	
	Variance		5.256	
	Std. Deviation		2.29251	
	Minimum		-2.65	
	Maximum		6.96	
	Range		9.61	
	Interquartile Range		3.42	
	Skewness		-.408	.183
	Kurtosis		-.691	.364

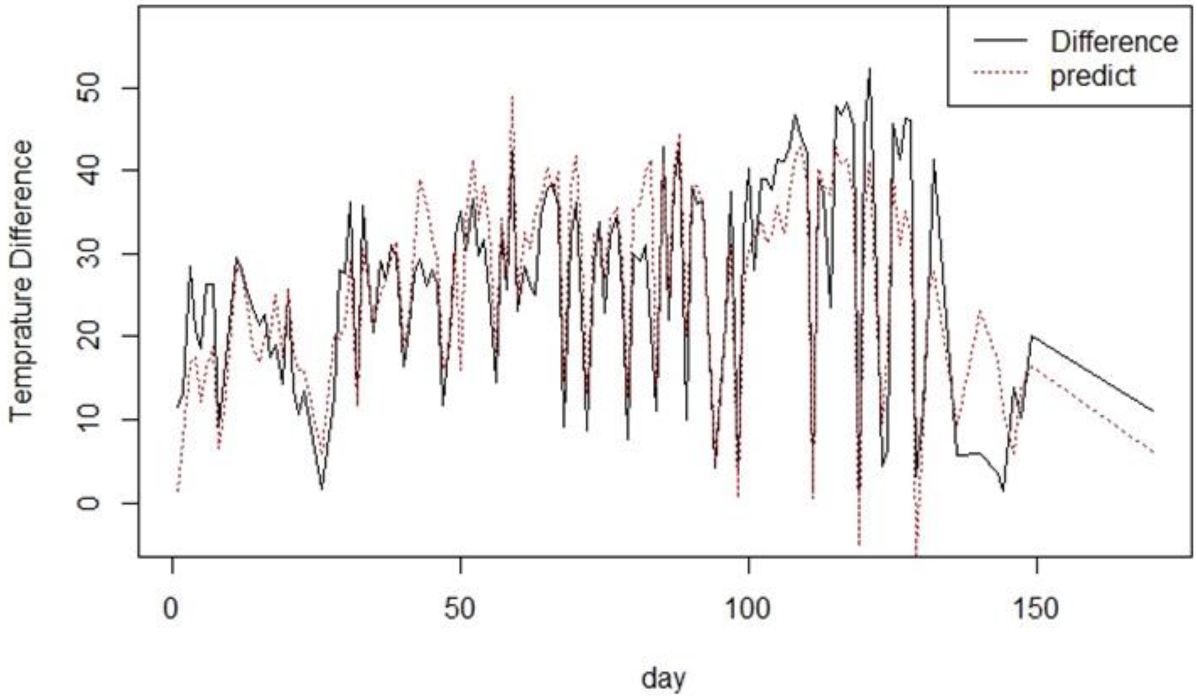
Appendix D: Coefficients and statistics for each variable and interaction term in South-DHD22 model. Where D is the numeric variable day difference (Date – 01/01)/(365/12), I is insolation (incoming solar radiation, W/m^2), AT is ambient air temperature (°C), RH is relative humidity (%RH) and W is wind speed (m/s).

	Value	Std.Error	t-value	p-value
(Intercept)	-19.4622	16.04365	-1.21308	0.2274
D	-3.93572	1.5207	-2.5881	0.0108
I	-0.03055	0.01816	-1.68221	0.095
W	0.706003	2.027364	0.348237	0.7282
AT	2.522209	0.400135	6.303402	0
RH	-0.15823	0.050128	-3.15659	0.002
D:I	0.0092	0.002788	3.300148	0.0013
W:AT	-0.19717	0.069815	-2.8241	0.0055

Appendix E: Overall p-values for significant variables in South-DHD22 model. Where D is the numeric variable day difference (Date – 01/01)/(365/12), I is insolation (incoming solar radiation, W/m^2), AT is ambient air temperature (°C) and W is wind speed (m/s).

	DF	P_value
D	3	<0.00001
I	2	<0.00001
AT	2	<0.00001
W	3	0.0072

Appendix F: Plot of South-DHD22 model.



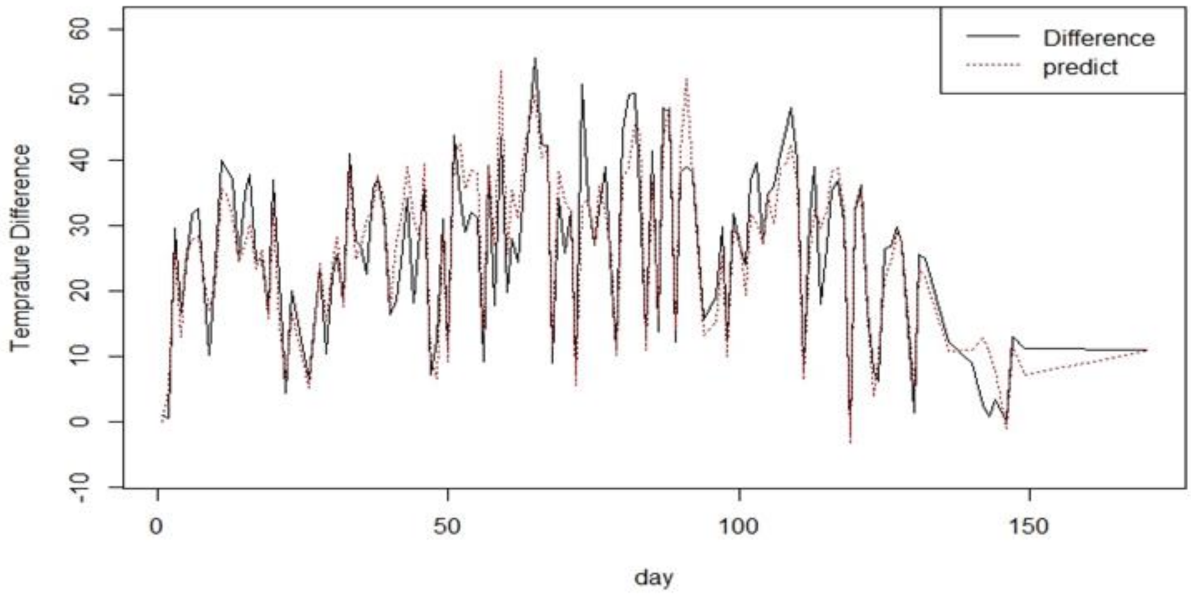
Appendix G: Coefficients and statistics for each variable and interaction term in West-DHD22 model. Where D is the numeric variable day difference (Date – 01/01)/(365/12), I is insolation (incoming solar radiation, W/m2), AT is ambient air temperature (°C) and W is wind speed (m/s).

	Value	Std.Error	t-value	p-value
(Intercept)	-0.59083	12.93338	-0.04568	0.9636
D	-2.01092	1.103516	-1.82228	0.0708
I	-0.04309	0.026388	-1.63287	0.105
AT	0.599572	0.390797	1.53423	0.1275
W	-1.41758	0.291385	-4.86496	0.000
D:I	0.008014	0.002445	3.27749	0.0014
I:AT	0.001987	0.000798	2.490613	0.014

Appendix H: Overall p-values for significant variables in West-DHD22 model. where D is the numeric variable day difference (Date – 01/01)/(365/12), I is insolation (incoming solar radiation, W/m2), AT is ambient air temperature (°C) and W is wind speed (m/s).

	DF	P_value
D	2	0.00017
I	3	<0.00001
AT	2	<0.00001

Appendix I: Plot of West-DHD22 model.



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