Impact of Extensive Green Roofs on Energy Performance of School Buildings in Four North American Climates

By

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B.Sc., Persian Gulf University, Iran, 2010

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Applied Science
in the Department of Mechanical Engineering

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Abstract

Buildings are one of the major consumers of energy and make up a considerable portion in the generation of greenhouse gases. Green roofs are regarded as an appropriate strategy to reduce the heating and cooling loads in buildings. However, their energy performance is influenced by different design parameters which should be optimized based on the corresponding climate zone. Previous investigations mainly analyzed various design parameters in a single climate zone. However, the interaction of parameters in different climate zones was not considered. Also, the studies have been conducted mostly for commercial or residential buildings. Among different building types, schools with large roof surface are one of the major consumers of energy in North America. However, the literature review shows the lack of study on the effect of green roof on the thermal and energy performance of this type of building. This study performs a comprehensive parametric analysis to evaluate the influence of the green roof design parameters on the thermal or energy performance of a secondary school building in four climate zones in North America (i.e. Toronto, ON; Vancouver, BC; Las Vegas, NV and Miami, FL). Soil moisture content, soil thermal properties, leaf area index, plant height, leaf albedo, thermal insulation thickness and soil thickness were used as variables. Optimal parameters of green roofs were found to be closely related to meteorological conditions in each city. In terms of energy savings, the results show that the light substrate has better thermal performance for the uninsulated green roof. Also, the recommended soil thickness and leaf area index in the four cities are 0.15 m and 5, respectively. The optimal plant height for the cooling dominated climates is 0.3 m and for the heating dominated cities are 0.1 m. The plant albedo had the least impact on the energy consumption while it is effective in mitigation effect of heat island effect. Finally, unlike the cooling load which is largely influenced by the substrate and vegetation, the heating load is considerably affected by the thermal insulation instead of green roof design parameters.

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Acknowledgments

I have been fortunate to have had the support, guidance, enthusiasm, wisdom, and friendship of many individuals throughout my two years as a graduate student at the University of Victoria. This thesis is dedicated to all of these persons who have made this journey such an enjoyable learning process.

First and foremost, I would like to thank my supervisor Dr. Phalguni Mukhopadhyaya for his mentorship, patience, friendship, and enthusiasm over the last two years.

My sincere thanks also go out to Dr. Caterina Valeo for her invaluable support and participation in this research.

I would also like to thank the Faculty, Staff, and Graduate Students in the Department of Mechanical Engineering at the University of Victoria for their daily assistance and guidance.

Finally, I would like to thank my friends and family for their support and encouragement over the past two years. To my parents for instilling in me the drive to persevere, and the freedom to make my own choices, and for always providing a listening ear, I would like to say thank you.

Nomenclature

C_{eg}	Latent heat flux bulk transfer coefficient at ground layer
C_f	Bulk heat transfer coefficient
C_{hg}	Sensible heat flux bulk transfer coefficient at ground layer
$C_{p,a}$	Specific heat of air at constant pressure
F_f	Net heat flux to foliage layer (W/m^2)
F_g	Net heat flux to ground surface (W/m^2)
H_f	Foliage sensible heat flux (W/m^2)
H_g	Ground sensible heat flux (W/m^2)
I_s	Total incoming short-wave radiation (W/m^2)
I_{ir}	Total incoming long-wave radiation (W/m^2)
l_f	Latent heat of vaporization at foliage temperature (J/kg)
L_f	Foliage latent heat flux (W/m^2)
L_g	Ground latent heat flux (W/m^2)
LAI	Leaf area index (m^2/m^2)
q_{af}	Mixing ratio for air within foliage canopy
$q_{f,sat}$	Saturation mixing ratio at foliage temperature
$q_{g,sat}$	Saturation mixing ratio at ground temperature
T_{af}	Air temperature with in the canopy (K)
T_f	Foliage temperature (K)
W_{af}	Wind speed with in the canopy (m/s)
a_g	Albedo (short-wave reflectivity) of ground surface
ε_f	Emissivity of canopy
ε_g	Emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_f \varepsilon_g$
ρ_{af}	Density of air at foliage temperature (kg/m^3)
δ	Stefan- Boltzmann constant (W/m^2K^4)
δ_f	Fractional vegetation coverage

1. Introduction

In recent years, due to the increasing population and migration from rural areas to cities, the rate of construction has increased significantly. Therefore, growth of new buildings has led to increased demand for energy and water [1]. According to the research in 2010, buildings contributed to 32% of total used energy in the world and one- third of greenhouse gasses [2, 3]. As a result, buildings can play a significant role in limiting global warming and reducing climate change impacts. Green or Vegetated roofs are regarded as an appropriate solution for reduction of heating and cooling loads in buildings. The vegetated roofs mitigate the heat flux through the roof by shading the roof surface with plants, evapotranspiration of the plants, and the additional thermal insulation and mass which are caused by the growing media [4]. There is a wide range of investigations that show the other advantages of green roofs such as reduction of water run-off (i.e. [5-8]), and urban heat island effects (i.e. [9-11]), sound insulation (i.e.[6, 12]), enhancement of the life span of roof (i.e.[13]) and creation habitats for species (i.e. [14-16]). Due to the above mentioned benefits of green roofs, many local authorities in different countries have implemented the policy for using green roofs in new buildings. For instance, in Toronto (Canada) the new buildings with surface area more than 2000 m^2 should have between 20% and 60% vegetated roof; in Tokyo (Japan) the new constructed buildings must have at least 20% vegetated roof; in Portland (USA) all new buildings should have at least 70% green roofs on their rooftops; and in Basel (Switzerland) the roofs of new or retrofitted buildings need to be covered with at least 15% vegetation [1]. Although the environmental advantages of green roofs are the main goal of local authorities in most cities, the thermal benefits of green roofs are of great importance and should be considered by the constructors and engineers for designing this type of roof.

A wide range of experimental and numerical studies to evaluate the effect of green roof on the energy consumption of buildings in different climates have been conducted. For instance, the results of green roof effects for a one-story office building in European climates indicated that the cooling load could be saved between 1 to 11% in warm climates and up to 7% in cold climates [17]. Another study was conducted to evaluate the energy performance of green roof for a supermarket in Athens, Greece. The results showed that the cooling and heating loads reduced by 18.7% and 11.4% respectively [18]. However, green roof was not effective in energy saving of a mock up building in Pennsylvania (USA) [19]. Another study in the Mediterranean climate in Italy compared the energy performance of conventional roof with green roof, in which green roof had

100% reduction of thermal energy entering the roof in summer and 30 to 37% of heat losses during the winter [20].

To evaluate the influence of green roof on the building energy performance, the architects and engineers should evaluate the importance of design variables, external conditions and building type. The main design parameters, which affect the thermal performance green roofs are plants coverage and growing media. The design variables for the plants are leaf area index (LAI), plant height, stomatal resistance and leaf albedo and emissivity. The growing media characteristics are thickness, thermal properties and moisture content.

Several studies analyzed the energy performance of green roofs by conducting the parametric analysis. For instance, the energy consumption varied from 1% to 15% for a five-story building in Singapore by changing the soil thickness, moisture content of substrate and plant type [21]. The parametric study in the Mediterranean climate showed that the LAI was the most influential parameter in reducing the cooling demand through the evapotranspiration effect [22]. Furthermore, the LAI and substrate thermal properties were the most effective parameters in reduction of cooling and heating loads for a supermarket in a semiarid climate respectively [23]. Sailor in his study investigated the effect of climate, LAI and soil thickness in four cities including Houston, New York, Portland and Phoenix. The results reported that the green roof with deeper soil thickness could reduce the heating demand in cold cities. However, the LAI saved energy for the cooling dominated cities by using evapotranspiration and surface shading of plants [24]. The investigation in Midwestern U.S., for a city with hot and humid summer and cold and snowy winter, concluded that green roof reduces the heat flux in summer and winter 16 and 13% respectively [25]. Ascione [17] used the EnergyPlus software to compare the effect of leaf index area on the green roof in two different cities in Tenerife (Spain) and Oslo (Norway). The investigation found that by increasing the leaf index area from 0.8 to 5 the energy saving for the cooling load in Tenerife increased from 1% to 11%, and the heating energy saving in Oslo was 5% with LAI= 5 and 6% with LAI= 0.8 because of lower solar absorption. In another study with EnergyPlus in Portugal, the thermal performance of three types of green roofs (extensive, semi-intensive and intensive) with two conventional roofs with different surface color (black and white) was studied. Also, the effects plants of height and leaf area index were evaluated. The results showed that the semi-intensive and intensive green roofs with moderate thermal insulation had better energy saving compared to the black and white roofs. However, the extensive green roof had good performance in buildings without insulation (old buildings). In addition, the leaf area index and plant height improved the energy saving in cooling seasons considerably and the soil depth had a major effect in heating seasons [26]. The Design Builder was used in another numerical simulation to study the effects of different parameters such as leaf area index, soil depth and insulation thickness in different climates including warm-dry, warm-coastal and cool-humid. The results demonstrated that the insulation thickness has a positive effect in reducing the energy use intensity (EUI) effect in Phoenix while it was reversed for Chicago. The EUI in Los Angeles was affected by leaf area index [27].

The aforementioned studies were mostly for warm and the Mediterranean climates and few research studies were conducted for the energy saving of green roof in cold climates. To illustrate, the effects of snow depth and vegetation types were evaluated in Saint Mary's University. The research found that the green roof had lower heat loss compared to the conventional roof. However, there was no difference in heat loss between green roof and conventional roof when the growing media was frozen or snow covered the surfaces of roofs. In addition, the variety of vegetation affected the depth of snow, required time for snow coverage and substrate temperatures [28]. The effect of phase change in the green roof growing media was recently investigated during the winter at Purdue University. The analysis showed that on the one hand the green roof reduce heat loss up to 17.9% during the entire winter in comparison with conventional roof. Also, during the phase change period (liquid to ice) the growing media stored a lot of energy and as a result the growing media had a higher temperature. The heat loss was reduced during the phase change period in the winter by 19% while the heat loss reductions during the period without phase change (the water was completely liquid or ice) were between 15-17 % [29].

In Canada, although the government provided cities with funding for implementing the green roofs on buildings, few studies considered the energy benefits of green roof in this country, and they were mostly experimental. For example, results of a study in Toronto for single family and low-rise commercial buildings concluded that $11 M of energy can be saved by using the combination of cool roofs and shaded trees. The study also reported that the urban heat island (UHI) effect of green roofs can reduce the electricity demand for cooling systems during the summer. It mentioned that an 0.6 °C increase of ambient temperature will increases the cooling peak demand from 1.5% to 2% [30]. The National Research Council of Canada in one of its studies analyzed and compared a typical extensive green roof with a conventional roof in Ottawa. The results showed that green roof reduced the heat flow through the roof in summer considerably more than in winter. The energy consumption for space conditioning was 75% lower than reference roof. Also, during the days without snow, the green roof was slightly better than the conventional roof because of the growing media insulation effect. However, when the growing media was frozen, the thermal conductivity increased and the insulation effect was diminished. Therefore, both roofs had similar heat loss in under the snow coverage [31]. Another experimental study by NRC (National Research Council) analyzed two different green roofs with a reference roof in Toronto. The differences between green roofs were in the thickness and color of growing media. The analysis illustrated that both green roofs reduced the heat gain and heat loss through the roof as well as peak load significantly more than the reference roof. The green roofs reduced the heat gain during the summer 70-90% and heat losses during the winter 10-30% [32].

The British Columbia Institute of Technology (BCIT) conducted an experimental study to compare the energy performance of two green roofs with different growing media thicknesses with a reference roof on the west coast of British Columbia. The study concluded that the green roof with shorter growing media had a smaller heat loss compared to the thicker growing media. Similar to the previous studies, the results showed that green roofs had a better performance compared to the reference roof and they saved energy during the summer and spring from 83 to 85%, during the winter and fall 40-44% and overall 66% reduction of annual energy consumption [33]. The recent study for an office building in the Ryerson University in Toronto analyzed the effects of LAI and soil thickness on energy consumption. The results showed that the growing media thickness was more effective in reduction of energy. Also, the heating demand was reduced by 3% compared to the conventional roof [34]. One of the most important parameters that influences the effectiveness of green roof is thermal insulation of roof. To illustrate, the green roof without thermal insulation reduced the cooling load considerably more in the Mediterranean climate [22] . Likewise, another study in this climate for a room demonstrated that the insulated green roof consumed more energy than the conventional roof [26]. A single-family residential building in the Oceanic climate of LaRochelle (France) proved that uninsulated and insulated green roofs save energy 48% and 10% more than the conventional roof respectively [4]. Similarly, the energy reductions for well-insulated, moderately insulated and uninsulated green roof for an office building in the Mediterranean climate of Athens (Greece) were 2%, 7% and 48% respectively [35]. An experimental and simulation study in four US climates concluded that the green roof with insulation is less effective in reduction of energy consumption [36]. Pablo in his study proved that the green roof without insulation can have appropriate performance in the summer but not in the winter as the low heat transfer coefficient is needed for reducing the heating load [37].

Previous investigations mainly focused on the energy saving of green roof in commercial or residential buildings and a couple of studies have been conducted on other types of buildings such as retail stores or supermarkets [1, 23]. However, the effect of vegetated roof on the energy performance of school buildings in spite of their size and contributions in energy consumption, has not been taken into consideration. The National Center for Education Studies reported that the number of buildings for educations in the USA is more than 100,000 [38]. It is notable that for each of the above mentioned schools a considerable amount of energy is consumed for providing electricity for the students and teachers. According to the report by Xcel Energy, almost $6 million per year is spent for required energy in schools. So, it can be concluded that a significant amount of a country's budget is spent for required energy in school sectors. For instance, the average annual rate of energy in 2008 was $1.25/ft^2. Consequently, more than $1 million was the cost of energy for 800,000 square foot for mid-size school district[38]. According to the survey in U.S. Department of Energy in 2013, school buildings consumes 8% of energy among commercial and institutional buildings [39] . Energy use by building sector in USA is shown in Figure 1. Likewise, in Canada, schools are regarded as one the major consumer of energy with energy intensity of 0.88 GJ/m^2. According to Natural Resources Canada, the average annual energy consumption of schools in Canada is 472kWh/m^2 [40]. For example, the school buildings in Ontario make up a 30% portion of energy consumption in the public sector [41]. The study by NRCan (Natural Resource Canada) 2012 showed that after office and food store buildings, schools are the third largest energy consumer with 8% energy consumption among commercial and institutional buildings in Canada, as shown in Figure 2 [42]. Despite the necessity of energy saving in this sector in North America, previous research mostly focused on the specific locations and buildings to analyze the effectiveness of green roofs on the energy consumption. Also, there is no comprehensive study in this region to analyze the influence of green roofs' design parameters such as LAI, plant height, plant albedo, soil thickness, thermal insulation thickness and soil thermal properties on the use of energy in buildings. Hence, in this thesis a parametric analysis by focusing on a secondary school building in different climates in North America is investigated. The selected climates include the cool-humid climate of Vancouver (Canada), the cold-continental climate of

Toronto (Canada), the hot-dry climate of Las Vegas (USA) and the hot-humid climate of Miami (USA).

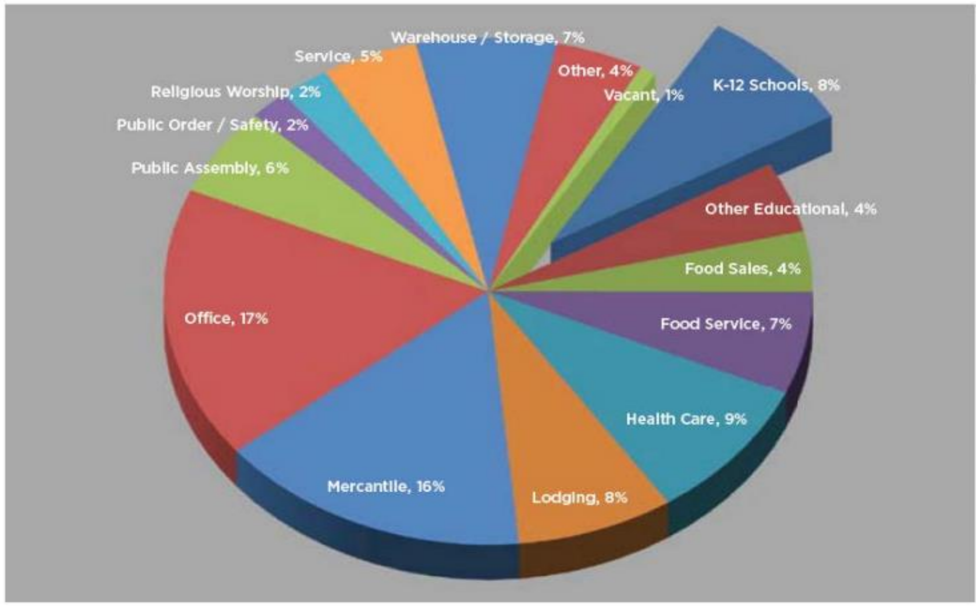


Figure 1. Energy use by building sector in USA [39].

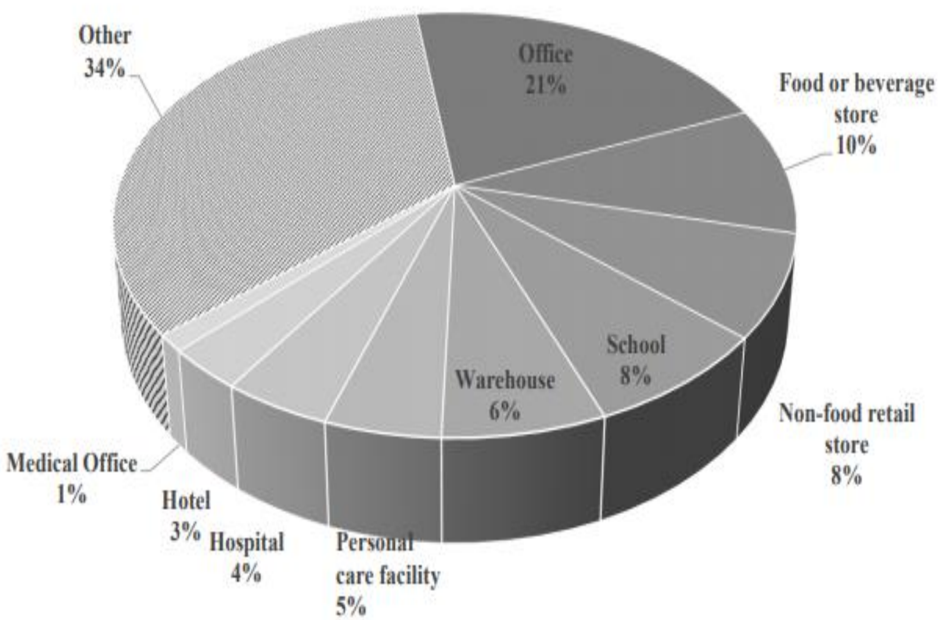


Figure 2. Total energy consumption by building type within Canada's commercial and institutional sector [42].

2. Methodology

2.1. Simulation tool

Numerous building energy simulation tools have been developed in recent years. The list of the most comprehensive building energy modeling software has been provided by the IBPSA-US in a directory [43]. EnergyPlus is one of the most known energy modeling software tools which was developed by the US Department of Energy (DOE) in the 1990's. It was developed by combining two energy modeling programs BLAST and DOE-2 which were developed by the US Department of Defense and the DOE respectively in 1970's [44].

EnergyPlus calculates the required energy for heating, cooling, lighting, and ventilating as well as water heating in buildings by considering all outdoor and indoor parameters including geographical location, outside temperature, solar radiation intensity and direction, wind speed and direction, glazing shading and radiation characteristics which have been provided in EPW file, and generated heat by internal loads such as occupant density and activities, lightening and miscellaneous equipment, infiltration, etc. Also, the heat flux through the building envelopes is calculated based on BLAST conduction transfer function (CTF) [44].

The energy performance of a building largely depends on the climatic conditions. Hence, one of the most important input for dynamic energy simulation is a weather file which has the hourly data of external conditions such as solar radiation, air temperature, relative humidity, atmospheric pressure, wind velocity, and wind direction for whole year. As the weather conditions may vary considerably from year to year, a Typical Meteorological Year (TMY) has been devised by researchers in different part of the world to indicate long-term typical weather conditions over a year. The first TMY file was defined based on the record of data between 1948 and 1980 for 229 locations in USA. The second typical meteorological year (TMY2) was collected based on 239 locations for the period between 1961 and 1990. The third typical meteorological year (TMY3) which is the latest weather file, has been collected based on data for 1020 locations in the USA including Guam, Puerto Rico, and US Virgin Islands, derived from a 1976-2005 period of record where available, and a 1991-2005 period of record for all other locations. Meteorological data is available in the EnergyPlus Weather format (EPW) for more than 2100 locations in over 100 countries [44] .

As the building envelopes are permanently exposed to the external conditions, improving the thermal performance of the building components such as walls and roof plays a key role in energy saving of buildings. One of the recent strategy to reduce the energy consumption in buildings is green roof. However, a few building energy modeling tools are able to model green roof. The green roof module developed by Portland State University and introduced in April 2007 in the "standard releases of EnergyPlus"[25]. The green roof model in EnergyPlus allows the user to implement the green roof as the outer layer of roof assembly. The user also can vary different green roof design parameters such as growing media thickness and thermal properties, plant canopy density, plant height, stomatal resistance, and soil moisture conditions (including irrigation and precipitations) [44]. The input design parameters are defined as follow:

Soil thickness:

There are three types of green roofs based on the growing media thickness including extensive, semi-intensive and intensive roofs. The main characteristics of extensive green roof is low maintenance, thin growing medium (6-25 cm) and using small plants. However, the intensive green roofs have thicker growing medium (15-70 cm) and mainly covered with various plants such as trees and bushes and need high maintenance. The semi-intensive roof has the intervening features of the extensive and intensive roofs [26]. The range of input values for the growing media thickness in EnergyPlus is between 0.05 m and 1.0 m [44].

Thermal conductivity of dry soil:

The thermal conductivity is an important property of soil in conduction heat transfer therough the roof specially during the winter. The thermal conductivity of soil varies with used materials and moisture content. The Unit of this parameter is W/(m.K). Due to the limitation of EnergyPlus on considering the effect of water content on the variation of thermal conductivity, the users should input the thermal conductivity of dry soil or input the thermal conductivity of soil corresponding to its moisture content. The minimum allowable input for this parameter in EnergyPlus is 0.2 W/(m.K) and the maximum is 1.5 W/(m.K). The range of thermal conductivity for the soil typically varies from 0.3 W/(m.K) to 0.5 W/(m.K) [44].

Density of dry soil:

The density of soil depends on the soil composition. The main materials which are used for the soil in green roofs are aggregates (50 %- 80%), compost (0-15%) and sand (0-50%). The unit of soil density is kg/m^3. Similar to the thermal conductivity the users should input the density of dry soil or the density of soil according to its water content. It is evident that the density of soil by increasing the water content increases [45]. The minimum allowable input value in EnergyPlus 300 kg/m^3

and maximum is 2000 kg/m^3. Typically, the range of soil density is from 400 kg/m^3 to 1000 kg/m^3[44].

Specific heat of dry soil:

The specific heat of soil defines as the required heat to increases the temperature of 1 kg soil by 1˚ C. The unit of specific heat in EnergyPlus is J/(kg.K). Similar to the previous properties, the users should input the specific heat of dry soil or specific heat of corresponding to the its water content. It is notable that by increasing the water content of soil the specific heat increases as the pores of soil are filled with water and the water has higher heat capacity compared to the air[45]. The input values for this variable in EnergyPlus must be positive [44].

Thermal Absorptance:

Soil can absorb a fraction of long wavelength infrared radiation of incident solar radiation. This ability is given by thermal absorptance coefficient. Values of this coefficient range from 0 and 1 in which the amount of 1 is corresponded to the black body condition. The values for the soil are mainly between 0.9 to 0.98 [44].

Solar Absorptance:

The ability of soil material to absorb the incident solar radiation is defined by the solar absorptance coefficient. This parameter has a major effect on the heat balance on the soil surface. The more solar absorption results in higher surface temperature and heat transfer through the soil. Similar to the thermal absorptance it ranges between 0 and 1.0 The values for the soil are mainly from 0.6 to 0.85 [44].

Visible Absorptance:

The soil absorbs a fraction of incident visible wavelength radiation. The defined coefficient is visible absorptance of soil which ranges from 0 to 1. Values for this factor in EnergyPlus must be between 0.5 and 1.0 [44].

Leaf Area Index (LAI):

Leaf Area Index defines as the projected leaf area per unit area of soil surface. LAI indicates the number of layers that can be covered from the leaves of plant on the soil surface where the plant is growing. Leaf area index is determined by measuring the surface area of all leaves. The summation of all leaves surface area is divided by the surface of soil that plant is growing. For instance, a LAI value of 1 means that with 1 layer of leaves a unit of ground surface area is covered and the leaf area index of 3 means that the soil, on which the plant is growing, can be covered with three layer of leaves. However, the LAI less than 1 means there is some bare ground which is not covered completely with leaves. Figure 3 schematically shows a soil area which is covered with one layer of leaves (LAI = 1) and three layers of leaves (LAI = 3), respectively [46]. The leaf area index ranges from 0 (bare ground) to more than 10 ("dense conifer forests") [47]. In EnergyPlus the acceptable values are between 0.001 and 5.

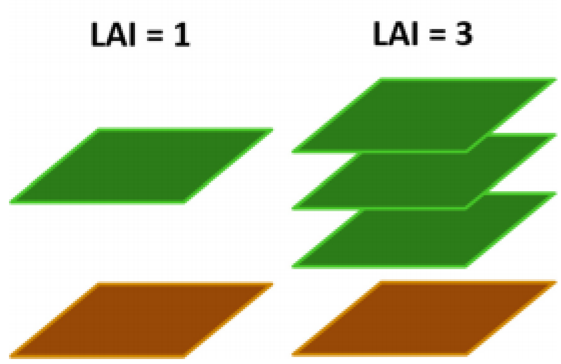


Figure 3. Schematic representation of a defined soil area which is completely covered with one and three layers of leaves [46].

Height of Plants:

The average height of plants in the green roof. This parameter ranges from 0.005 m to 1 m.

Leaf Reflectivity (Albedo):

The reflectivity of leaves shows the reflection of incident solar radiation by the surface of a leaf. Values of this coefficient depends on the plants type and surface color. The darker leaf reflects less radiation to the environment. The reflectivity ranges from 0 (corresponding to black body that absorbs all the incident radiations) to 1 (corresponding to a body that reflects all the incident radiations). Typically, it varies between 0.18 and 0.25. Values for this coefficient in EnergyPlus must be between 0.05 and 0.5 [44] .

Leaf Emissivity:

The leaf emssivity is defiend as the ratio of emitted radiation by the surface to that radiated from a black body at the same temperature and wavelength. This coefficient varies from 0 to 1. In EnergyPlus values for this parameter must be between 0.8 and 1.0 (with 1.0 representing "black body" conditions) [44].

Minimum Stomatal Resistance:

This parameter represents the plant's resistance to transfer moisture from the soil to the leaves and stem. The unit is s/m. The lower stomatal resistance of plant leads to the higher rate of evapotranspiration. The ranges of this variable in EnergyPlus should be between 50 to 300 based on the plant's type [44].

Roughness:

The roughness of surface layer of soil affects the convection coefficient, in particular for the exterior convection coefficient. The types of soil roughness in EnergyPlus are VeryRough, MediumRough, MediumSmooth, Smooth, and VerySmooth [44].

Max volumetric moisture content of the soil layer (saturation):

Maximum volumetric moisture content of the soil depends on the properties of the soil and in particular the porosity. The unit is m^3/m^3 and the range of input value in EnergyPlus must be between 0.1 and 0.5 [44].

Min (residual) volumetric moisture content of the soil layer:

The minimum possible volumetric moisture content of the soil layer. The unit is m^3/m^3 and the permissible value in EnergyPlus must be between 0.01 and 0.1 [44].

Initial volumetric moisture content of the soil layer:

The volumetric moisture content of the soil layer at the start of the simulation. The moisture content of soil will be updated at each time step based on surface evaporation, irrigation and precipitation. The unit is m^3/m^3 and the range of this factor in EnergyPlus must be between 0.05 and 0.5 [44].

Moisture diffusion calculation method:

There are two methods of moisture diffusion in EnergyPlus: Simple and Advanced:

Simple is the original model in which the moisture diffusion through the soil is based on constant rate. The function of this method is based on the difference of moisture level at two layers. Then, at each time step the model compares the moisture content of two layer and define which layer has a larger moisture. Finally, it transfers moisture from the higher layer to the lower layer at a constant rate [44].

Advanced is the newest model for moisture diffusion in soil. This model works based on the finite difference method and divides the soil into the different layers. It redistributes the moisture in the soil based on Schaap and van Genuchten model in which the moisture transfer method Mualem–van Genuchten (MVG) was modified. In Schaap and van Genuchten model the hydraulic conductivity of soil in both unsaturated and saturated conditions are considered [48]. The user should increase the time step of simulation at least by 20 in an hour if this method is used [44].

2.2. Green roof model description

The green roof model in EnergyPlus is based on a defined models including: " Fast All-season Soil Strength"[48], " Biosphere Atmosphere Transfer Scheme" [49] and the Simple Biosphere models [50].The energy balance in green roof assemblies is dominated by balancing the solar radiation (similar to that of a conventional roofing system). The solar radiation is balanced by the sensible and latent heat flux through the soil and plants, conductive heat transfer through the soil and long-wave radiation to and from the soil and plant surfaces. The energy in the foliage layer (F_f) and the ground surface (F_g) are the main sources of energy in green roof assemblies [51]. The heat flux through the roof is determined by calculating the foliage (T_f) and ground surface (T_g) temperatures from equations (1) and (2). It is seen that the energy budgets depend on the physical properties of the plants and ground such as the fractional vegetation coverage σ_f, the emissivity of canopy ε_f or ground surface ε_g, the albedo of the canopy α_f and the ground surface α_g .

$$F_f = \sigma_f [\, I_s\, (1-\alpha_f) + \varepsilon_f I_f - \varepsilon_f \sigma T_f^4 \,] + \frac{\sigma_f\, \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_f + L_f \quad (1)$$

$$F_g = (1- \sigma_f) [\, I_s\, (1-\alpha_g) + \varepsilon_g I_{ir} - \varepsilon_f T_g^4 \,] + \frac{\sigma_f\, \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + K \frac{\partial T_g}{\partial Z} + H_g + L_g \quad (2)$$

Sensible heat flux between the soil surface and air depends on the temperature difference between them and the wind speed within the canopy. The soil thermal properties such as thermal conductivity, specific heat capacity, density and ground albedo are considered in calculation of sensible heat flux. However, the plant albedo and LAI (which represent the plant coverage with leaves) influence the sensible heat transfer between plant surface and air.

$$H_f = (1.1\, LAI\, \rho_{af}\, C_{p,a}\, C_f\, W_{af})(T_{af} - T_f) \quad (3)$$

$$H_g = \rho_{ag}\, C_{p,a}\, C_{hg}\, W_{af}\, (T_{af} - T_g) \quad (4)$$

The latent heat flux is due to the evaporation of water in the plant and soil. The process is called evapotranspiration as it is caused by the respiration of the plants through the closing and opening of stomata, and the evaporation of water in the soil. The latent heat transfer depends on the rate of vaporization, saturation mixing ratio at the surface temperature of foliage and the mixing ratio of air within the canopy. It is clear that higher LAI leads to the higher evapotranspiration and reduces the soil surface temperature [52].

$$L_f = l_f \, LAI \, \rho_{af} \, C_f \, W_{af} \, r'' \, (q_{af} - q_{f,sat}) \quad (5)$$

$$L_g = C_{e,g} \, l_g \, \rho_{afg} \, W_{af} \, (q_{af} - q_g) \quad (6)$$

It is worthwhile to note that the rate of evapotranspiration is influenced by the external conditions such as relative humidity, solar radiation, ambient air temperature, wind speed and substrate moisture content. As a results, the above defined variables are considered in evaluating the effect of green roof on the building energy consumption. The governing equations for calculating the above-mentioned coefficients are represented in Appendix A.

2.3. Building model and green roof parameters

This study was performed by using the building simulation tool, EnergyPlus that has the green roof model which has been developed by Sailor [51]. EnergyPlus has a number of prototype buildings according to ANSI/ASHRAE/IES Standard 90.1– 2013, and in this research the "Secondary school" building has been selected [53, 54]. The building geometry was created using "Google Sketch-up)". Google Sketch-up has an EnergyPlus plug-in that allows Sketch-up building geometry to be used by Energyplus. The geometry of building is shown in Figure 4. The school building consists of two floors, 19592 m^2 of conditioned space, 11902 m^2 of roof area, and a total of 46 thermal zones. The building has constant thermostat set points for both heating (21 ℃) and cooling (24 ℃), occupancy of 0.3 people/m^2, and lighting intensity of 12.5 W/m^2. As the green roof thermal performance is better on the lightweight roof assembly because of its thermal capacity, a metal roof is considered for the building. The characteristics of the materials used in the roof structure and schematic of roof are shown in Table 1 and Figure 5.

Table 1. Thickness and thermal properties of the roof materials layer

Material	**Thickness (m)**	**Density (kg/m^3)**	**Thermal conductivity (W/m.K)**	**Specific heat J/(kg·K)**
Roof membrane	0.0095	1121	0.16	1460
Thermal insulation (polyurethane)	0.05	40	0.04	1600
Metal decking	0.002	7680	45	418

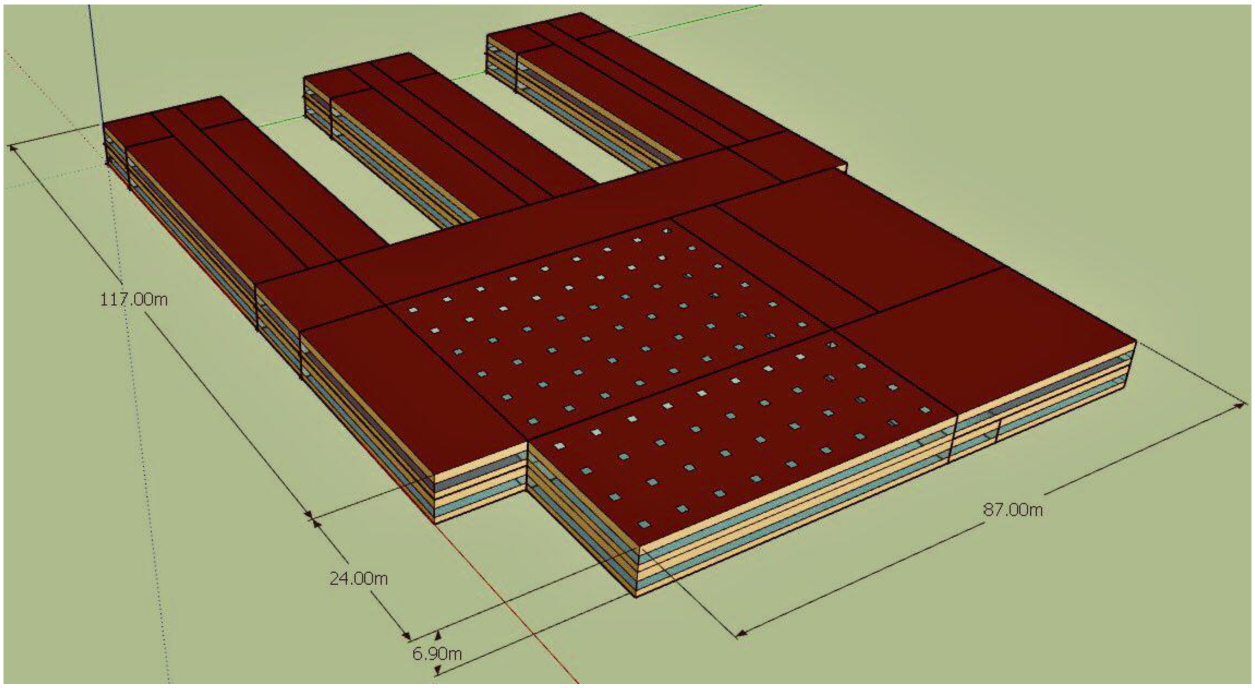


Figure 4. Secondary school building geometry.

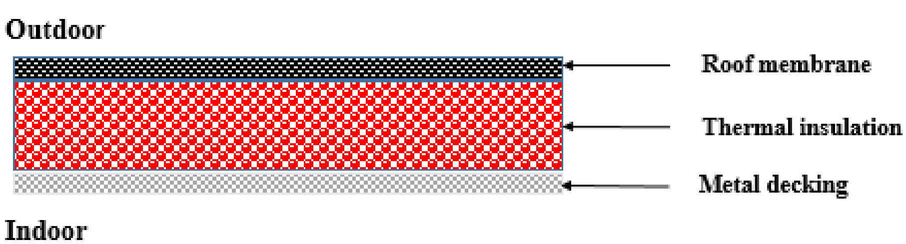


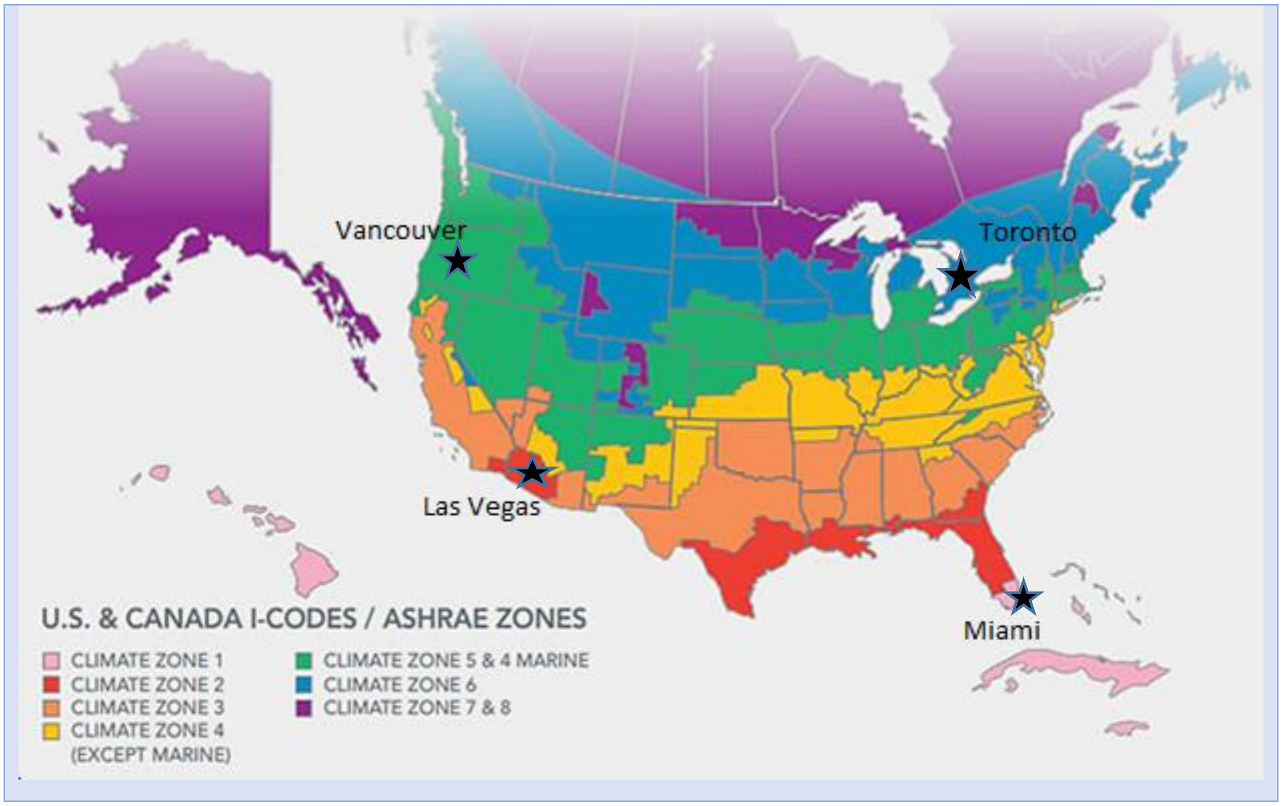
Figure 5. Schematic of roofing materials.

The building location is a key parameter in determining the used energy in buildings. To design and optimize the thermal performance of building envelopes such walls and roofs the climatological conditions of buildings should be considered by designers. The concepts of heating degree days (HDD)[1] and cooling degree days (CDD)[2] are good measures of heating and cooling loads in buildings. Hence, to study the effect of climate change on the energy performance of green roof, the same building is considered for four different climates consisting of hot-dry, hot- humid, cool-humid and humid-continental. Here, simulations were performed for each city using third typical meteorological year (TMY3) weather files for US cities and Canadian Weather for Energy Calculations (CWEC) weather files for Canadian cities [43]. The climatic information for the four selected cities is summarized in Table 2.

Table 2. Summary climate data for the four cities modeled [43,64].

City	Annual HDD Base 18 ℃	Annual CDD Base 10 ℃	Summer conditions	Winter conditions	ASHRAE climate zone
Toronto	3956	1316	Humid, Warm	Cold	6A
Vancouver	2932	951	Moderate	Mild	5C
Las Vegas	1169	3908	Dry, Hot	Mild	2B
Miami	72	5447	Humid, Hot	Moderate	1A

[1] HDD is the number of degrees that a day's average temperature is below 18^o Celsius.
[2] CDD the number of degrees that a day's average temperature is above 18^o Celsius.



Except for the roof assembly, all the building characteristics such as building envelopes, internal loads and schedules remain unchanged to understand the impacts of different parameters on the energy performance of the building. An extensive green roof which has a shallow growing media and structurally appropriate for building retrofitting is considered. The vegetation types which are used in green roofs must be adapted to the harsh environmental conditions on the roof. Hence, the extensive green roofs are planted mainly with sedums and other tough, drought-resistant and low growing plants. The sedums are appropriate for green roofs because they are drought resistant,

Resilient to diseases and insects and adaptable in different climates range from -25°C and up to 40°C [55]. However, the stomatal resistance of sedum is high, generally above 200 s/m. It can be concluded that the rate of evapotranspiration is low and the cooling effect is lower compared to the other types of plants [34]. Here, the stomatal resistance of 300 s/m is considered.

In this study, the selected parameters are for an extensive green roof with sedum coverages and consists of different growing media, leaf area index (LAI), plant height, plant albedo, soil thickness and thermal insulation thickness as shown in Table 3. It is notable that the two selected plant albedos are based on the two types of sedum including Sedum Album (Albedo = 0.23) and Mixed

Sedum Specifies (Albedo = 0.11) [56]. The constant characteristics of the green roof are shown in Table 4.

The moisture diffusion models as mentioned-above includes two methods (Simple and Advanced). A few studies the studied difference between the behaviors of these methods. A simple model as is the original model in the green roof which is based on the constant moisture diffusion through the soil. However, the Advanced method is a new method which is based on Schaap and van Genuchten model [57]. The most important factor that should be considered in modeling with Advanced method is that the time steps should be at least 20. The Figures 6 and 7 shows the moisture content of soil for during the January in Vancouver. It is seen that in the Simple method the moisture content of soil reduces while this is not realistic for the Vancouver as during the January there are lots of rainy days and the moisture content increases. However, the results with the Advanced model is more accurate as the moisture content of soil varies in different days. Therefore, in this study, the Advanced model is selected for parametric analysis.

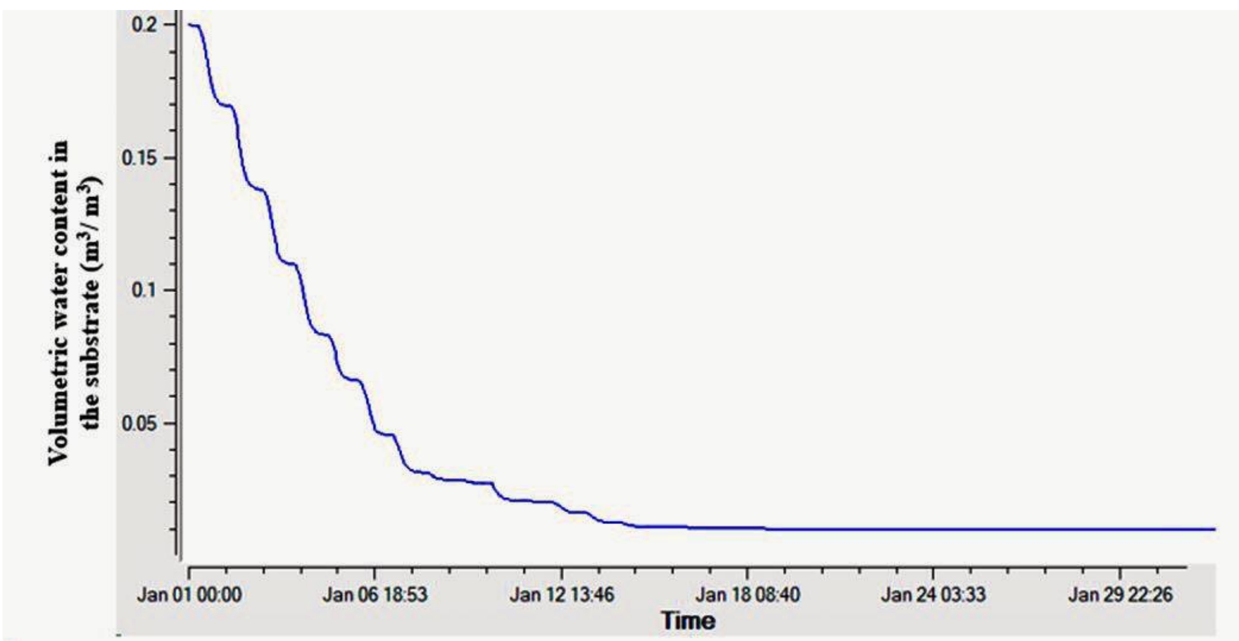


Figure 6. Moisture diffusion based on the Simple method.

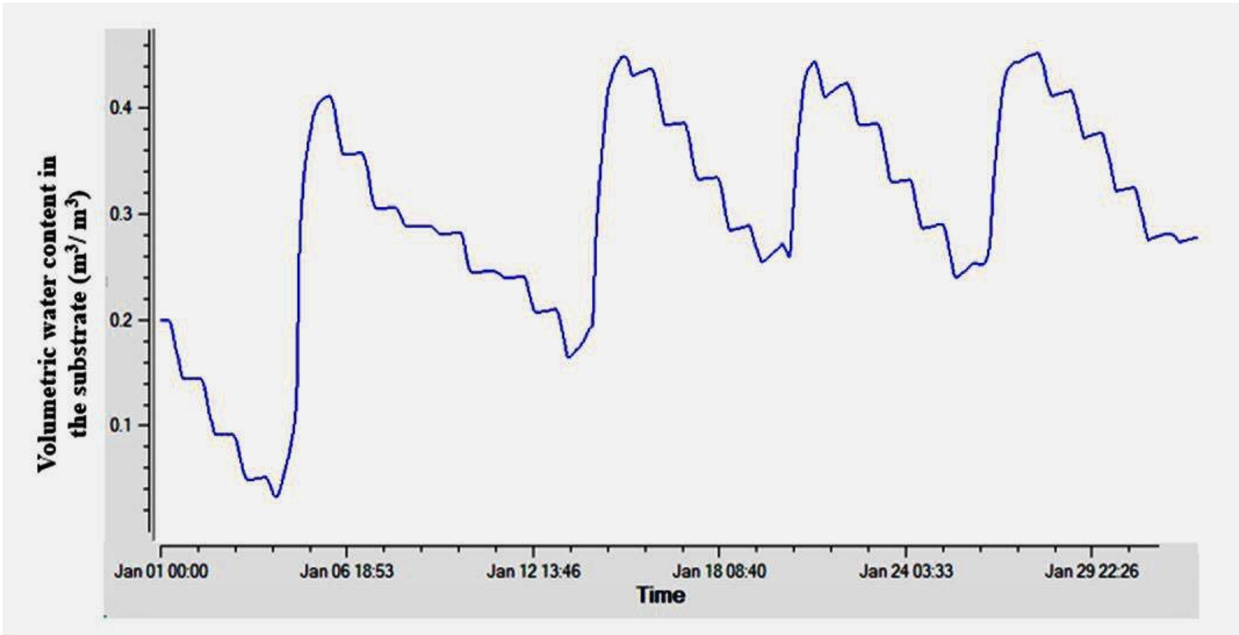


Figure 7. Moisture diffusion based on the Advanced method.

Also, this study examined the influence of substrate thermal properties and moisture content on the energy performance of the green roof assembly by considering two different substrates: heavy and light weight based soil [45]. The lightweight growing media has low density and thermal conductivity in comparison to the heavy weight growing media. In EnergyPlus, the thermal properties of soil are constant and do not vary with moisture content. Therefore, to analyze the effects of green roof design parameters on the energy consumption more accurately the influence of soil- moisture content at 20%, 60% and 100% were considered. Then, the other parameters based on one level of soil moisture are evaluated. Due to lack of field study for validation of numerical results, a study which has been performed by Silva [26] has been benchmarked to accredit the following results from EnergyPlus. The detail of benchmarked study has been provided in Appendix B.

Table 3. Design parameters for the parametric analysis

Parameter	Value
Growing Media	lightweight and heavyweight substrates
Leaf Area Index (LAI)	0.1, 2, 5
Plant Height (cm)	10, 30
Leaf Reflectivity (Albedo)	0.11, 0.23
Soil Thickness (cm)	7.5, 15
Thermal Insulation (cm)	0, 5, 10

Table 4. Green roof constant parameters values.

Parameters	Value
Leaf Emissivity	0.95
Thermal Absorptance	0.9
Visible Absorptance	0.75
Minimum Stomatal Resistance	300 ($s\ m^{-1}$)
Roughness	Medium Rough
Saturation Volumetric Moisture Content of the Soil Layer	0.5 (m^3/m^3)
Residual Volumetric Moisture Content of the Soil Layer	0.01 (m^3/m^3)
Initial Volumetric Moisture Content of the Soil Layer	0.2 (m^3/m^3)
Moisture Diffusion Calculation Method	Advanced

3. Results and discussions

3.1. Influence of soil type and moisture content

In this section the effect of soil thermal properties and moisture content on the energy performance of the green roof are analyzed. The soils selected in this research initiative are based on the results of a study conducted by Sailor [45] looking into the thermal property measurements for ecoroof (green roof) soils common in the western U.S. In this paper, the materials used in the light-weight soil were 75% pumice, 10% compost and 15% sand. It was shown to have the highest moisture capacity, the lowest thermal conductivity, and the lowest density among all the soils in their study [51]. The heavy soil consisted of 50% expanded shale and 50% sand which had the highest density and thermal conductivity among the samples. To evaluate the effect of moisture on the substrate thermal properties three levels of moisture content (20%, 60% and 100% saturation) were considered. As can be seen in Tables 5 and 6, by increasing the moisture content of the soil the thermal conductivity and density increased almost linearly. Also, as the pores of the soil are filled with water the specific heat of soil increased as well due to the fact that water has a higher thermal storage capacity than air. However, by increasing the water content the soil reflectivity (albedo) reduced significantly.

Table 5. Lightweight substrate thermal properties for different level of moisture.

Saturation level (%)	**Density (kg/m^3)**	**Thermal conductivity W/(m.K)**	**Specific heat J/(kg·K)**	**Albedo**	**Thermal diffusivity ($m^2\ s^{-1}$)**
20	765	0.21	1284	0.27	2.12 e-7
60	870	0.31	1602	0.18	2.22 e-7
100	934	0.41	1853	0.12	2.36 e-7

Table 6. Heavyweight substrate thermal properties for different level of moisture.

Saturation level (%)	**Density (kg/m^3)**	**Thermal conductivity W/(m.K)**	**Specific heat J/(kg·K)**	**Albedo**	**Thermal diffusivity ($m^2\ s^{-1}$)**
20	1385	0.37	936	0.09	2.85 e-7
60	1450	0.60	1035	0.04	3.91 e-7
100	1500	0.84	1095	0.02	5.10 e-7

To analyze the impact of the soils on the cooling and heating loads of the building, the effects of thermal properties such as thermal conductivity, heat capacity and thermal diffusivity were assessed. For instance, during the summer the temperature oscillation is high, the thermal diffusivity (which represents the ability of materials to conduct energy relative to its thermal capacity) plays a key role in evaluating the thermal performance of materials. The light soil, because of high specific heat and low thermal conductivity, has a lower thermal diffusivity compared to the heavy soil. It is seen that by increasing the moisture content of the soils, the thermal diffusivity of light soil unlike heavy soil, remains almost unchanged. Therefore, it is expected that during the summer the cooling load of the uninsulated green roof with lightweight soil will vary marginally with different levels of moisture. The results in Table 7 prove this statement.

However, for the heavy weight soil, by increasing the moisture content the thermal diffusivity increases. As a result, the cooling load for the uninsulated green roof with the heavy substrate increased considerably more than the lightweight soil. Moreover, the graphs indicate that at a moisture level of 20% the heavy and light soils have similar thermal diffusivity, their cooling loads were almost equal to each other. However, at higher levels of moisture content, the light soil had better thermal performance compared to the heavy soil. It was expected that the heavy soil would have better performance compared to the light soil during the summer months because of its higher thermal capacity. However, due to the low thermal diffusivity of the light soil, it was found to perform better during the large daily temperature fluctuations between day and night in the summer. Hence, the thermal diffusivity of soil should be considered when the soil is designed for cooling dominated regions.

On the other hand, in winter, thermal conductivity plays a key role in heat transfer through the roof. The thermal conductivity of heavy soil at higher moisture levels is almost twice that of lightweight soil. Therefore, the results demonstrate that heating load for the roof with lightweight soil is considerably lower than heavyweight soil. The importance of thermal conductivity is more evident for cities such as Toronto, Vancouver and Las Vegas that experience cold winters. However, in Miami which has a mild winter, the heating load difference between the light and heavy soil is minimal. That is to say that the heating load is not largely effected by soil-type in regions with this climate. Therefore, the uninsulated green roof with light soil had better thermal performance in all four cities.

There were no differences between the thermal performance of heavy and light soils when the roof is insulated. The results in Tables 7 and 8 show that the energy consumption of the building with an insulated greed-roof assembly is not largely dependent on the soil type used. When the roof assembly is insulated, the effectiveness of the green-roof decreases. Also, the moisture content of the soil did not have an effect on the variation of cooling and heating loads when the roof was insulated.

For the uninsulated roof, the lightweight soil should be selected because of its low thermal diffusivity and conductivity. However, for the insulated roof, both soils have similar thermal performance. In a case where heavy soil is selected, the structural support of the roof should be such that it can accommodate increased loads. Another important factor in determining the soil is the availability of materials. For instance, in the western part of USA, pumice is commonly used due to its availability instead of expanded shale, which is used primarily in the east.

Due to the limitations of EnergyPlus for considering the effect of moisture content on the thermal properties of the substrate, and by considering the results in Tables 7 and 8, the light soil with a 50% saturation level was considered for the duration of this report. The thermal properties of the soil were calculated based on the 50% level of saturation which are shown in Table 9.

Table 7. Cooling load (kWh/m^2) variation with moisture content for insulated and uninsulated roofs in different climates

	20% saturated		**60% saturated**		**100% saturated**	
City	Light weight	Heavy weight	Light weight	Heavy weight	Light weight	Heavy weight
Toronto (Insulated)	8.31	8.46	8.37	8.53	8.41	8.68
Toronto (Uninsulated)	11.11	11.48	11.85	12.42	12.37	12.90
Vancouver (Insulated)	3.01	3.08	3.03	3.13	3.05	3.15
Vancouver (Uninsulated)	3.98	4.24	4.36	5.11	4.62	5.54
Las Vegas (Insulated)	41.81	45.52	42.13	42.95	42.30	43.52
Las Vegas (Uninsulated)	57.10	58.66	57.76	62.63	58.50	66.22
Miami (Insulated)	69.12	70.16	69.64	70.42	70.44	70.64
Miami (Uninsulated)	82.93	84.24	84.81	89.37	87.22	93.70

Table 8. Heating load (kWh/m^2) variation with moisture content for insulated and uninsulated roofs in different climates

	20% saturated		**60% saturated**		**100% saturated**	
City	Light weight	Heavy weight	Light weight	Heavy weight	Light weight	Heavy weight
Toronto (Insulated)	142.60	145.23	144.23	146.46	144.90	147.00
Toronto (Uninsulated)	194.84	221.36	212.83	238.87	224.55	247.27
Vancouver (Insulated)	92.93	94.43	93.83	95.16	94.23	95.44
Vancouver (Uninsulated)	125.10	143.24	137.00	154.93	144.56	160.83
Las Vegas (Insulated)	26.64	26.92	26.77	27.10	26.84	27.11
Las Vegas (Uninsulated)	35.72	40.74	38.83	45.10	40.82	46.84
Miami (Insulated)	2.25	2.26	2.25	2.29	2.26	2.31
Miami (Uninsulated)	2.90	3.41	3.14	3.90	3.32	4.33

Table 9. Thermal properties of the 50% saturated lightweight substrate.

Soil	**Density (kg/m^3)**	**Thermal conductivity W/(m.K)**	**Specific heat J/(kg·K)**	**Albedo**	**Thermal diffusivity (m^2 s^{-1})**
Lightweight	840.00	0.28	1500.00	0.20	2.85 e-7

3.2. Influence of the leaf area index (LAI)

The leaf area index is one of the most influential parameters on the energy performance of green roofs. It is defined as the projected area of all leaves divided by the soil surface area which typically ranges from 0.001 to 5 [52]. The larger LAI indicates that less of the soil is exposed to solar radiation and as a result the soil surface temperature is lower. Figures 8 and 9 shows the temperature variation of green roof soil with different LAI and outdoor air for a typical day in summer and winter in Vancouver. On a typical cold winter day, the soil temperature was warmer than the outdoor air temperature by an average of 6 °C, 5.7°C and 5.1°C when the LAI were 0.1, 2 and 5 respectively. This is attributed to the thermal storage behavior of the soil as some of the heat is absorbed into the soil as it transfers from the warm interior to the cold exterior. It is worthwhile to note that with LAI equal to 5 the soil surface is still warmer than ambient air which indicates the insulating behavior of foliage limits the heat losses from soil surface to the ambient air. On a typical hot summer day, due to the higher rate of solar radiation absorption, the surface temperature was warmer than the outdoor air temperature by an average of 18°C, 12°C and 7°C for LAI ranges from 0.1 to 5 respectively. It is clear that the soil surface is shaded with higher plant coverage which results in lower surface temperature. This is beneficial as the conduction heat transfer through the roof during the summer decreases significantly. Appendix D provides details of the monthly variation of soil temperature with LAI in different cities.

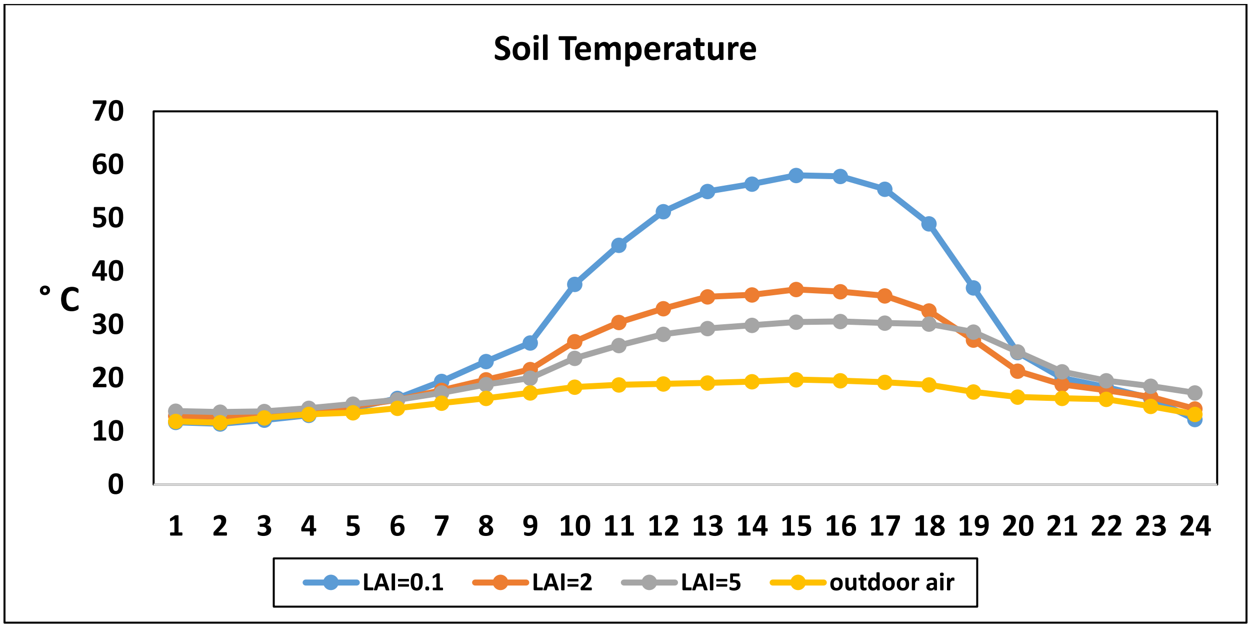


Figure 8. Variations of soil surface temperature with ambient air for a typical day in Summer.

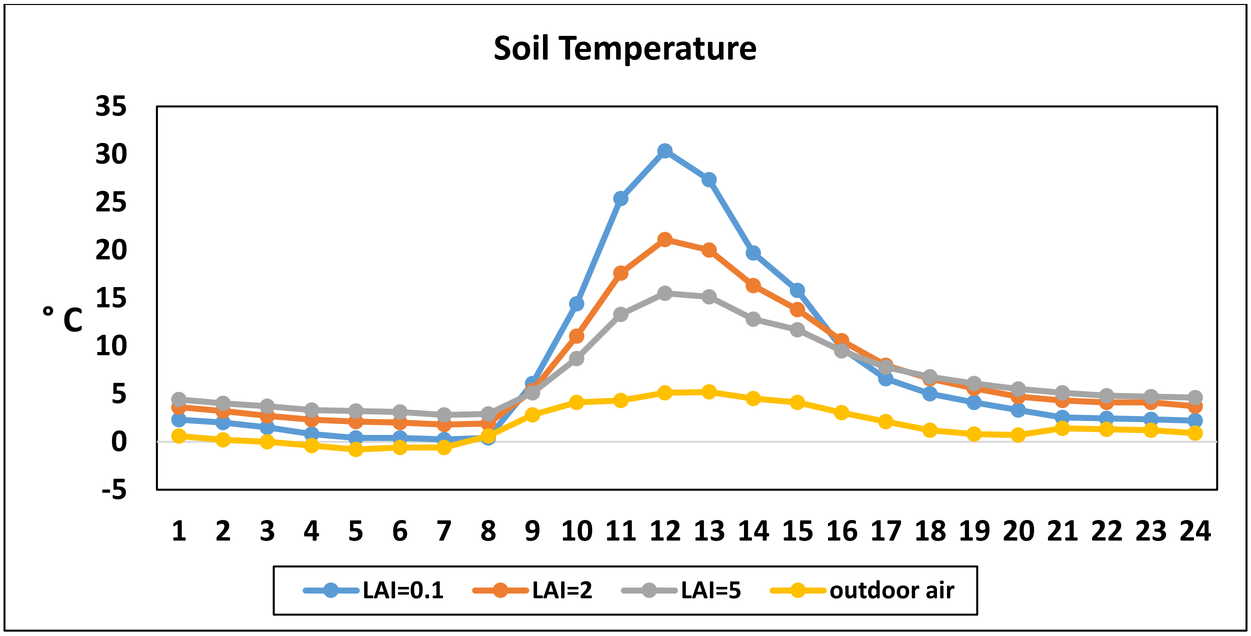


Figure 9. Variations of soil surface temperature with ambient air for a typical day in Winter.

On the other hand, the LAI has major effect on the rate of evapotranspiration in green roofs. By increasing the LAI the rate of evapotranspiration increases as the stomatal resistance of the plants exhibits an inverse relation with LAI. Therefore, it can be concluded that the greater LAI leads to an decrease in cooling load. Equation (7) shows the relation between the LAI and stomatal resistance [51]. The equation is as follow:

$$r_s = \frac{r_{s,min}}{LAI} \cdot f_1 \cdot f_2 \cdot f_3 \qquad (7)$$

In equation (7), $r_{s,min}$ is the minimum stomatal resistance. The actual stomatal resistance varies with the minimum resistance at any time and it has a reverse relation with LAI. To modify the stomatal resistance equation, fractional multiplying factors f_1, f_2 and f_3 that relate to the incoming solar radiation and atmospheric moisture are considered. The method for calculating the fractional multiplying factors are provided in detail in Appendix A.

It is notable that the rate of evapotranspiration indicates the effectiveness of LAI. However, the plant evapotranspiration individually depends on external conditions such as solar radiation, wind speed, ambient air temperature, relative humidity and soil moisture content. Therefore, to compare the effectiveness of LAI on the building energy consumption for the four selected cities, the impacts of the above-mentioned variables need to be considered in the analysis.

Because of the difficulty in measuring the evapotranspiration process, the rate (or flux) of evaporation is defined to indicate the degree of evapotranspiration [58]. Figures 10 and 11 compare the average monthly evapotranspiration rate for all four selected cities at two different level of LAI. It is evident that this rate during the winter is considerably lower than summer because of lower solar radiation and ambient temperature. Also, the rate of evapotranspiration is significantly lower when LAI = 2 because of less solar radiation absorption by the plants. The impact of LAI on the latent and sensible heat flux in different cities are presented in Appendix E and F. Also, the effect of solar radiation on the rate of evapotranspiration for a typical day in summer is presented in Appendix G. The heating and cooling load variations with different LAI are shown in Figures 12 and 13. It is seen that in Las Vegas higher solar radiation intensity and ambient air temperature as well as lower air relative humidity contributed to the high rate of evapotranspiration and cooling load reduction among all four cities. However, in Miami because of high relative humidity, low rate of solar radiation and wind velocity, the evapotranspiration rate remain almost unchanged even with greater LAI and the cooling load reduced slightly in comparison with other cities. The cooling load reduction in Miami was just 29% in comparison with 54%, 45% and 41% reduction in Vancouver, Toronto and Las Vegas respectively. This indicates the effect of solar radiation, wind speed and relative humidity on the effectiveness of LAI and evapotranspiration rate in different climates. The rate of evapotranspiration in Vancouver is higher than that of Toronto during the cooling seasons because Vancouver has lower relative humidity and higher insolation than Toronto. The average monthly amount of meteorological parameters are represented in Appendix C.

On the other hand, as mentioned-above the soil surface temperature decreases by increasing the LAI. The reduction of soil temperature contributes to the higher heat losses through conductive heat transfer in the soil during the heating seasons. The heating load in Las Vegas and Miami increased by almost 21% and 6.5%. It is notable that this trend for Vancouver and Toronto is reversed. It can be concluded that during the winter the rate of evapotranspiration in these two cities is almost zero compared to that of Las Vegas and Miami because of lower ambient temperatures and solar radiation. In other words, during the winter, Vancouver and Toronto have many cloudy days and the number of sunny days are considerably lower than Miami and Las Vegas. Therefore, greater plant coverage acts as a barrier for the heat losses during the winter. The heat loss was reduced by almost 8% in both cities.

It can be concluded that although the LAI has major impacts on the reduction of long wave and short wave radiation incident on the roofing system during the summer, it influences the heat losses and heat gains during the winter as well. However, its performance predominantly depends on the climatic conditions. Therefore, LAI plays a key role in decreasing or increasing the heat flux through the green roof.

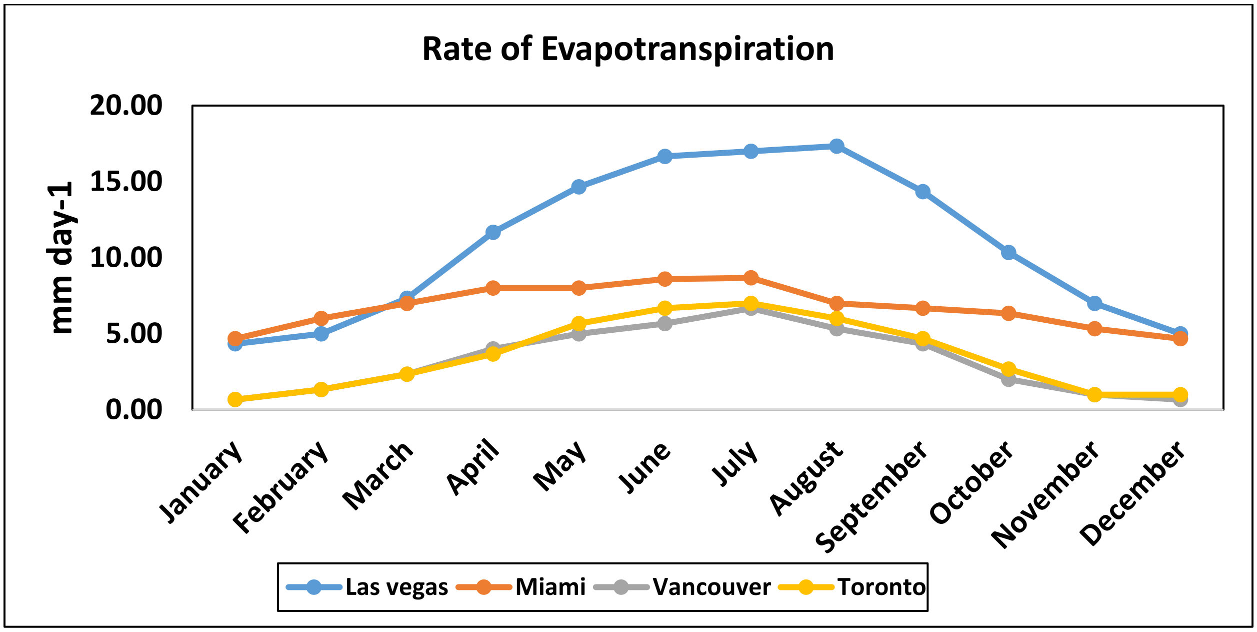


Figure 10. Monthly average rates of evapotranspiration for the high plant coverage (LAI = 5) condition.

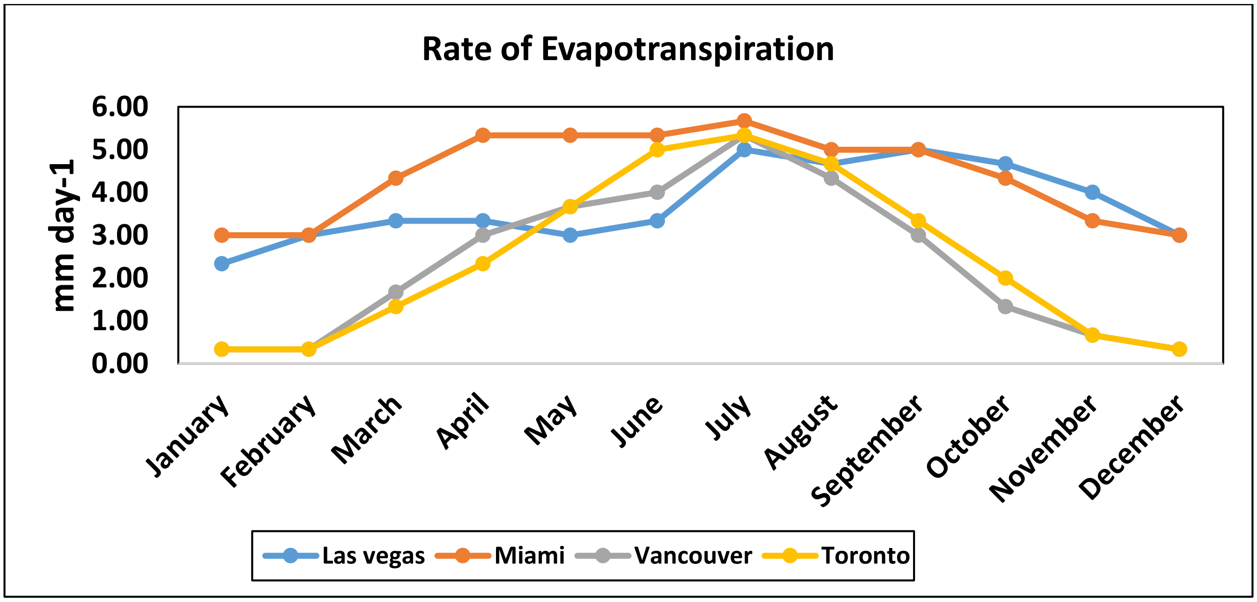


Figure 11. Monthly average rates of evapotranspiration for the low plant coverage (LAI = 2) condition.

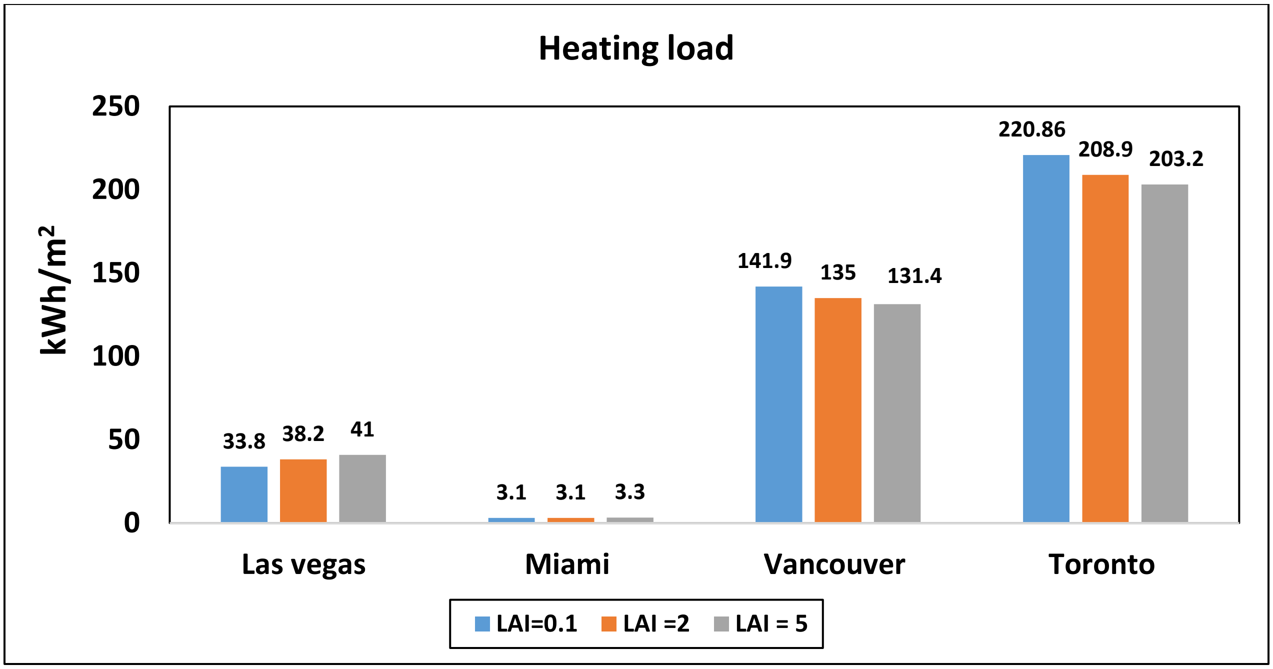


Figure 12. Sensitivity of heating load with LAI in different climates.

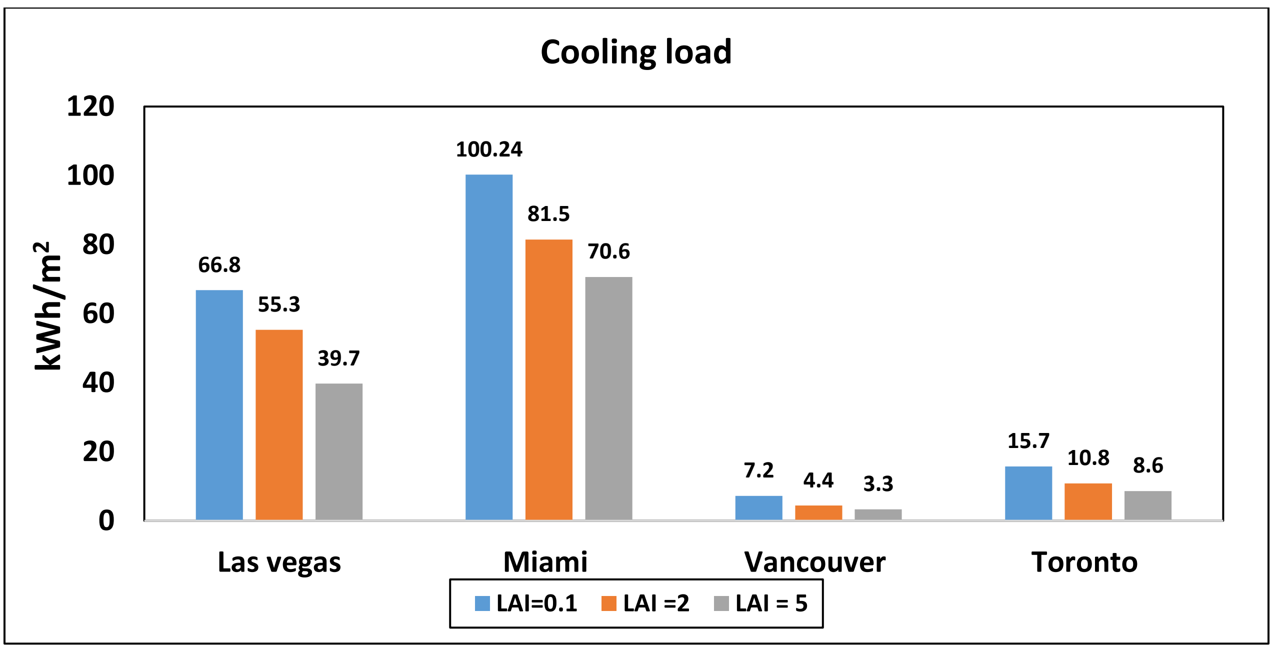


Figure 13. Sensitivity of cooling load with LAI in different climates.

3.3. Influence of soil thickness

The soil thickness has a massive effect on the reduction of heat flux during the winter and summer. Increasing the soil thickness results in lower heat flux because of thermal storage and insulation effects of the soil. The thicker soil contributes to a reduction in the operating costs of the HVAC system, however, it increases the initial costs [52]. As a result, the economic aspects should be considered in determining the soil thickness. The soil thickness is much more influential during the winter as during the cooling seasons the evapotranspiration of plants decreases its effect on the cooling reduction. So, it can be concluded that the performance of soil thickness depends on the plant coverage and height. For instance, in Figures 14 and 15 it is seen that the roof can take advantage of soil thickness significantly more when the LAI is equal to 2 in all cities. The results in Figure 15 demonstrate that the highest reduction in cooling load is for Vancouver is 27% when the soil thickness doubled. It can be deduced that, as the summer in Vancouver is cooler compared to the other cities, the thicker soil has greater impacts on the cooling load. The minimum reduction is in Miami (6%) as it has a hot and humid summer and the extra thermal storage of the soil is not as effective as in the other cities because of the low temperature fluctuation during the day. These reductions are lower when the LAI is equal to 5, which is justifiable because of the cooling effect of the plants. Similarly, as can been seen in Figure 14 during the winter, the soil thickness is more effective when the LAI is low. For instance, with LAI =2, the heat loss is reduced by 30% in Miami when the soil thickness is doubled. However, this reduction in Toronto was found to be lower (16%) as a result of the extremely cold winters. With LAI equal to 5 the radiative heating capability of the thicker soil is reduced as the vegetation cools the roof and increases the heat losses. It is evident from Figures 14 and 15 that the soil with 15 cm thickness saved the energy significantly in all climates.

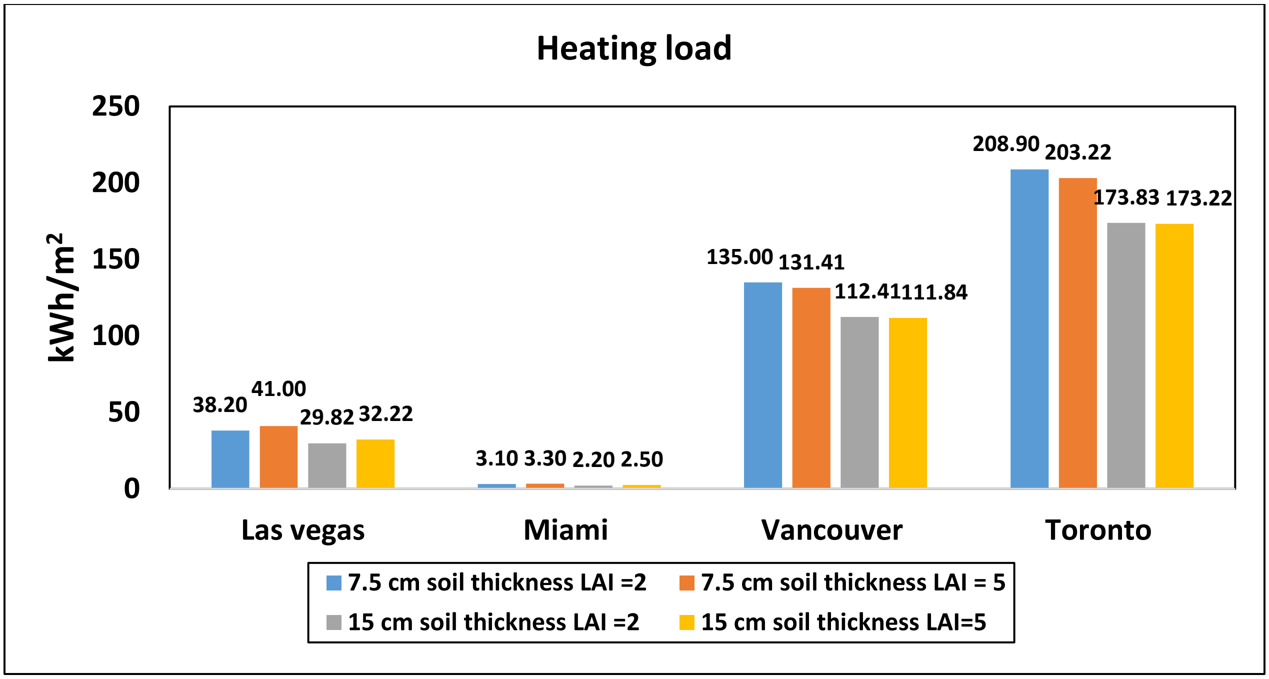


Figure 14. Sensitivity of heating load with LAI and soil thickness in different climates.

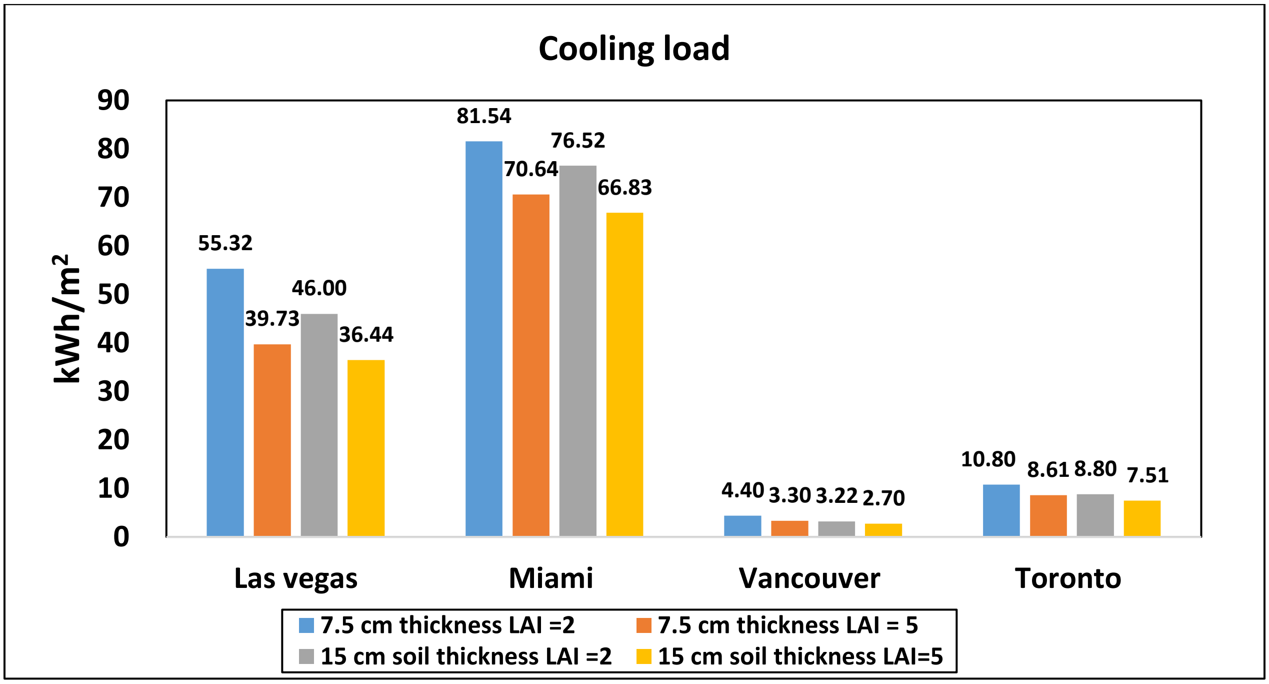


Figure 15. Sensitivity of cooling load with LAI and soil thickness in different climates.

3.4. Influence of plant albedo

The plant surface temperature has major impacts on the mitigation effect of green roof. This is because of the convective heat transfer between the leaves surface and air within the canopy. The higher surface temperature of foliage results in an increase in the ambient air, and reduces the mitigation effect of green roofs. The surface temperature depends on the amount of solar and thermal radiation absorption, emission, convective heat transfers with ambient air and the latent heat flux by transpiration [10]. The variations of vegetation latent heat fluxes, foliage temperature and soil temperature with plant albedo are represented in Figures 16 to 18 for a green roof with LAI 5 and soil thickness 15 cm in Vancouver. It is observed that the plant with albedo 0.11 has higher foliage and soil temperature due to the higher solar absorption. The higher foliage temperature also contributes to the higher rate of transpiration. Nevertheless, the cooling effect of high transpiration is canceled out by the higher surface temperature of the soil. The variation of latent heat fluxes (evapotranspiration) with plant albedo are shown in Appendix H. Also, Figure 19 depicts the impact of LAI on the plant surface temperature. By increasing the LAI, the leaf surface temperature decreases because of high rate of evapotranspiration and less long wave radiation from the soil towards the plants. The cooler foliage surface is beneficial if the mitigation effect of the green roof is targeted. The effect of plant albedo and LAI on the foliage temperature in different cities are provided in Appendix I and J.

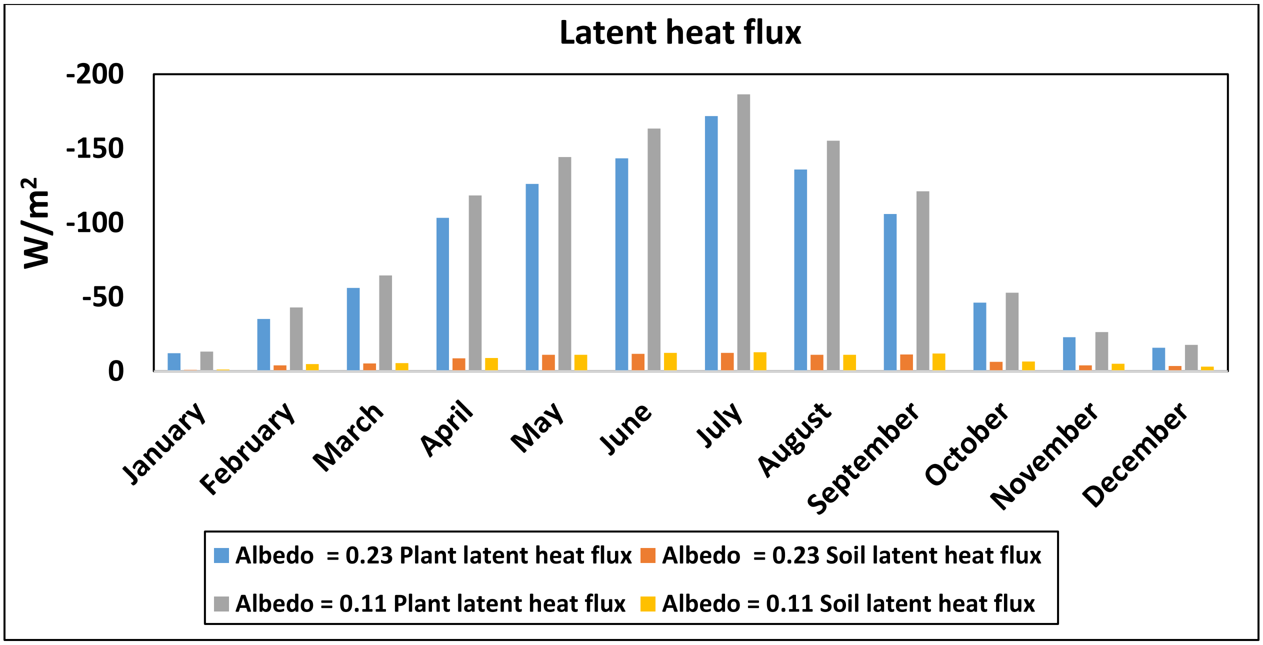


Figure 16. Effect of plant albedo on the plant and soil latent heat fluxes in Vancouver.

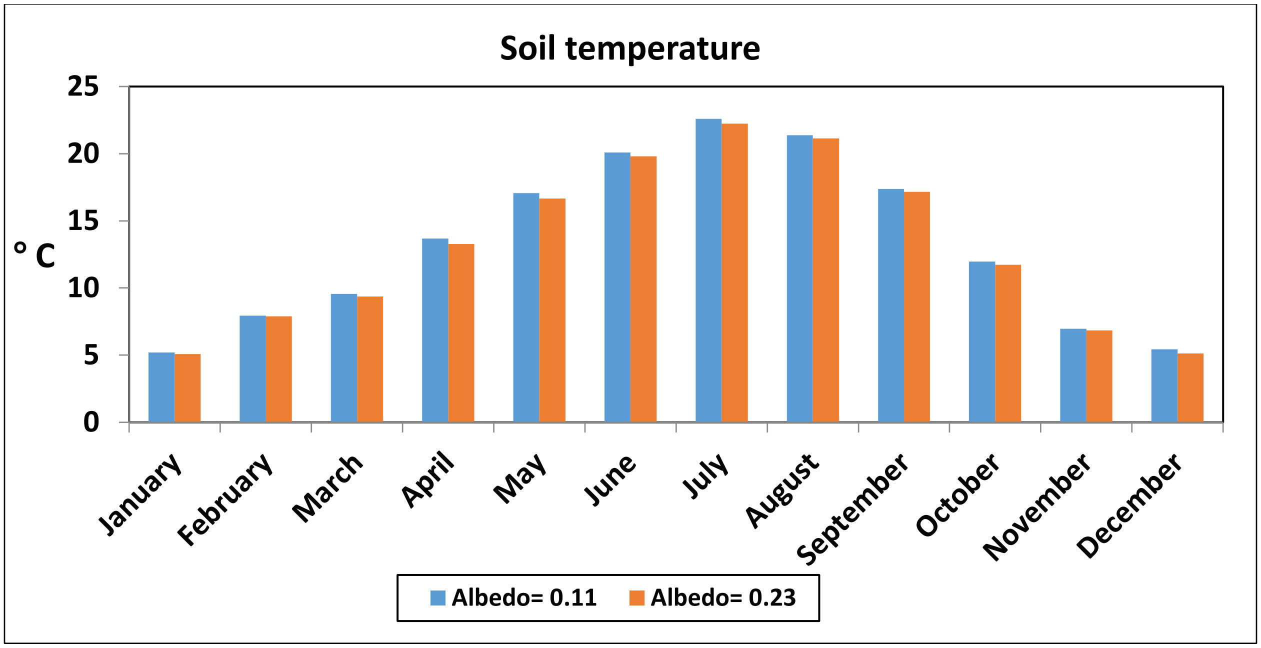


Figure 17. Monthly average variations of soil temperature with plant albedo in Vancouver.

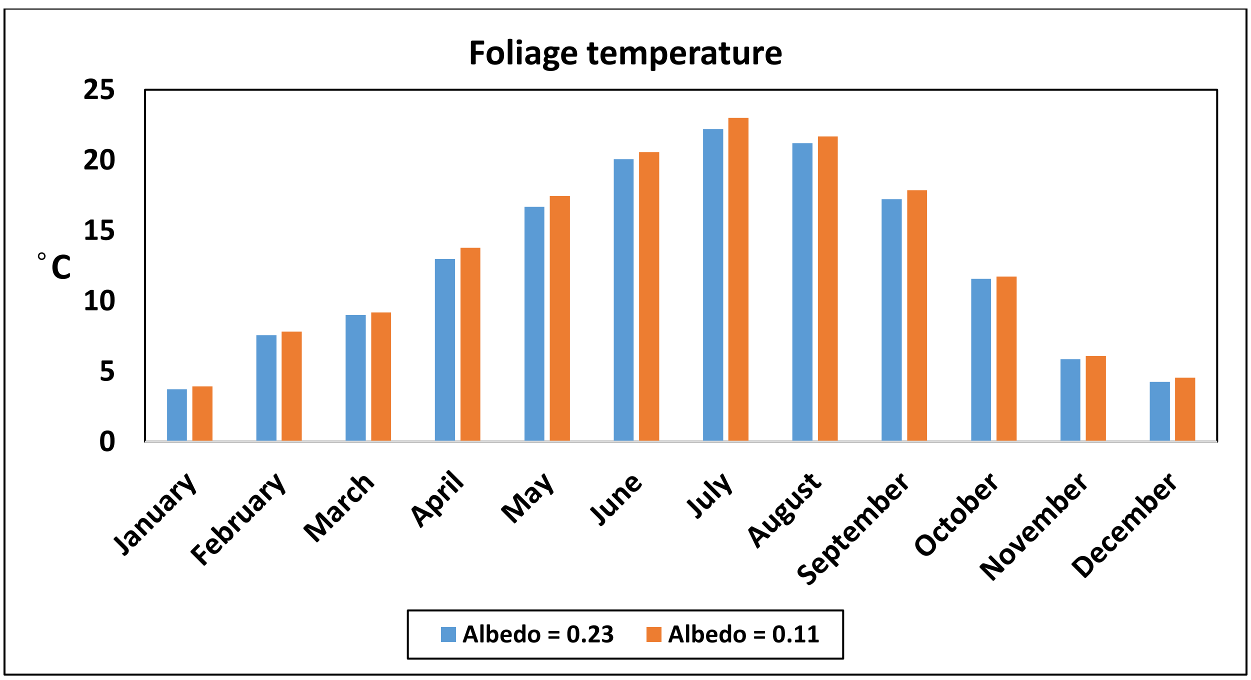


Figure 18. Monthly average variations of foliage temperature with plant albedo in Vancouver.

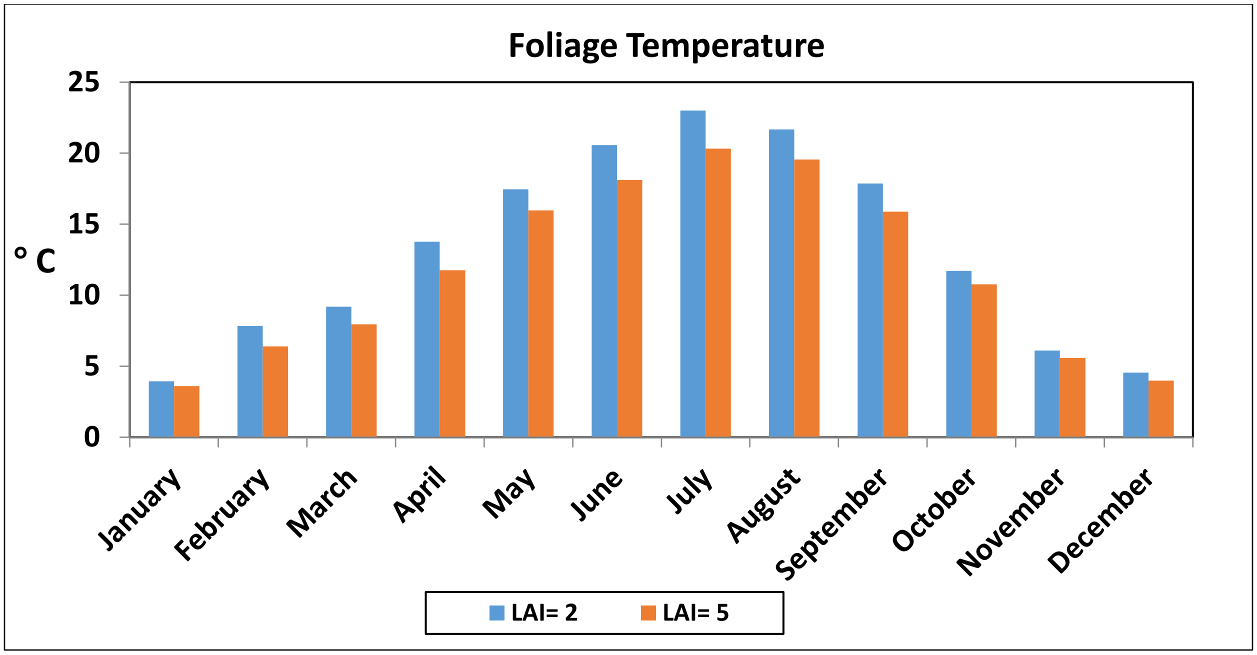


Figure 19. Effect of LAI on the foliage temperature in Vancouver.

Similar to the other parameters, the effect of leaf reflectivity on the thermal performance of the green roof is evaluated. The results in Figures 20 and 21 show that the plant albedo did not have effect on the energy performance of the green roof because of the tradeoff between the cooling effect of evapotranspiration and the increase in soil temperature. The cooling and heating load in all four cities changed less than 1% by altering the plant albedo from 0.11 to 0.23. Therefore, although the plant albedo had negligible effect of the green roof energy performance, for the cities such as Vancouver and Toronto which are heating dominated climates, the plant with lower reflectivity 0.11 is considered and for the Miami and Las Vegas which are cooling dominated climates the plant with higher reflectivity 0.23 is suitable.

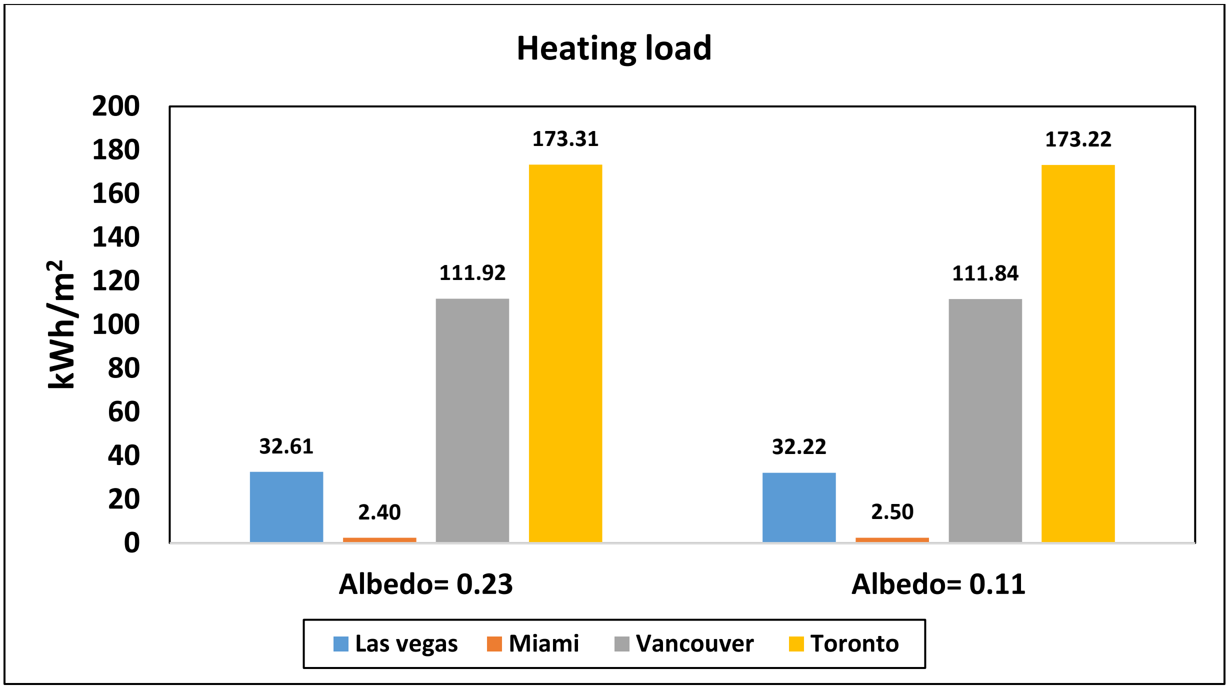


Figure 20. Sensitivity of heating load with plant albedo in different climates.

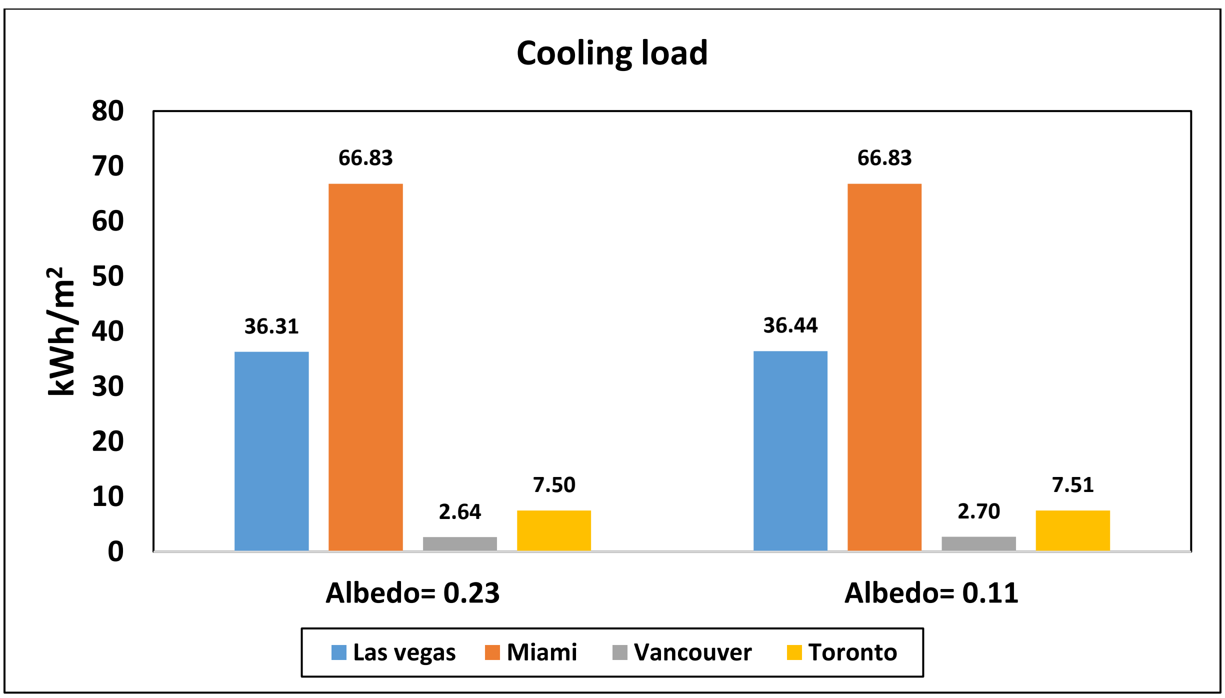


Figure 21. Sensitivity of cooling load with plant albedo in different climates.

3.5. Influence of plant height

Plant height is another important parameter which influences the energy performance of green roofs. The plant height like LAI has impacts the shading of the soil surface and the rate of evapotranspiration. For instance, with short plants the soil temperature increases more than with tall plants because a larger part of the soil is exposed to the solar radiation. Consequently, the solar radiation absorption by the soil cancels out the cooling impacts of evapotranspiration process [52]. On the other hand, it is expected that by increasing the plant height the cooling load reduces. By increasing the plant height, the wind velocity within the canopy increases, therefore, the higher wind speed will lead to a higher rate of evapotranspiration. The increase in evapotranspiration by higher wind velocity is strongly related to the concept of formed boundary layers (a thick layer of stagnant air) on the leaf surface. It is evident that in order to have transpiration, the water vapor which leaves the stomata has to transfer through this motionless layer to reach the atmosphere where the moving air removes the water vapor. Hence, the rate of transpiration is slower when the boundary layer is larger or in other words, when the wind velocity is low.

The aerodynamic resistance factor shows the resistance that is caused by the boundary layer for exchanging moisture. Wind velocity, surface roughness and stability of the atmosphere are the main parameters which influence the aerodynamic resistance. As mentioned in the last section, the wind speed greatly impacts transpiration rates by removing the boundary layer which has been created by motionless air on the leaf surface. Equation (8) shows that the aerodynamic resistance of plant is inversely proportional to wind velocity and the unit is (s/m) [51].

$$r_a = \frac{1}{C_f W_{af}} \tag{8}$$

The aerodynamic resistance also affects the leaf surface wetness. The surface wetness is defined as the ratio of the aerodynamic resistance to the total resistance. The leaf wetness factor ranges from 0 to 1 and by reducing the aerodynamic resistance it approaches zero, which demonstrates that the moisture is transferred rapidly to the leaf surface and evaporated easily. By contrast, when it approaches one, the moisture does not evaporate easily while the moisture transfers to the leaf surface [51].

$$r'' = \frac{r_a}{r_a + r_s} \tag{9}$$

The effect of plant height and LAI interaction on the cooling and heating loads are shown in Figures 22 and 23. It is seen that the growth of the plant does not always lead to a cooling load reduction and the effectiveness of plant height depends on LAI and climate zone. For instance, there was an interactive relationship between LAI and plant height in Miami and Las Vegas. The cooling load in Las Vegas and Miami (unlike Vancouver and Toronto) raised slightly by increasing the plant height when the plant coverage was low (LAI=2). However, the results expressed that the cooling load decreased by increasing the plant height in all four cities when the LAI was high. Generally, the plant height was not as effective as LAI in reduction of cooling load. The influence of plant height on the latent heat flux for the different plant coverage condition in different cities is presented in Appendix K.

By contrast, the heating load increased as the taller plants results in more shading on the soil surface. It is important to notice that the increase in heating load with plant height is slightly lower when the LAI is lower. This is justifiable as surface of the green roof is exposed to more solar radiation when the plant coverage is less. As Las Vegas and Miami are cooling dominated climates, the annual energy savings with a 30 cm plant is more than with a 10 cm plant. However, in Toronto and Vancouver (which have heating dominated climates), the 10 cm plant had better performance on the building energy consumption.

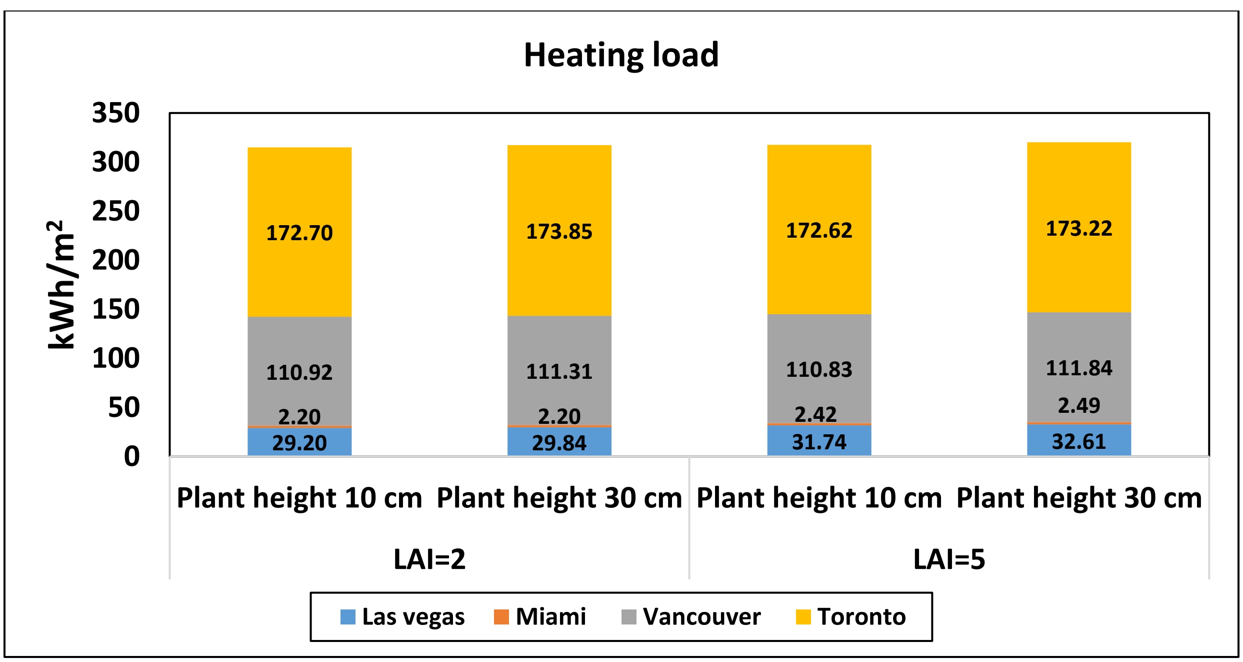


Figure 22. Sensitivity of heating load with LAI and plant height in different climates.

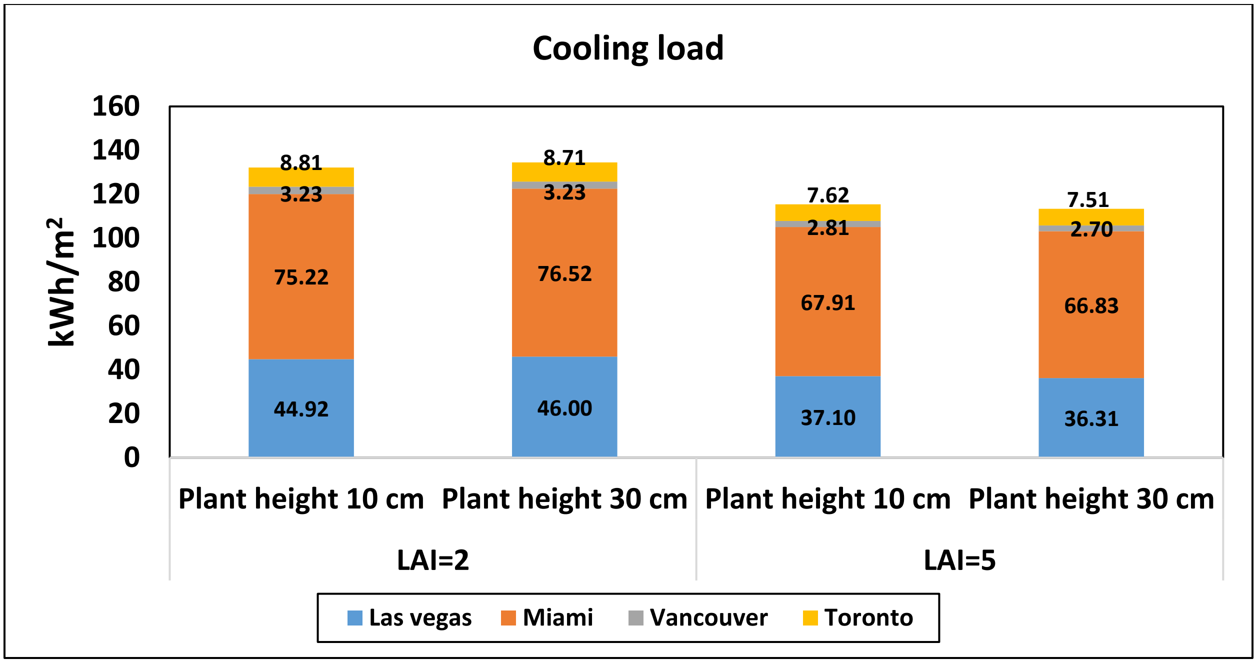


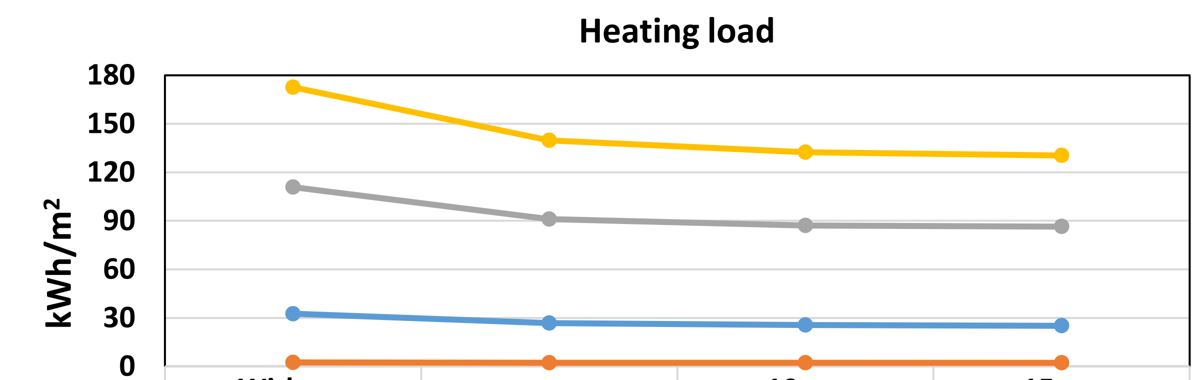
Figure 23. Sensitivity of cooling load with LAI and plant height in different climates.

3.6. Influence of thermal insulation on the optimized green roof

Figures 24 and 25 show the role of thermal insulation on the thermal performance of the school building with optimized design parameters of green roof as described above. The results demonstrate that thermal insulation would be more effective for the heating dominated climates. The heating load of optimized vegetated roof in Miami and Las Vegas changed minimally with thermal insulation compared to Vancouver and Toronto. For example, in Miami the uninsulated green roof has almost equal heating load with insulated conventional roof. However, in Las Vegas the heating load for the insulated green roof is slightly better than uninsulated green roof.

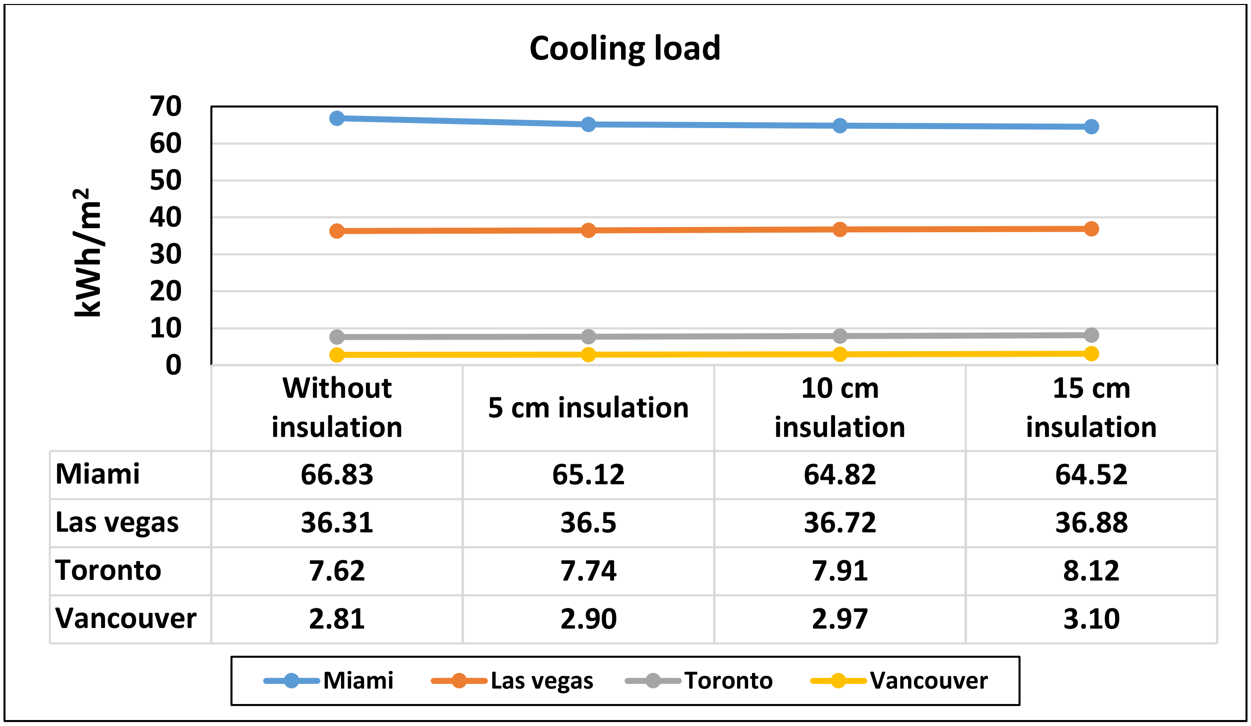
Nevertheless, the uninsulated vegetated roofs in Vancouver and Toronto have considerably higher heating loads than insulated vegetated roofs. It can be concluded that vegetated roofs cannot replace the thermal insulation in heated dominated climates like Canada. However, the insulated green roof with 5 cm thermal insulation has almost the same heating load and lower cooling load compared to the conventional roof with 10 cm thermal insulation and without a green roof system in these two cities. This means that the green roof could be an appropriate retrofit choice in Canada instead of adding extra insulation to the roof.

By contrast, vegetated roofs are more effective at reducing cooling loads and the uninsulated vegetated roof has lower cooling loads than the insulated roofs in all cities except Miami. The cooling load decreased with insulation in Miami as the thermal storage is not as effective as it is in other cities because of the low oscillation of ambient air temperature in this warm-humid climate zone. As a result, adding thermal insulation could reduce the cooling load in this climate. In other cities, by increasing the thermal insulation from 0 to 100 mm the cooling load of the vegetated roof increased. Increasing the thermal insulation levels decouples the indoor environment from the outdoor environment and reduces the ability of the vegetated roof to remove heat from the building. Thus, it can be concluded that there are no benefits from continuously adding insulation to reduce cooling load.



	Without insulation	5 cm insulation	10 cm insulation	15 cm insulation
Las vegas	32.61	26.72	25.54	25.11
Miami	2.49	2.23	2.22	2.21
Vancouver	110.83	91.11	87.14	86.44
Toronto	172.62	139.82	132.5	130.42

Figure 24. Sensitivity of heating load with thermal insulation for the optimized green roof in different climates.



	Without insulation	5 cm insulation	10 cm insulation	15 cm insulation
Miami	66.83	65.12	64.82	64.52
Las vegas	36.31	36.5	36.72	36.88
Toronto	7.62	7.74	7.91	8.12
Vancouver	2.81	2.90	2.97	3.10

Figure 25. Sensitivity of cooling load with thermal insulation for the optimized green roof in different climates.

Tables 10 to 13 present the total energy saving of the optimized green roof in comparison with the conventional roof. Here, the conventional roof is considered the reference roof type. It is seen that the annual energy saving varies among the four selected cities. The annual energy consumption with optimized green roof saved more in heating dominated cities than the cooling dominated cities. The uninsulated optimized green roof performed better than the insulated conventional roof in cooling dominated climates such as Miami and Las Vegas. For instance, installation of optimized green roof assembly on the uninsulated conventional roof saved almost 41 % and 29% of annual energy consumption in Las Vegas and Miami respectively. Also, the optimized green roof without insulation saved energy almost 4% more than the poorly insulted conventional roof. Ultimately, the total energy consumption of the school building with the uninsulated green roof was slightly lower than the well-insulated conventional roof in both cities. It can be concluded that in Miami and Las Vegas, the optimized green roof is an appropriate replace for the insulated conventional roofs.

However, in heating dominated cities such as Vancouver and Toronto the uninsulated optimized green roof is not a good choice for replacing the insulated conventional roof. It can be a suitable substitute for retrofitting the building with a poorly insulated roof. For instance, the heating load was reduced by 12.5% in retrofitted conventional roof by the optimized green roof in both cities. Also, the annual energy consumption was saved by 8.30% and 6.22% in Toronto and Vancouver respectively. It can be deduced that in cold climates thermal performance of the school building could be retrofitted by the green roof instead of adding extra thermal insulation to the conventional roof.

Table 10. Comparing the energy consumption (kWh/m^2) of the green roof with and without thermal insulation in Vancouver.

	Without insulation			With 5 cm insulation			With 10 cm insulation		
	Optimized green roof	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**
Heating	110.83	238.32	53.49 %	91.11	104.00	12.39 %	87.14	92.52	5.81 %
Cooling	2.81	8.61	67.36 %	2.90	3.56	18.54 %	2.97	3.26	8.89 %
Total	227.84	382.73	40.46 %	207.33	221.07	6.22 %	203.01	209.00	2.86 %

Table 11. Comparing the energy consumption (kWh/m^2) of the green roof with and without thermal insulation in Toronto.

	Without insulation			With 5 cm insulation			With 10 cm insulation		
	Optimized green roof	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**
Heating	172.62	354.50	51.31%	139.82	159.34	12.25%	132.50	141.22	6.17%
Cooling	7.62	19.33	60.57%	7.74	9.55	18.95%	7.91	8.74	9.49%
Total	295.51	513.80	42.48%	261.46	285.14	8.30%	254.70	264.34	3.64%

Table 12. Comparing the energy consumption (kWh/m^2) of the green roof with and without thermal insulation in Las Vegas.

	Without insulation			With 5 cm insulation			With 10 cm insulation		
	Optimized green roof	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**
Heating	32.61	82.32	60.38%	26.72	29.44	9.23%	25.54	26.66	4.20%
Cooling	36.31	84.63	57.09%	36.50	43.82	16.70%	36.72	40.74	9.86%
Total	183.10	309.93	40.92%	177.94	190.70	6.69%	177.10	183.73	3.61%

Table 13. Comparing the energy consumption (kWh/m^2) of the green roof with and without thermal insulation in Miami.

	Without insulation			With 5 cm insulation			With 10 cm insulation		
	Optimized green roof	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**	**Optimized green roof**	**Without green roof**	**Difference**
Heating	2.49	12.10	79.42%	2.23	2.65	15.85%	2.22	2.40	7.50%
Cooling	66.83	113.42	41.07%	65.12	71.94	9.48%	64.82	68.30	5.09%
Total	185.34	260.11	28.74%	183.50	192.22	4.54%	183.14	187.44	2.29%

3.7. Impact of green roof on the indoor conditions

The heating and cooling loads for the first and second floor of a classroom in Vancouver have been calculated as shown in Tables 14 and 15. The results show that cooling load for the first floor reduced by 2.7%, i.e. from 29.16 kwh/m^2 to 28.36 kwh/m^2. Also, the heating load declined by 23.4% from 3.12 kWh/m^2 to 2.39 kWh/m^2. However, the cooling for the second floor was reduced by 26.5% from 52.81 kWh/m^2 to 38.82 kWh/m^2 and the heating load was decreased by 54.4% from 14.18 kWh/m^2 to 6.47 kWh/m^2. It can be concluded that the reduction of cooling and heating loads were considerably more for the second floor because of the direct contact to the green roof. It is seen that the green roof would be beneficial for the reduction of heating and cooling loads even for the other floors of the building. In other words, it reduced the energy consumption of whole building.

Table 14. The calculated heating loads of the first and the second floor, with and without green roof

Month	First Floor		Second Floor	
	With green roof W/m^2	Without green roof W/m^2	With green roof W/m^2	Without green roof W/m^2
October	0.04	0.07	0.14	0.49
November	0.43	0.57	1.23	2.58
December	0.62	0.74	1.75	3.39
January	0.65	0.82	1.78	3.76
February	0.31	0.47	0.77	1.81
March	0.29	0.39	0.66	1.58
April	0.06	0.08	0.14	0.57
Total	**2.39**	**3.12**	**6.47**	**14.18**

Table 15. The calculated cooling loads of the first and the second floor, with and without green roof

Month	**First Floor**		**Second Floor**	
	With green roof W/m^2	Without green roof W/m^2	With green roof W/m^2	Without green roof W/m^2
May	6.06	5.98	8.09	10.32
June	8.20	8.55	10.53	13.83
July	4.52	4.89	6.51	10.27
August	5.41	5.62	7.53	10.74
September	4.22	4.11	6.16	7.65
Total	**28.36**	**29.16**	**38.82**	**52.81**

4. Conclusions

Improving the energy performance of school buildings plays a key role in saving energy in US and Canada. As the roof has a key role in heat transfer in this type of building, implementing green roofs is an appropriate method in increasing the energy savings. To this goal, this numerical simulation study, using EnergyPlus, evaluates the influence that leaf area index (LAI), plant height, leaf albedo, substrate properties, and the roof's thermal insulation has on the thermal performance of a secondary school building. The study is performed in four cities: Las Vegas and Miami (USA), Toronto and Vancouver (Canada). The two first cities are cooling dominated cities while the latter two are heating dominated cities. The following conclusions can be made from this study.

- The effect of the substrate's thermal properties on the heating load is strongly related to its thermal conductivity. However, the substrate effect on the cooling loads depends on its thermal diffusivity.
- For the uninsulated green roof, the lightweight substrate had considerably better performance that heavyweight substrate in all four cities. However, for the insulated green roof there was a small difference between lightweight and heavyweight substrate energy performance.
- The leaf area index (LAI) is the most influential parameter in energy consumption and its thermal performance depends on the climate zones. It has major impacts on the cooling

reduction in all four selected cities. However, the LAI effect on the heating load is related to the climatic condition. With regard to energy saving, the optimum LAI is 5 for the four reference cities.

- Thicker soil has better energy savings in all four cities. In summer, the cooling effect of LAI reduces the effectiveness of soil thickness on the cooling load reduction. However, in the heating seasons, soil thickness has a large effect on the heating load reduction. The thicker soil (15 cm) has better thermal performance compared to the thinner soil (7.5 cm)
- The thermal performance of plant height is affected by the LAI and climate zone. Plant height should be optimum to 30 cm, except in Toronto and Vancouver, where it should be 10 cm.
- Plant albedo has the least effect on the thermal performance of the school. For the heating dominated climate darker leaves with albedo 0.11 and for the cooling dominated climates lighter leaves with albedo 0.23 is beneficial.
- The vegetated roofs cannot replace thermal insulation to reduce heating loads in cities that experience cold winters. However, it can retrofit the energy performance of the poorly insulated buildings in heating dominated climates.
- Installation of optimized green roof on the uninsulated conventional roof could be implemented instead of insulating the roofs in cooling dominated climates.
- The green roof reduces the cooling and heating loads in both floors while it is more effective on the second floor.

In summary, the climatological conditions have a major role in optimization of green roof design parameters. Comparing the heating degree days (HDD) and cooling degree days (CDD) in different cities could be a good index to show the effectiveness of green roofs in various climates. Also, the interaction between parameters and their influences on the building energy consumption should be analyzed. Further, it has to be noted that that the energy saving of green roofs is one of the benefits of green roofs. Eventually, the other environmental benefit of green roofs should be integrated to have a comprehensive evaluation for green roofs' performance in different climate zones.

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Appendix A (Green roof model equations)

Foliage energy budget:

$$F_f = \sigma_f [\, I_s (1-\alpha_f) + \varepsilon_f I_f - \varepsilon_f \sigma T_f^4 \,] + \frac{\sigma_f\, \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_f + L_f \qquad (1)$$

It is seen the effect long and short wave radiation by the vegetation along with convective and sensible heat transfer are considered. The latent and sensible heat flux terms in the above equation H_f and L_f are complicated and need to be discussed in detail.

Sensible heat flux in the foliage layer

The temperature differences the leaf surface and the air within the canopy, wind velocity and the Leaf Area Index (LAI) is affected the sensible heat flux.,. The sensible heat flux is obtained from the following equation:

$$H_f = (1.1\, LAI\, \rho_{af}\, C_{p,a}\, C_f\, W_{af})(T_{af} - T_f) \qquad (2)$$

In this equation the constant coefficient 1.1 is considered due to the heat transfer from the stems, twigs and limbs. The properties of air within the canopy is determined by the average from the foliage and "instrument conditions":

$$\rho_{af} = 0.5\, (\rho_a + \rho_f) \qquad (3)$$

where ρ_a and ρ_f represent the density of air at the instrument height and at the leaf temperature respectively.

The air temperature within the foliage is calculated by:

$$T_{af} = (1-\sigma_f)(T_a) + \sigma_f\, 0.3\, T_a + 0.6\, T_f + 0.1\, T_g \qquad (4)$$

where, the air temperature at the instrument height in Kelvin is T_a, leaf temperature in Kelvin is T_f, and the ground surface temperature in Kelvin is T_g,. The wind speed within the foliage is given by:

$$W_{af} = 0.83\, \sigma_f\, W \sqrt{C_{hn}^f} + (1-\sigma_f)\, W \qquad (5)$$

Here W is real wind velocity above the canopy and C^f_{hn} is the transfer coefficient at "near-neutral atmospheric stability conditions":

$$C_{hn}^f = K_v^2 \cdot \left(\ln \frac{Z_a - Z_d}{Z_0^f} \right)^{-2} \qquad (6)$$

In this equation K_v, is von Karmen's constant (0.4), Z_a is the instrument height, Z_d is the zero displacement height in meters (height above soil within which the wind speed is effectively zero), and Z^f_o is the foliage roughness length scale (m). The equations which estimate the zero displacement height and the roughness length are based on Balick et al.[44, 59]:

$$Z_d = 0.701\ Z_f^{0.979} \tag{7}$$

$$Z_o = 0.131 Z_f^{0.997} \tag{8}$$

Finally, the bulk transfer coefficient as estimated by Deardorff is given by [60]:

$$C_f = 0.01*\left(1+\frac{0.3\ (\frac{m}{s})}{W_{af}\ (\frac{m}{s})}\right) \tag{9}$$

Latent heat flux in the foliage layer

The resistance of plants to diffuse water vapor from the opening spaces such as stoma is called stomatal resistance. It depends on some variables such as soil moisture content, light intensity and the vapor pressure difference between the air inside leaf and outside atmosphere. The unit is s/m and determined as follow:

$$r_s = \frac{r_{s,min}}{LAI}\ .\ f_1 .\ f_2 .\ f_3 \tag{10}$$

where, $r_{s,min}$ is the minimum stomatal resistance. The actual stomatal resistance varies with the minimum resistance at any time and it has a reverse relation with LAI. The fractional multiplying factors f_1, f_2 and f_3 are the correction for the stomatal resistance equation and depends on incoming solar radiation and atmospheric moisture. The inverse of multiplying factors f_1, f_2, and f_3 are calculated based on the Frankenstein and Koenig method [44, 61] :

$$\frac{1}{f_1} = min\left[1, \frac{0.004*I_S+0.005}{0.81*(0.004*I_S+1)}\right] \tag{11}$$

$$\frac{1}{f_2} = \begin{Bmatrix} 0 & when \quad \theta_r > \bar{\theta} \\ \frac{\bar{\theta}-\theta_r}{\theta_{max}-\theta_r} & when \quad \theta_r \leq \bar{\theta} \leq \theta_{max} \end{Bmatrix} \tag{12}$$

$$\frac{1}{f_3} = \exp\left[-g_d(e_{f,sat} - e_a\right] \tag{13}$$

where, θ_r is the residual moisture content which determined based on the moisture content of soil when the plant starts to wilt , θ_{max} is the maximum moisture content which indicates the maximum amount of moisture that soil can hold before run off, and $\bar{\theta}$ is the average amount of water content at the root area. The residual moisture content is mainly about 0.01 m^3/m^3 (Frankenstein and Koenig [61]). The maximum moisture varies for different soil and it depends on the soil composition content, but typically ranges from 0.3 to 0.6 m^3/m^3 (Guymon et al. [62]). In the above equation for determining f_3, g_d is a plant specific characteristic which in not zero just for the trees, $e_{f,sat}$ is the saturated vapor pressure at the leaf temperature, and e_a is the air vapor pressure.

The aerodynamic resistance factor shows the resistance that is caused by the boundary layer for exchanging moisture. Wind velocity, surface roughness and stability of the atmosphere are the main parameters which influence the aerodynamic resistance. As mentioned-above the wind speed greatly impacts transpiration rates by removing the boundary layer which has been created by motionless air on the leaf surface. Equation (14) shows that the aerodynamic resistance of plant is inversely proportional to wind velocity and the unit is (s/m) [44].

$$r_a = \frac{1}{C_f W_{af}} \tag{14}$$

The aerodynamic resistance also affects the leaf surface wetness. The surface wetness is defined as the ratio of the aerodynamic resistance to the total resistance. The leaf wetness factor ranges from 0 to 1 and by reducing the aerodynamic resistance it approaches zero, which demonstrates that the moisture is transferred rapidly to the leaf surface and evaporated easily. By contrast, when it approaches one, the moisture does not evaporate easily while the moisture transfers to the leaf surface[44].

$$r'' = \frac{r_a}{r_a + r_s} \tag{15}$$

The latent heat flux is then given by:

$$L_f = l_f \, LAI \, \rho_{af} \, C_f \, W_{af} \, r'' \, (q_{af} - q_{f,sat}) \tag{16}$$

Where, l_f is the latent heat for evaporation (J/kg), $q_{f,sat}$ is the saturation mixing ratio at the leaf surface temperature and q_{af} is the mixing ratio of the air within the canopy. The mixing ration within the canopy is determined by the develoed method of Frankenstein and Koenig [44, 61]:

$$q_{af} = \left[\frac{1-\sigma_f \, q_a + \sigma_f 0.3 \, q_a + 0.6 q_{f,sat} r'' + 0.1 q_{f,sat} M_g}{1-\sigma_f\left[0.6\,(1-r'') + 0.1\,(1-M_g)\right]}\right] \tag{17}$$

Where M_g is the ratio of volumetric moisture content (VWM) to the porosity of the soil (Koenig) which ranges from 0 to 1. The latent of evaporation is estimated from Hendeson-Sellers method in which it has a reverse relation with temperature [44, 49].

$$\mathrm{l_f} = 1.91846 * 10^6 \left[\frac{\mathrm{T_f}}{\mathrm{T_f} - 33.91}\right]^2 \quad (18)$$

Soil Energy budget

The energy budget at the soil surface is affected by the thermal properties of soil, the moisture content of soil and the amount of foliage coverage (σ_f). By increasing the plant coverage the soil surface is less exposed to the solar radiation and as a result the soil surface temperature is lower. In the soil energy budget, the heat released or gain because of the phase of change of water in the soil and precipitation heat flux and heat flux because of the vertical transport of water in the soil are ignored. The energy balance at the soil surface is:

$$F_g = (1 - \sigma_f)[\, I_s (1 - \alpha_g) + \varepsilon_g I_{ir} - \varepsilon_f T_g^4 \,] + \frac{\sigma_f\, \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + K \frac{\partial T_g}{\partial Z} + H_g + L_g \quad (19)$$

Similar to the energy budget for the foliage in this equation the H_g and L_g represent the sensible and latent heat fluxes. Also, the terms associated with long and short wave radiation are on the left side of equation. The final term on the right side gives the conduction of heat into the soil substrate [44].

Sensible heat flux in the soil layer

Sensible heat flux depends on the temperature difference between the soil surface and air near the surface and the wind velocity within the canopy [44].

$$H_g = \rho_{ag}\, C_{p,a}\, C_{hg}\, W_{af}\, (T_{af} - T_g) \quad (20)$$

where C_{hg} is the bulk transfer coefficient and ρ_{ag} is the density of air near the soil surface (kg/m^3) obtained from the following equation:

$$\rho_{ag} = 0.5\, (\rho_a + \rho_g) \quad (21)$$

Here, ρ_g is the density of air at the ground surface temperature [44].

The bulk transfer coefficient is obtained by multiplying the stability factor (Γ_h) to the linear combination of bulk transfer coefficient near ground C_{hn}^f and the near foliage-atmosphere interface C_{hn}^g:

$$C_h^g = \Gamma h \left[1 - \sigma_f\, C_{hn}^g + \sigma_f C_{hn}^f\right] \quad (22)$$

The ground and foliage bulk transfer coefficients are formulated by:

$$C_{hn}^{g} = r_{ch}^{-1}\left[\frac{K_v}{ln\left(\frac{Z_a}{Z_o^g}\right)}\right]^2 \tag{23}$$

And

$$C_{hn}^{f} = \left[\frac{K_v}{ln\left(\frac{Z_a - Z_d}{Z_o^f}\right)}\right]^2 \tag{24}$$

where Z_o^g and Z_o^f are the ground and foliage roughness lengths, r_{ch} is turbulent Schmidt number which is constant (0.63), and K_v is the von Karman which is constant (0.4) .

The condition of the atmosphere (Γ_h) is calculated as stable or unstable based on the sign of the bulk Richardson number:

$$R_{ib} = \frac{2gZ_aT_{af} - T_g}{T_{af} + T_gW_{af}^2} \tag{25}$$

The atmospheric stability factor is then determined by Businger and Lumley and Panofsky as [44, 63]:

$$\Gamma_h = \begin{Bmatrix} \frac{1.0}{1.0 - 5.0\, R_{ib}} & for\ R_{ib} > 0 \\ \frac{1.0}{1.0 - 16.0 R_{ib}} & for\ R_{ib} < 0 \end{Bmatrix} \tag{26}$$

Latent heat flux in the soil layer

The water evaporation from the soil surface depends on the difference between the mixing ration of the soil surface and air and the wind velocity within the canopy. The latent heat flux is determined as:

$$L_g = C_{e,g}\, l_g\, \rho_{afg}\, W_{af}\ (q_{af} - q_g) \tag{27}$$

where, $C_{eg}$is the bulk transfer coefficient, l_g is the latent heat for the evaporation at the ground surface temperature, q_{af} is the mixing ratio at the foliage-atmosphere interface, and $q_f$is the mixing ratio at the ground surface, given by:

$$q_g = M_g q_{g,sat} + 1 - M_g q_{af} \tag{28}$$

The bulk transfer coefficient for latent heat exchange is analogous to that for sensible heat exchange and is given by:

$$C_{eg} = \Gamma_e\left[1 - \sigma_f C_{en}^{g} + \sigma_f C_{hn}^{f}\right] \tag{29}$$

where C_{en}^{g} is the near ground bulk transfer coefficient for Latent heat flux and Γ_e is the latent heat "exchange stability correction factor" which is considered to be the same as Γ_h [44].

Appendix B (Benchmarking)

A technical sound room with a total area of 17.2 m^2 and ceiling height 2.2 m in Lisbon (Portugal) which has a Mediterranean climate has been benchmarked. The room was assumed fully adiabatic, except roof. The green roof consists of 0.20 m concrete slab, 0.90 m beam and was covered with 0.10 m drainage layer of gravel and filter layer. It has been modeled in the Google SketchUp and analyzed with building simulation tool, EnergyPlus. In simulation tool (EnergyPlus) several schedules were considered such as occupancy, air conditioning system and green roof irrigation. The schedule for the internal heat gain such as people activity and light intensity were defined for every day from 9:00 a.m. to 20:00 p.m. Also, the air conditioning systems worked with a set point temperature of 19 ˚C in the winter and 24 ˚C in the summer. The irrigation system was for the period from June to September, every Monday, Wednesday and Friday for 30 minutes and the total value of 6 mm/day was adopted. The effect of three variables including soil thickness, plant height and leaf area index (LAI) on the energy performance extensive, semi-intensive and intensive green roofs were evaluated with different thermal insulation thickness [26]. The results of paper and benchmark are shown here.

Table 16. Green roof parameters for different types of roof [26].

Parameters	Type of green roof		
	Extensive	Semi- intensive	Intensive
Plant height	0.05	0.5	1.0
LAI	1	2.5	5
Soil thickness	0.1	0.35	0.7

Table 17. Cooling and heating load variations with thermal insulation thickness for extensive green roof [26].

Thermal insulation thickness (cm)	**Cooling load (kWh/m^2)**			**Heating load (kWh/m^2)**		
	Paper	Benchmark	Error (%)	Paper	Benchmark	Error (%)
0	55.20	53.11	3.78 %	17.50	18.66	6.62 %
2	42.90	41.08	4.24 %	8.70	9.14	5.05%
4	34.70	32.11	7.46 %	5.60	6.11	9.11 %
8	27.30	25.04	8.28 %	3.10	3.32	7.09 %

Table 18. Cooling and heating load variations with thermal insulation thickness for semi-intensive green roof [26].

Thermal insulation thickness (cm)	**Cooling load (kWh/m^2)**			**Heating load (kWh/m^2)**		
	Paper	Benchmark	Error (%)	Paper	Benchmark	Error (%)
0	19.70	18.76	4.77 %	19.40	20.82	7.31%
2	17.70	16.65	5.93 %	11.90	12.94	8.74 %
4	16.20	15.10	6.79 %	8.40	10.33	22.97 %
8	15.40	13.96	9.35 %	4.80	6.10	27.08 %

Table 19. Cooling and heating load variations with thermal insulation thickness for intensive green roof [26].

Thermal insulation thickness (cm)	**Cooling load (kWh/m^2)**			**Heating load (kWh/m^2)**		
	Paper	Benchmark	Error (%)	Paper	Benchmark	Error (%)
0	9.40	8.44	10.21 %	17.30	18.73	8.26 %
2	10.00	9.23	7.72 %	11.60	12.43	7.15 %
4	10.50	10.04	4.38 %	8.50	9.12	7.29 %
8	11.10	10.84	2.34 %	5.20	5.63	8.27 %

Appendix C (Meteorological Parameters)

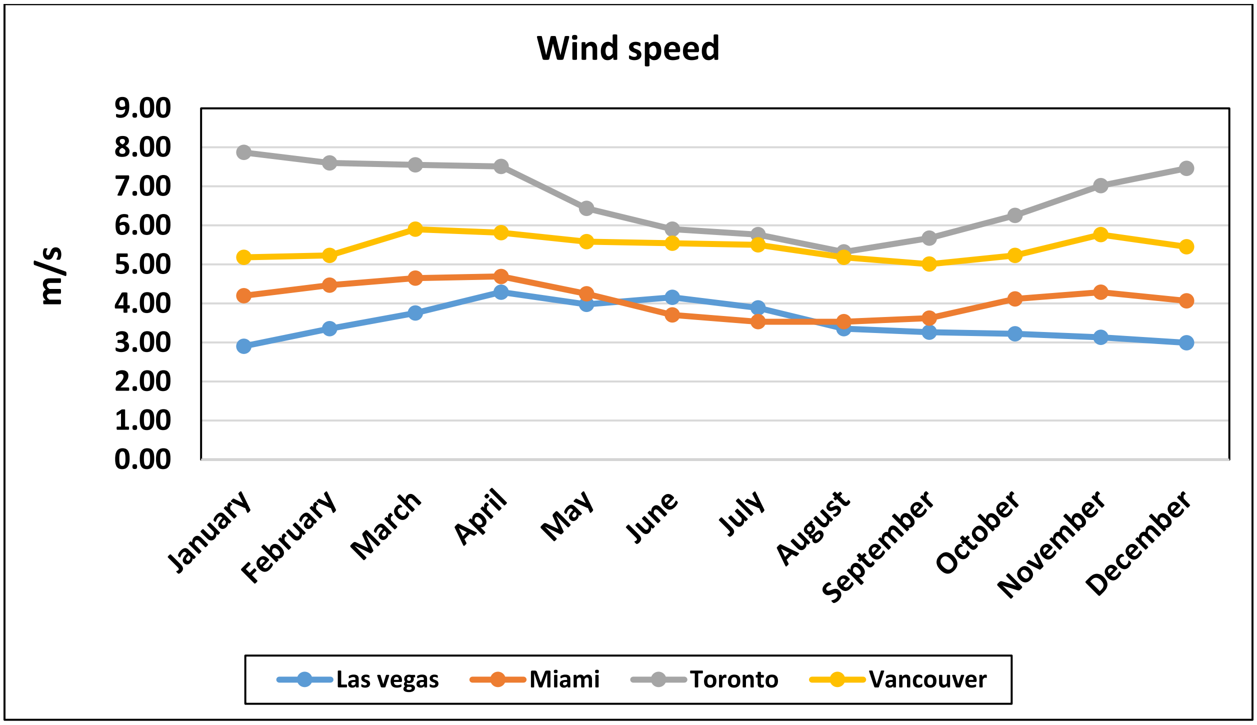

Figure 26. Monthly variations of wind velocity for all four selected cities

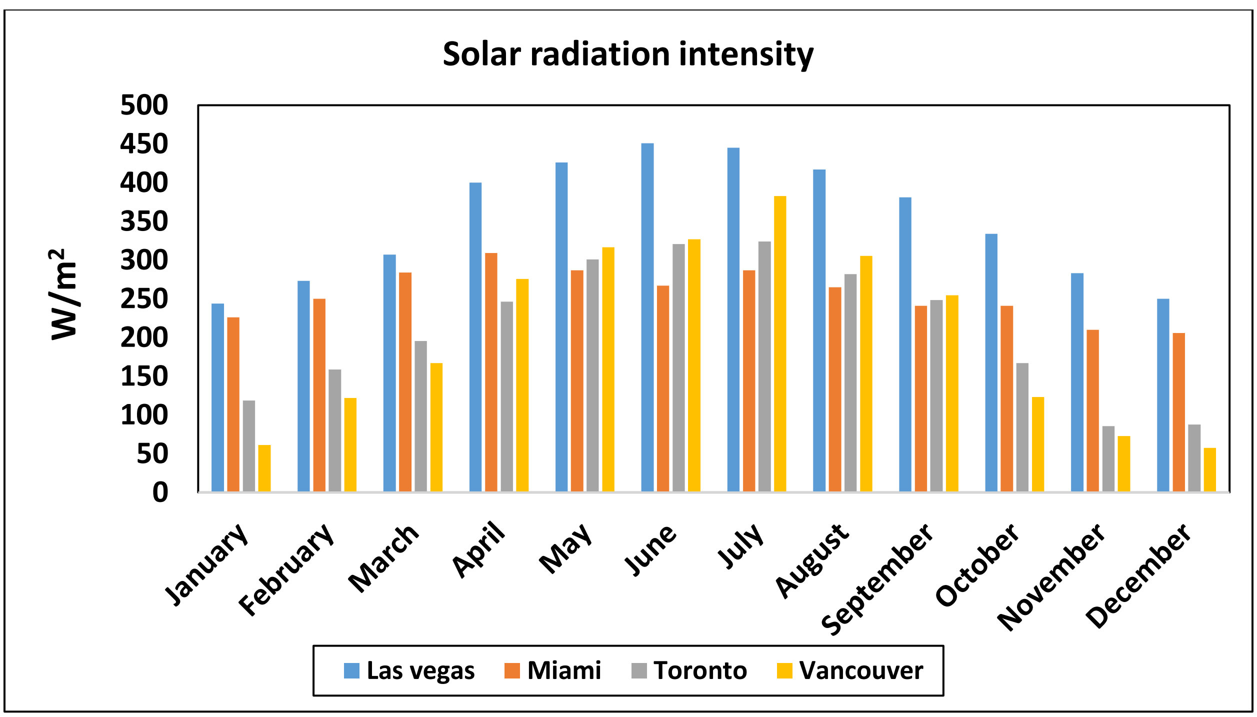

Figure 27. Monthly variations of solar radiation intensity for all four selected cities.

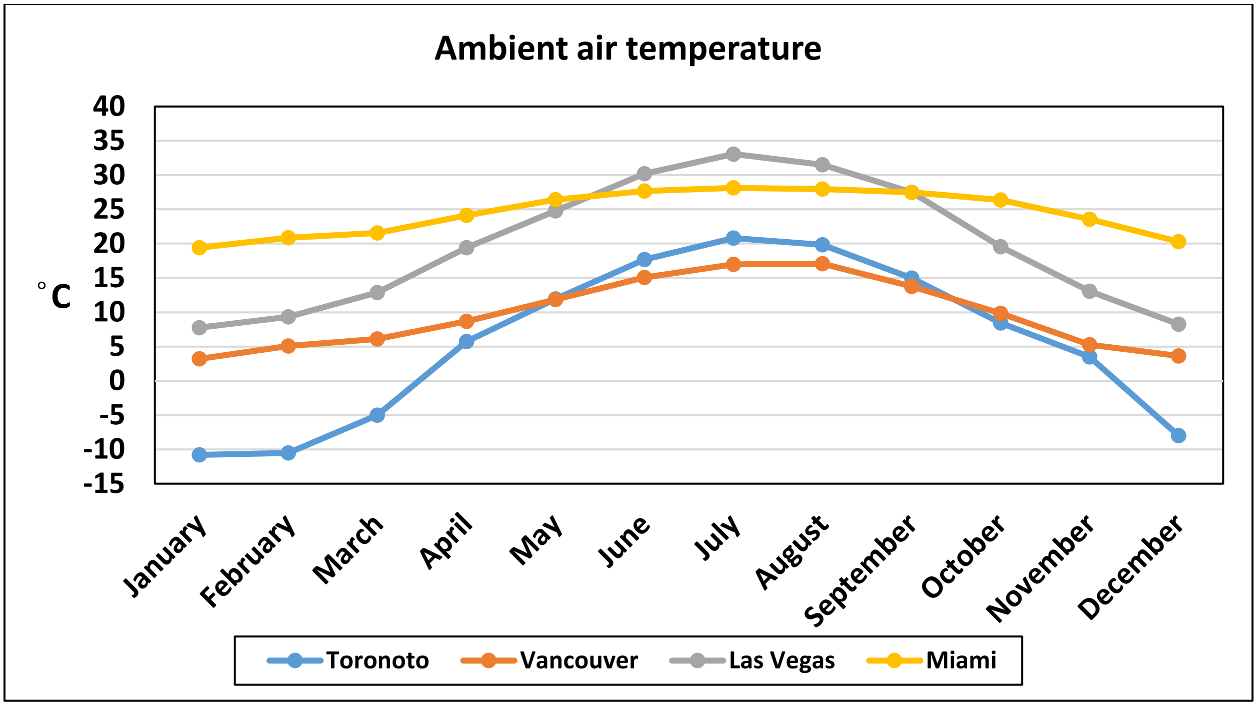

Figure 28. Monthly variations of air temperature for all four selected cities.

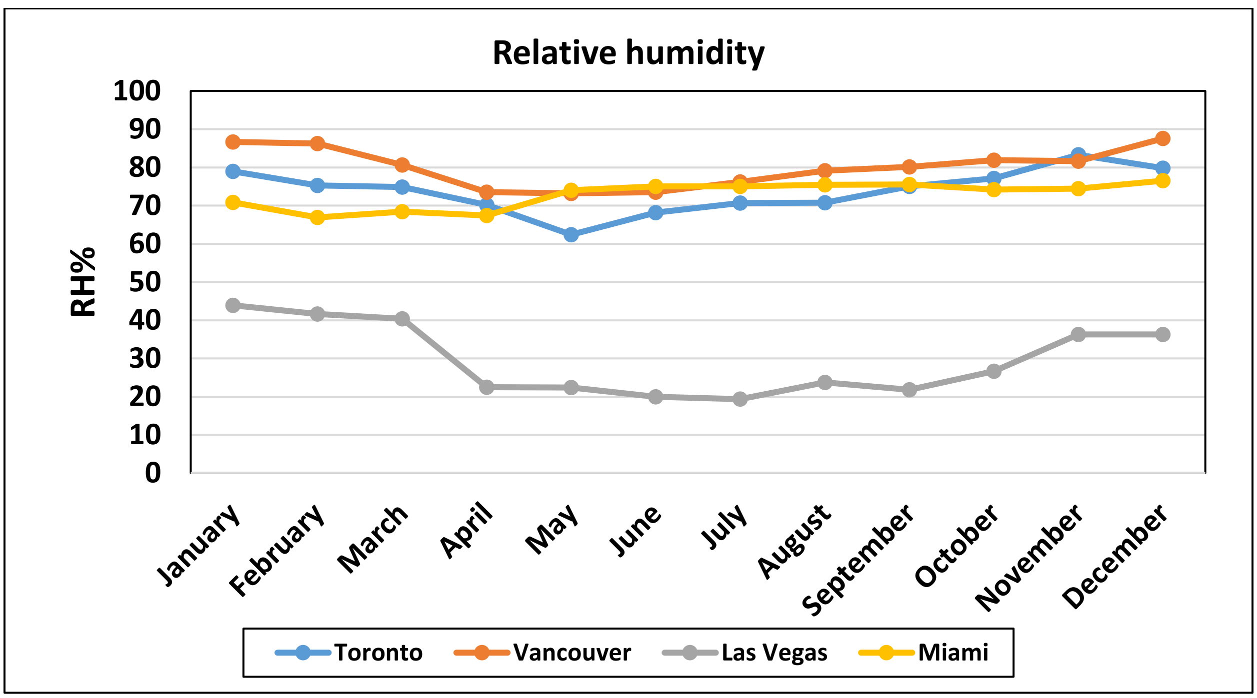

Figure 29. Monthly variations of relative humidity for all four selected cities.

Appendix D (Soil temperature vs. LAI)

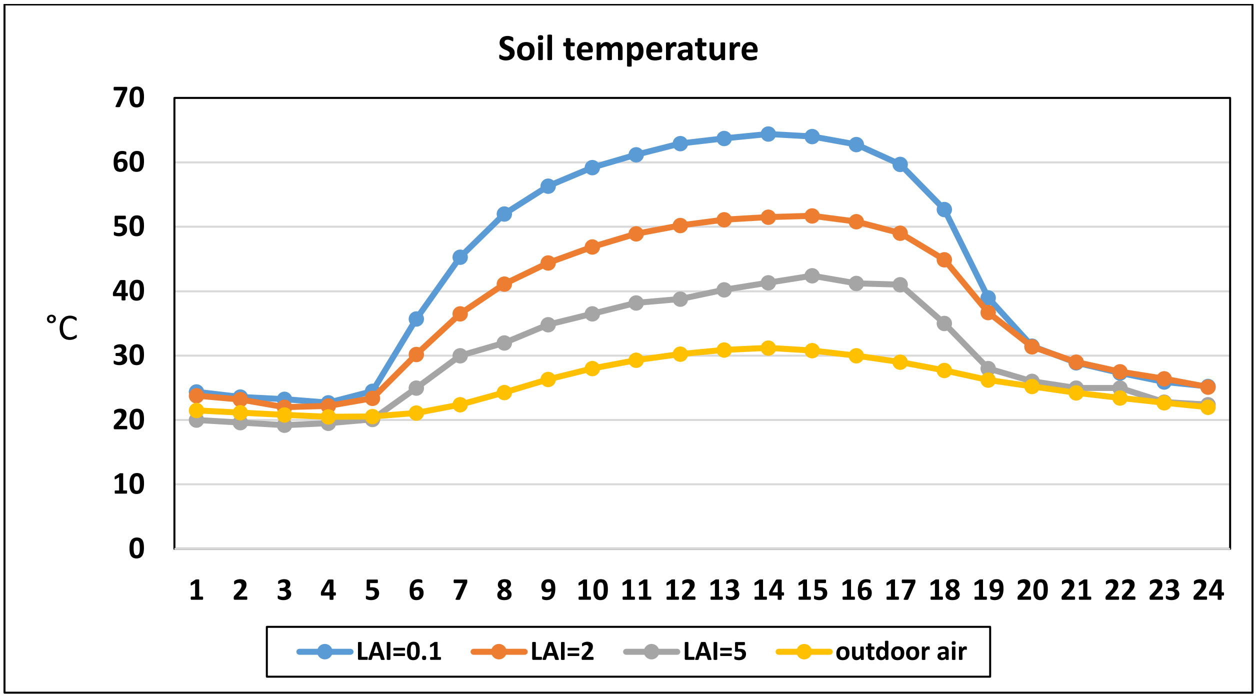

Figure 30.Variations of soil surface temperature with ambient air for a typical day in Summer in Toronto.

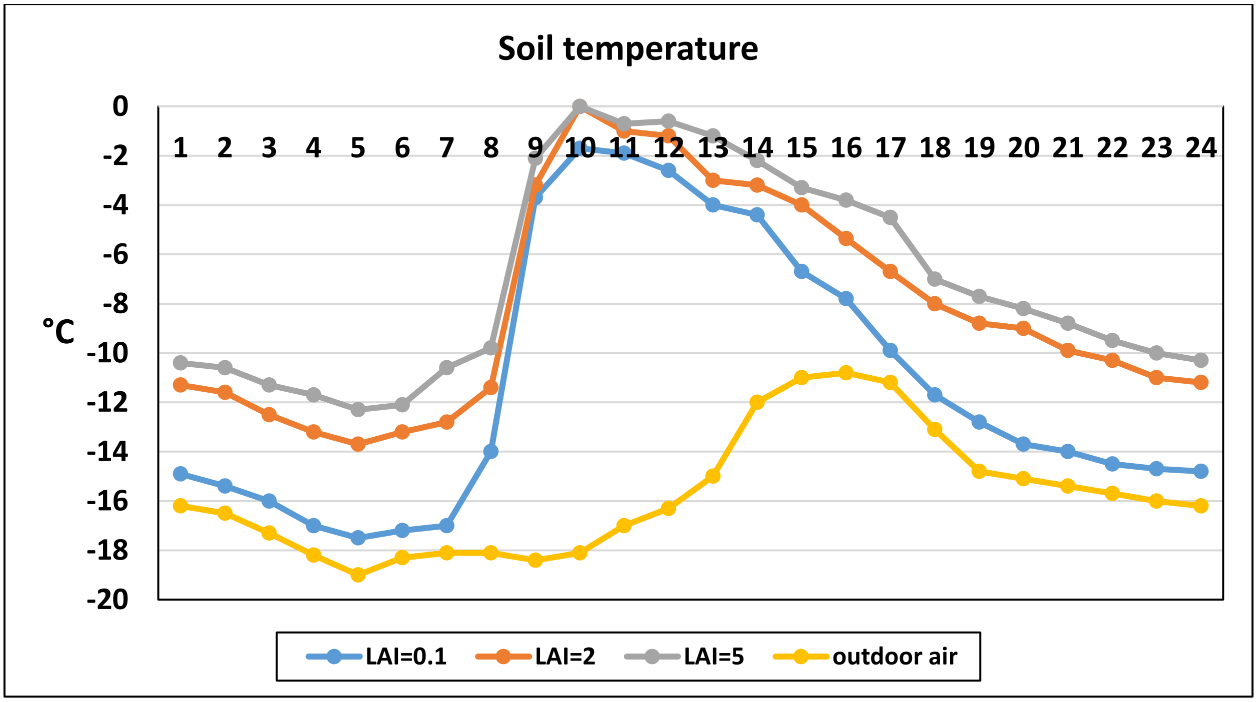

Figure 31. Variations of soil surface temperature with ambient air for a typical day in winter in Toronto.

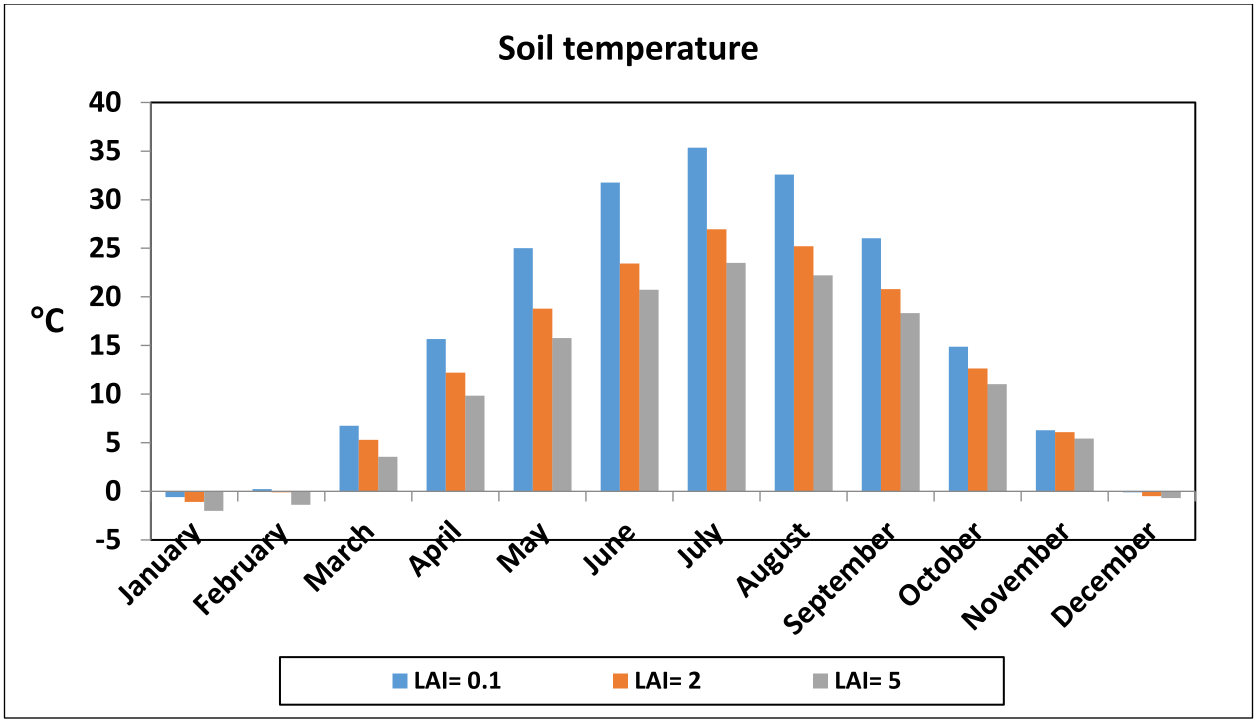

Figure 32. Monthly variation of soil temperature with leaf area index (LAI) in Toronto.

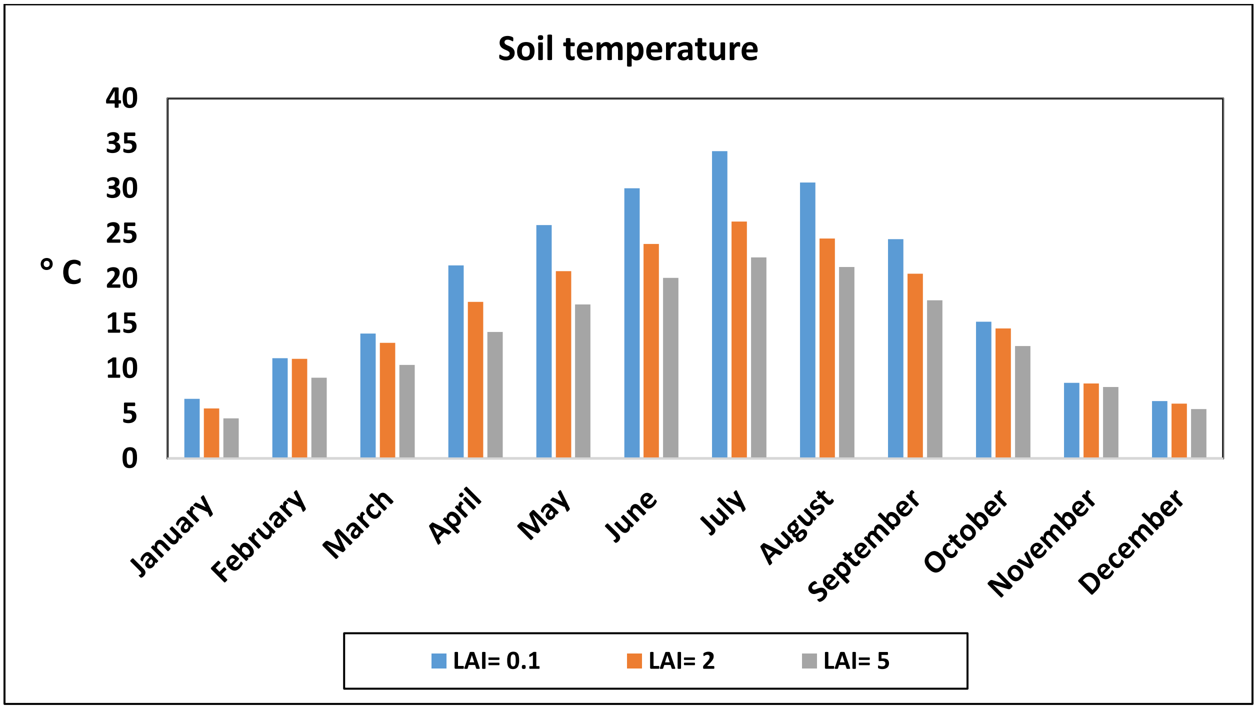

Figure 33. Monthly variation of soil temperature with leaf area index (LAI) in Vancouver.

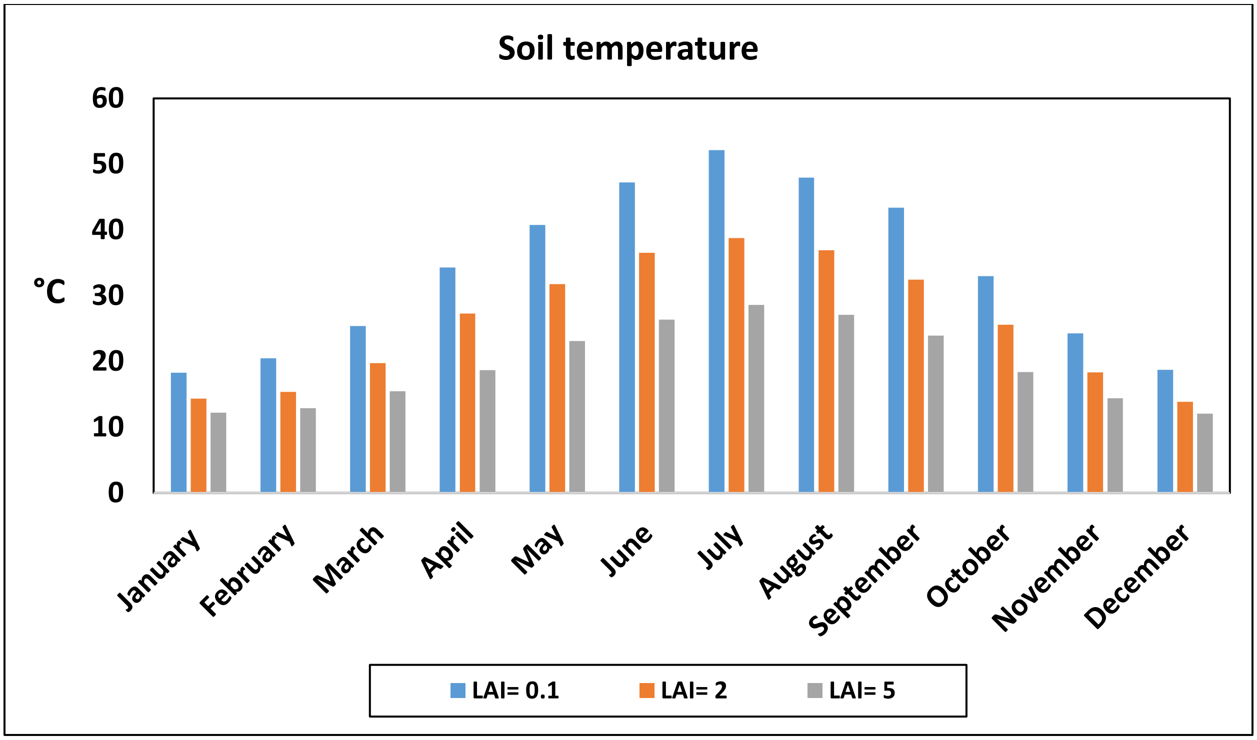

Figure 34. Monthly variation of soil temperature with leaf area index (LAI) in Las Vegas.

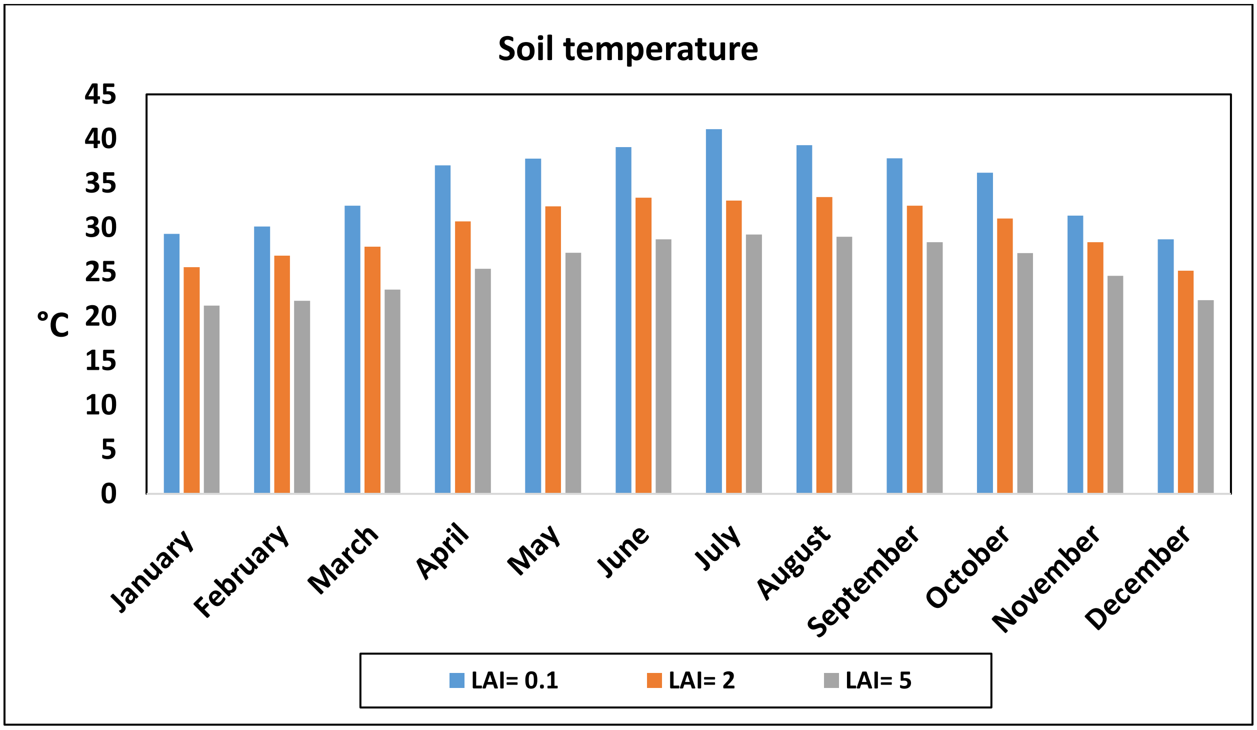

Figure 35. Monthly variation of soil temperature with leaf area index (LAI) in Miami.

Appendix E (Latent heat flux vs. LAI)

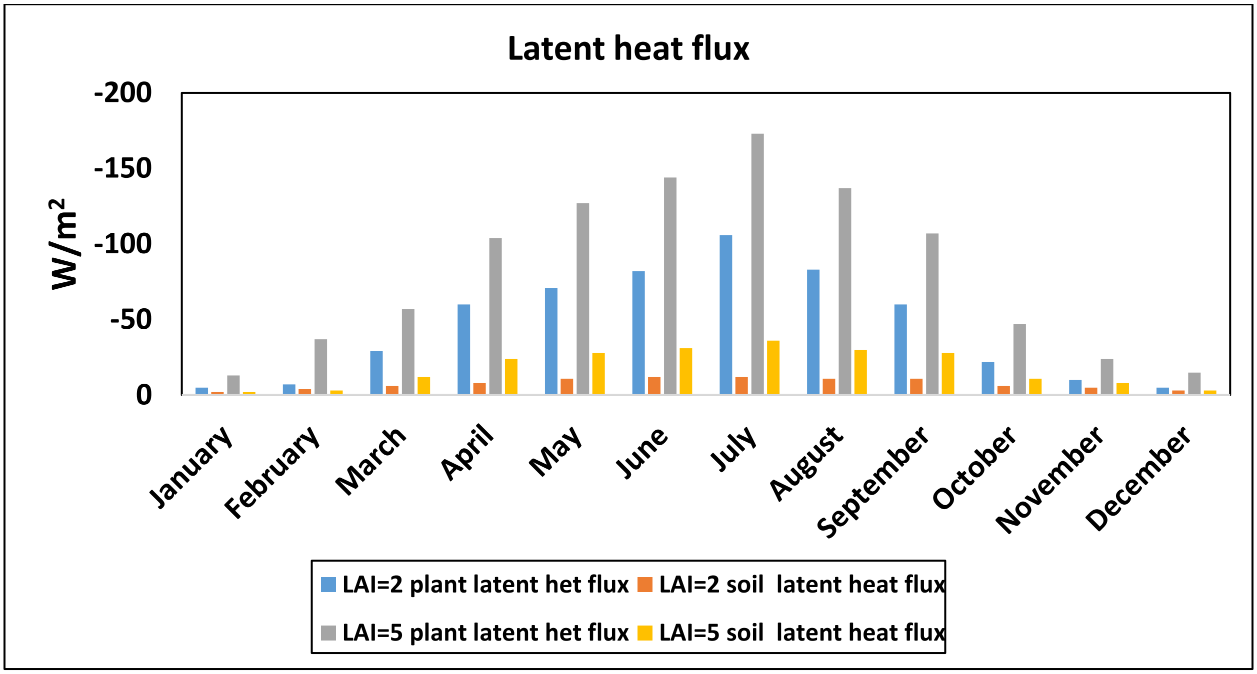

Figure 36. Monthly variations of soil and plant latent heat flux with leaf area index (LAI) in Vancouver.

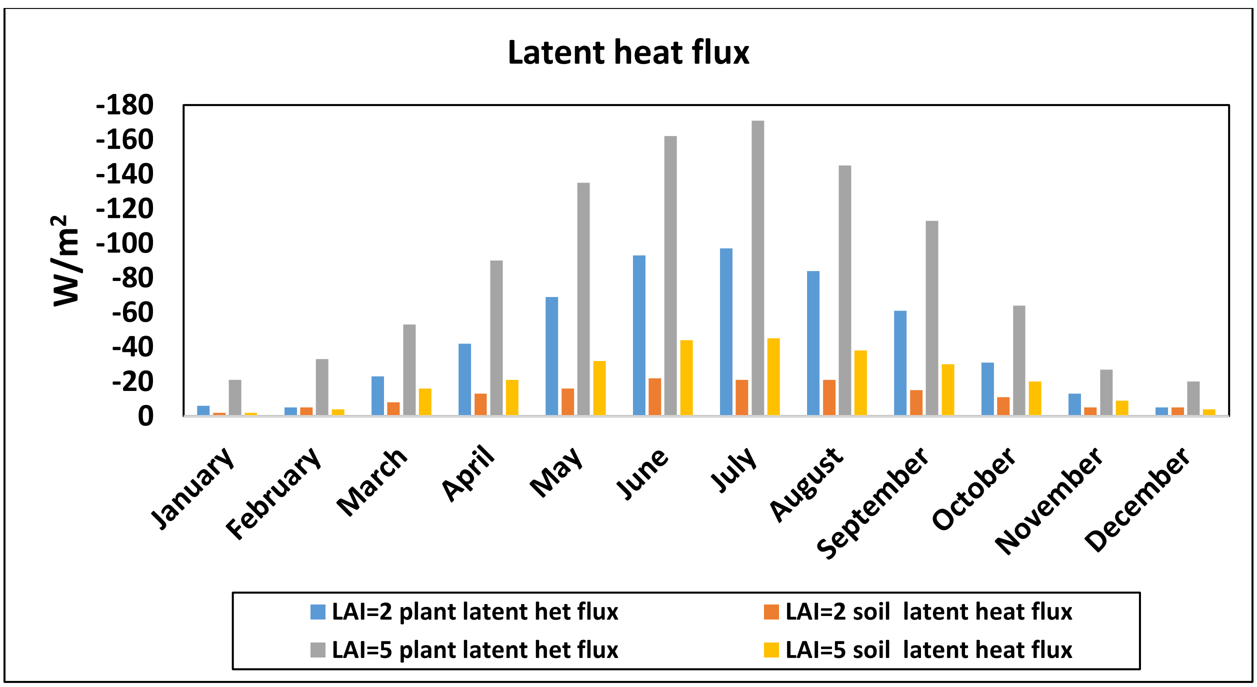

Figure 37. Monthly variations of soil and plant latent heat flux with leaf area index (LAI) in Toronto.

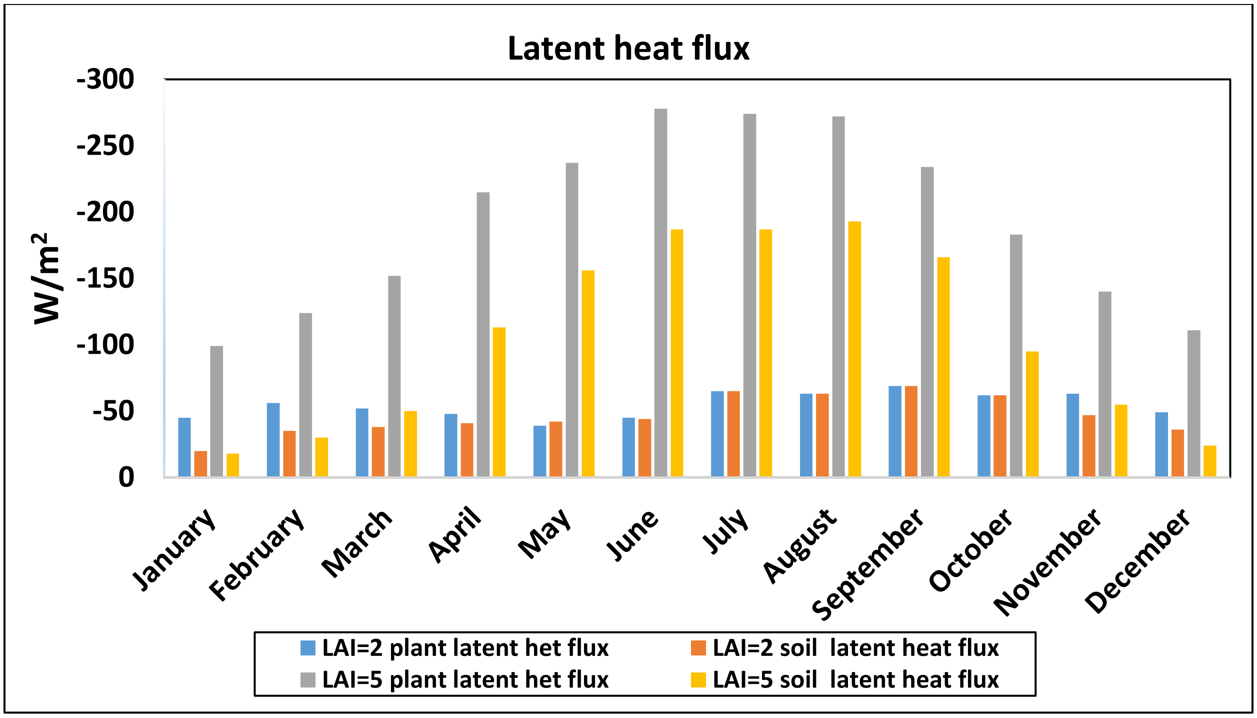

Figure 38. Monthly variations of soil and plant latent heat flux with leaf area index (LAI) in Las Vegas.

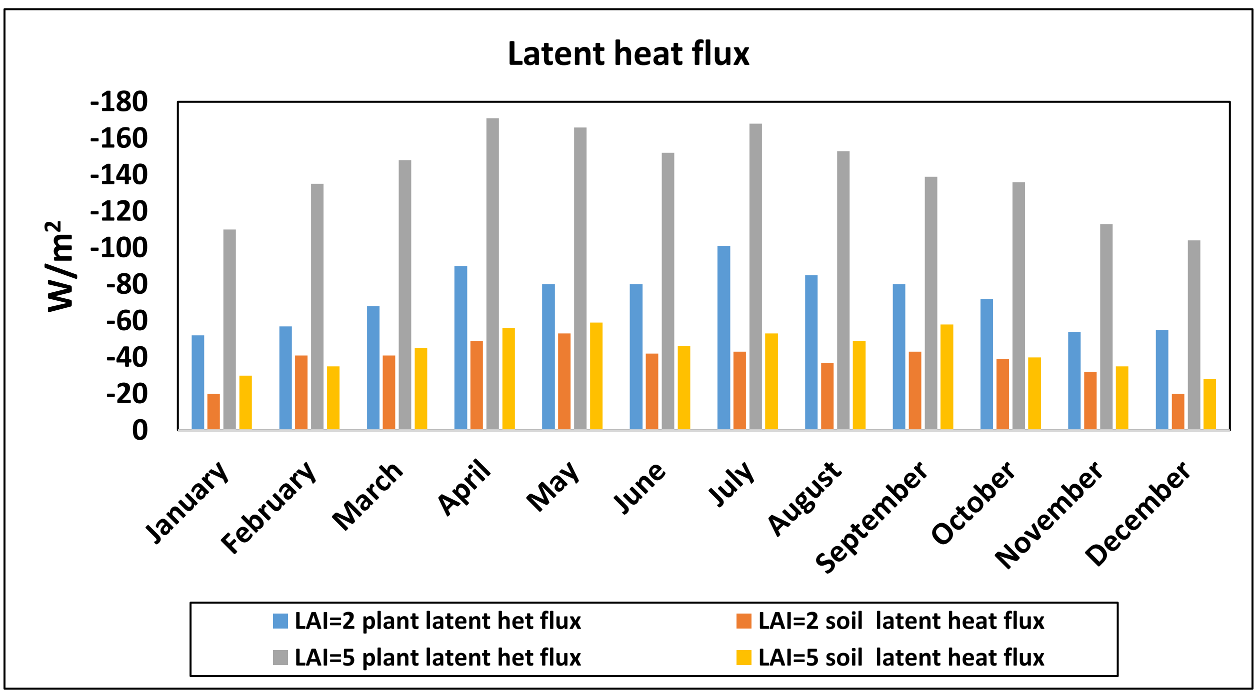

Figure 39. Monthly variations of soil and plant latent heat flux with leaf area index (LAI) in Miami.

Appendix F (Soil sensible heat flux vs. LAI)

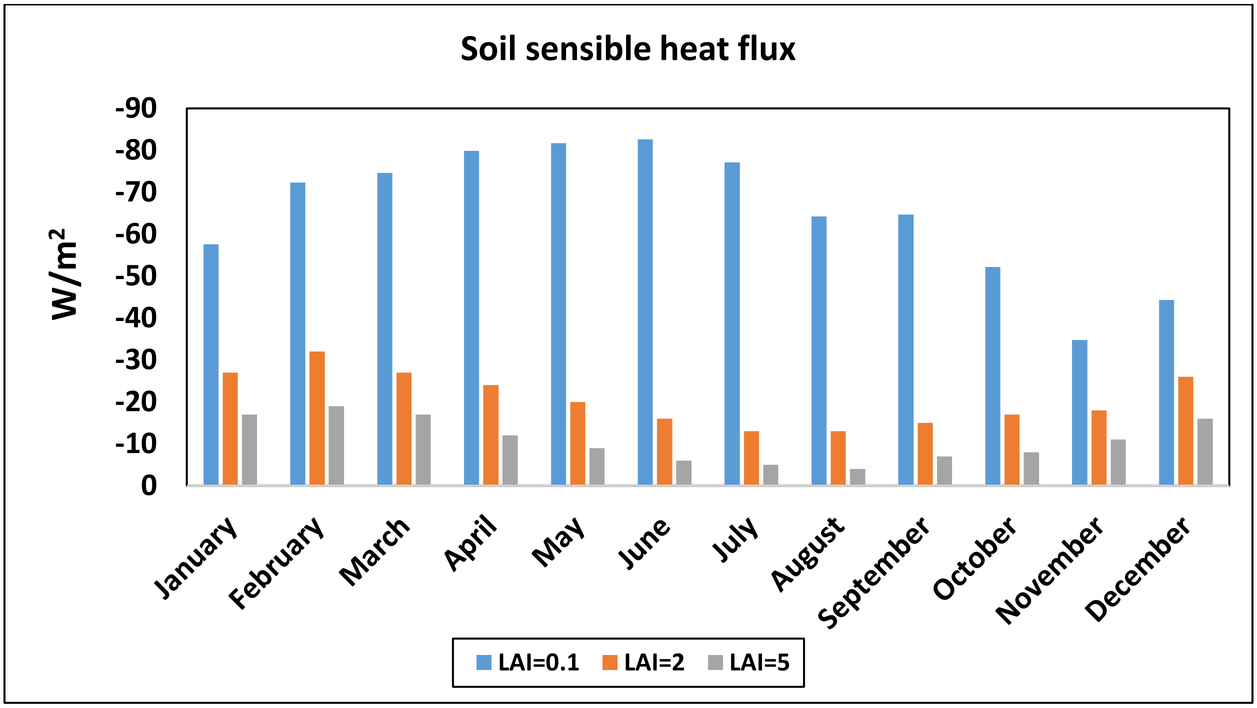

Figure 40.Monthly variations of soil sensible heat flux with leaf area index (LAI) in Toronto.

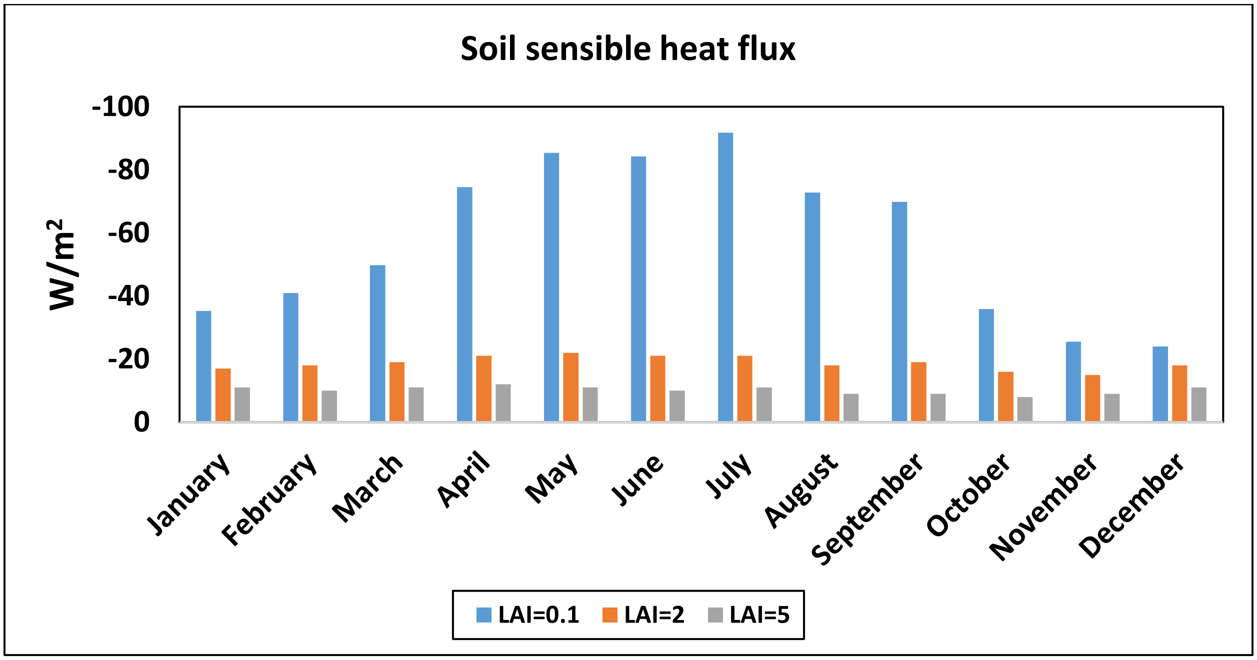

Figure 41. Monthly variations of soil sensible heat flux with leaf area index (LAI) in Vancouver.

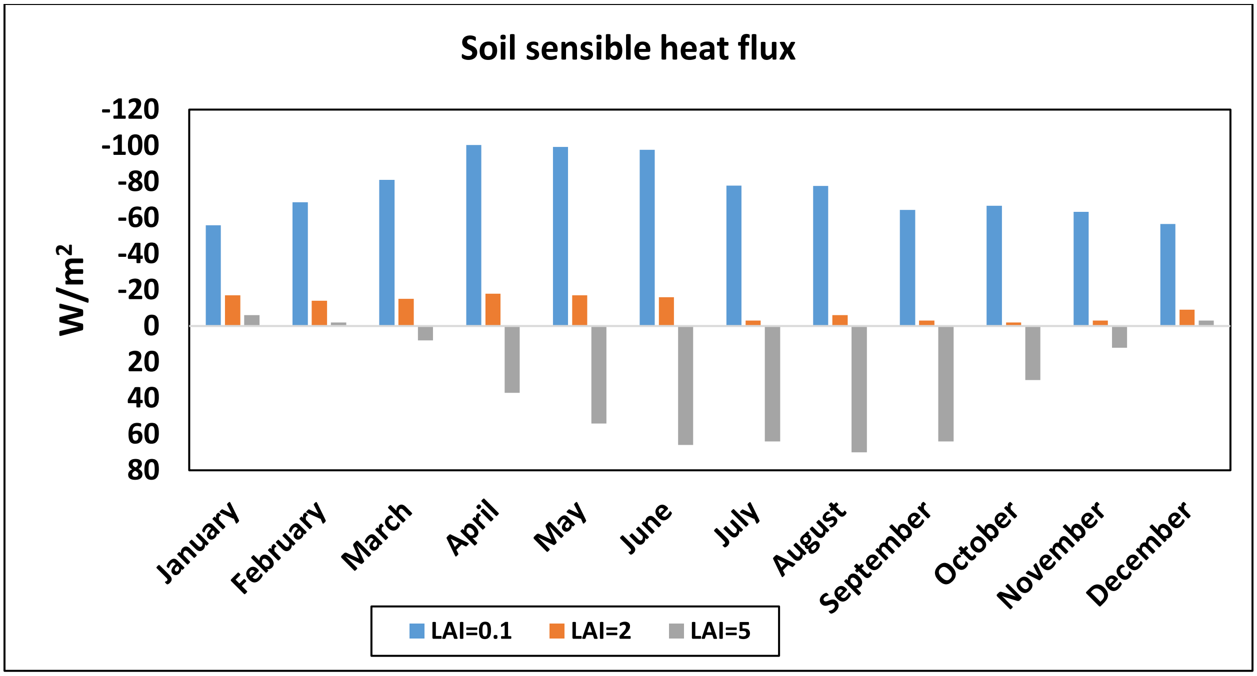

Figure 42. Monthly variations of soil sensible heat flux with leaf area index (LAI) in Las Vegas.

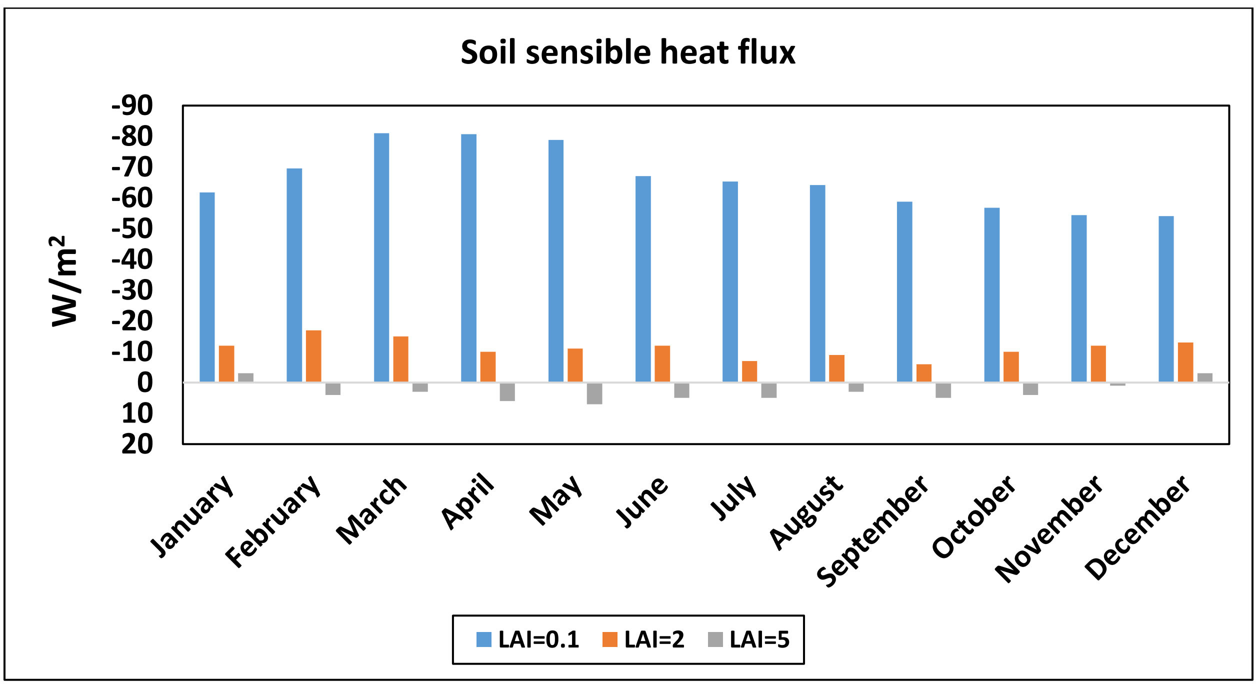

Figure 43. Monthly variations of soil sensible heat flux with leaf area index (LAI) in Miami.

Appendix G (Hourly depth of evapotranspiration)

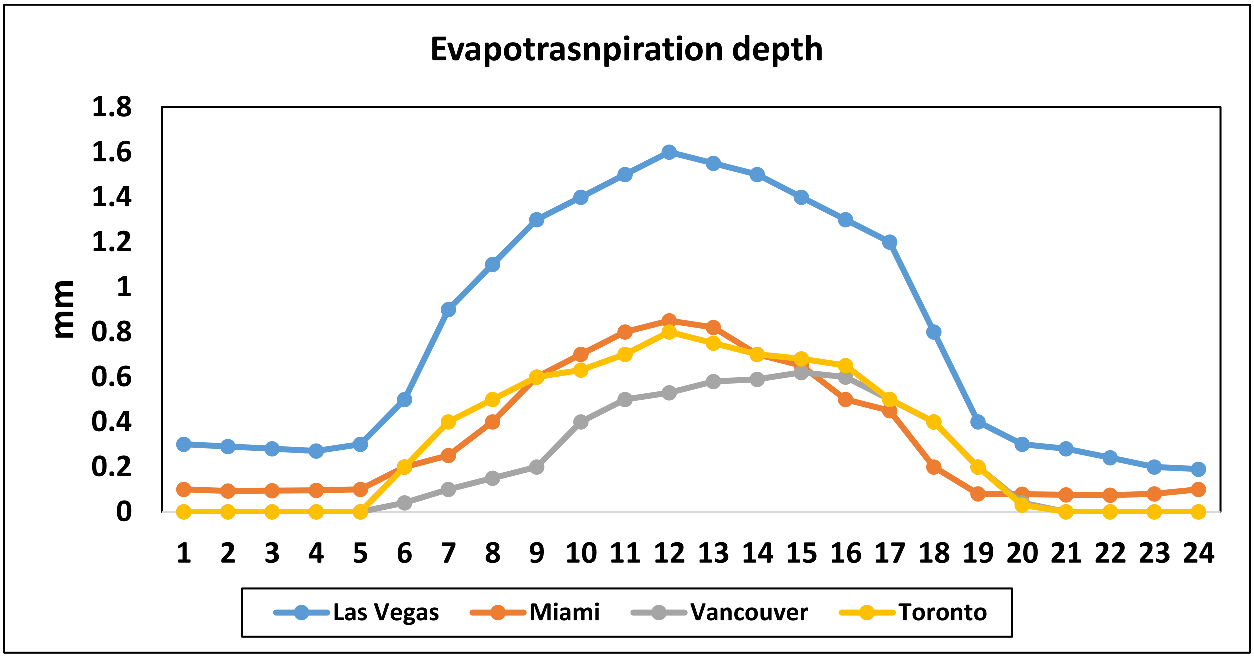

Figure 44. Hourly variation of evapotranspiration depth for a typical sunny day in summer for all selected cities.

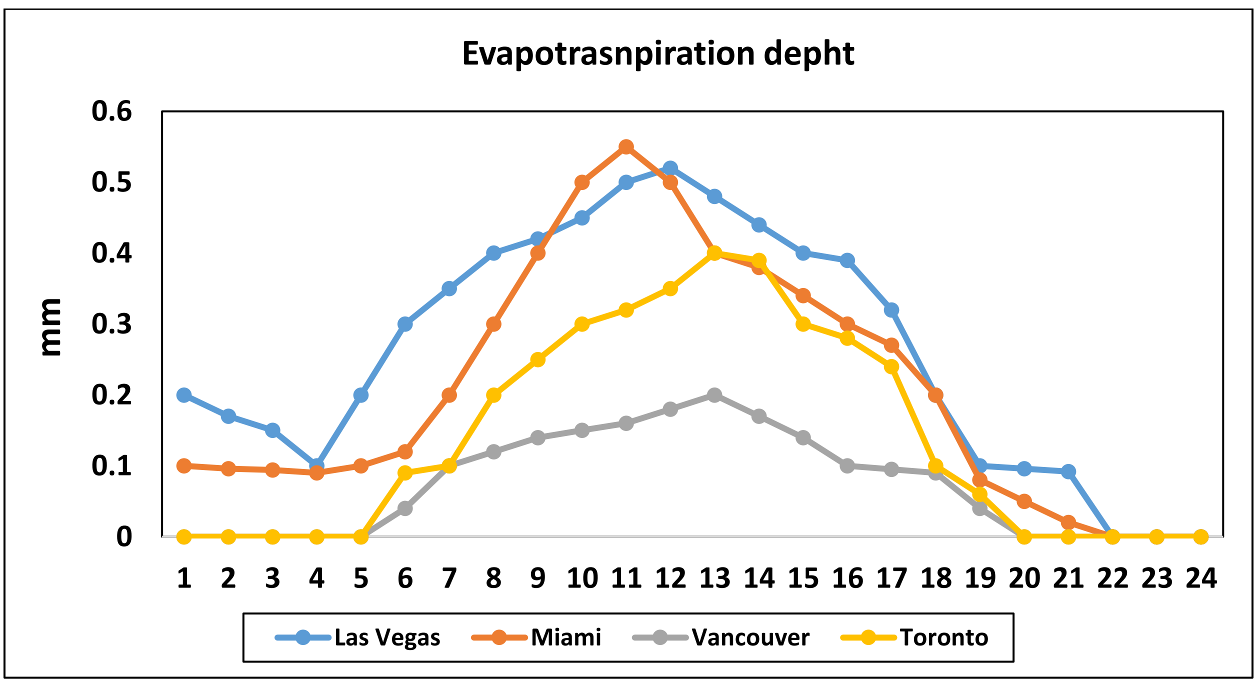

Figure 45. Hourly variation of evapotranspiration depth for a typical cloudy day in summer for all selected cities.

Appendix H (Latent heat flux vs. Plant albedo)

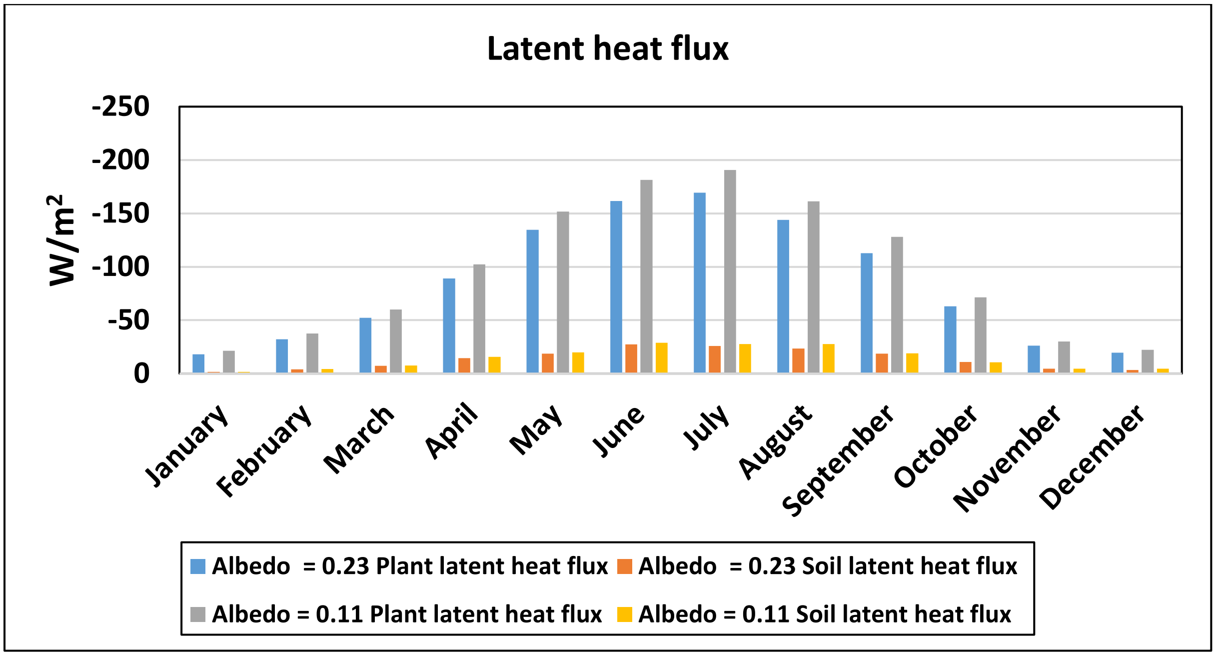

Figure 46. Monthly variations of latent heat flux of soil and plant with plant albedo in Toronto.

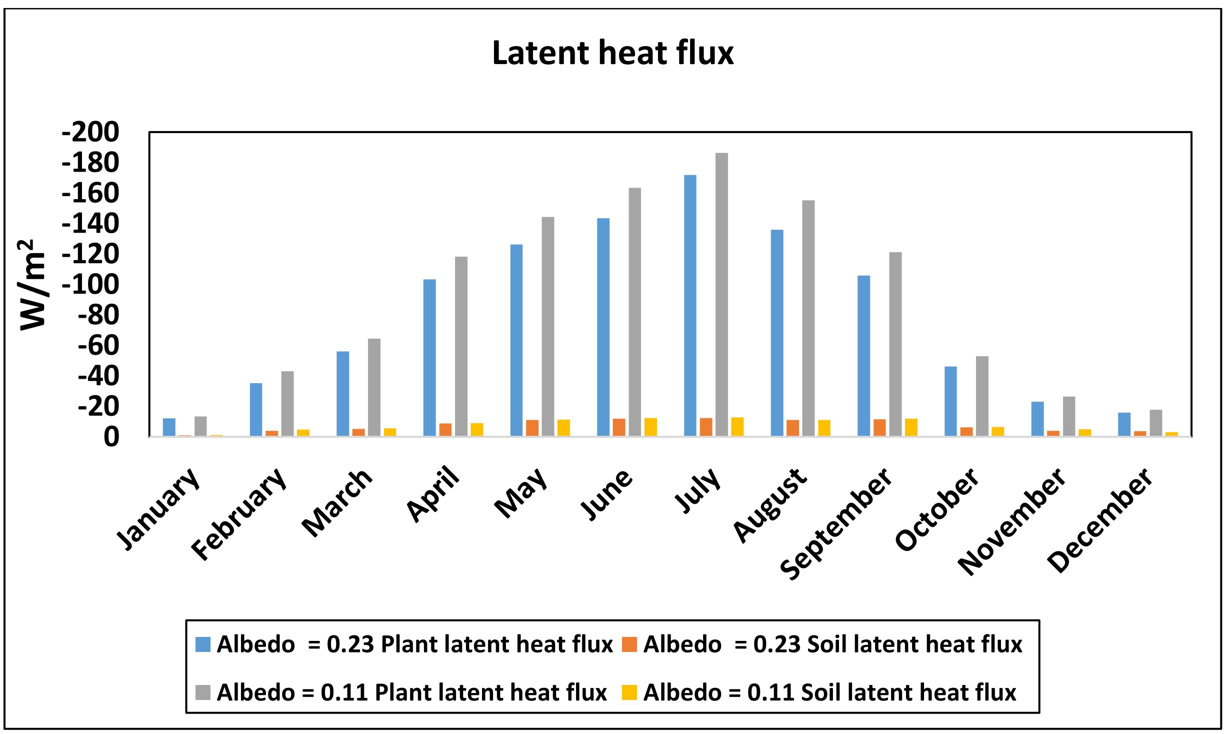

Figure 47. Monthly variations of latent heat flux of soil and plant with plant albedo in Vancouver.

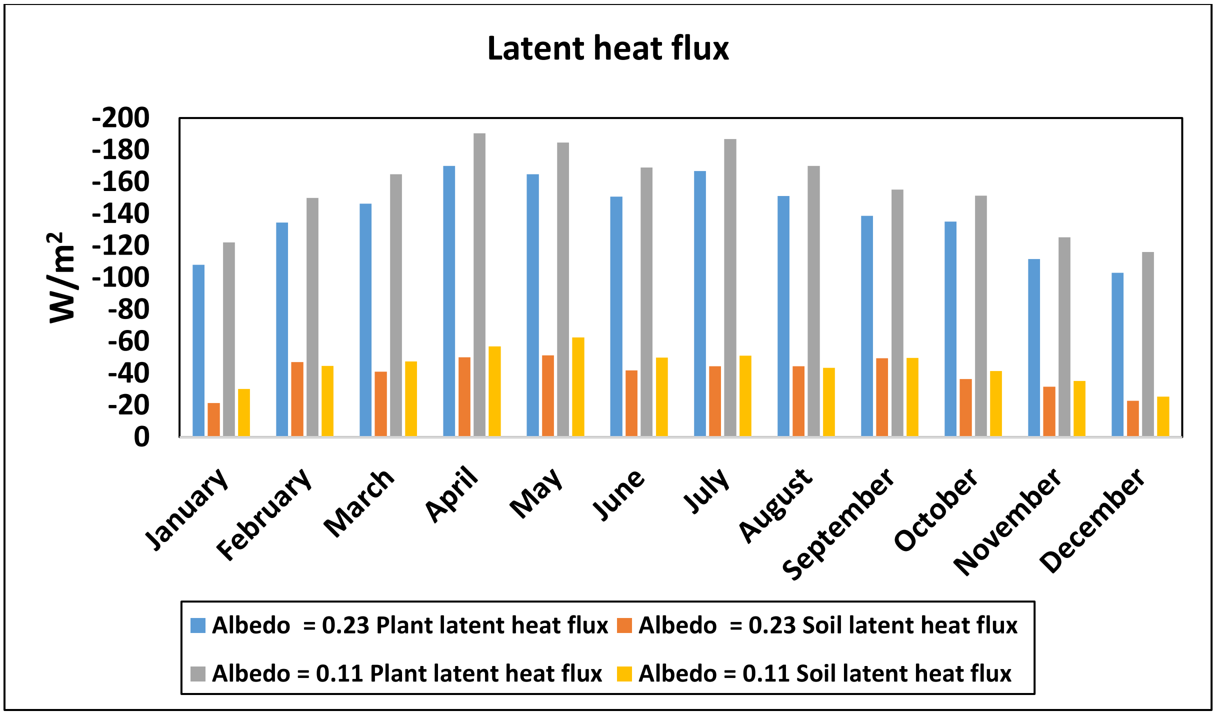

Figure 48. Monthly variations of latent heat flux of soil and plant with plant albedo in Las Vegas.

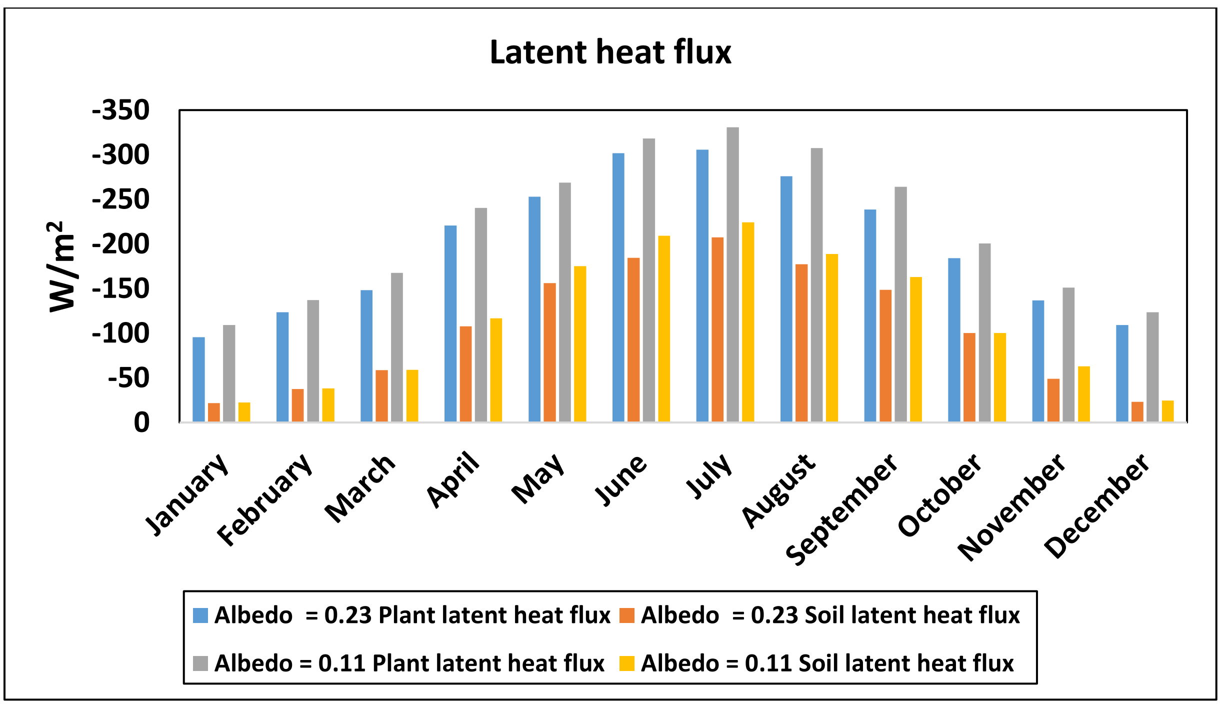

Figure 49. Monthly variations of latent heat flux of soil and plant with plant albedo in Miami.

Appendix I (Foliage temperature vs. Plant albedo)

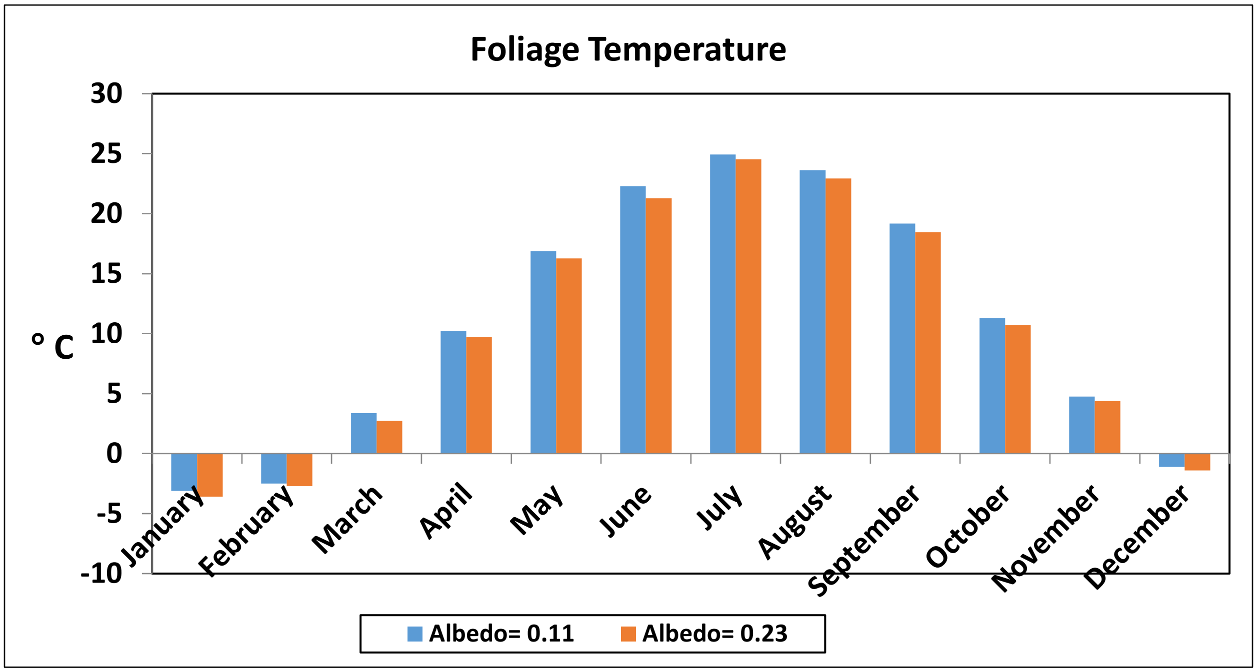

Figure 50. Monthly variations of foliage temperature with plant albedo in Toronto.

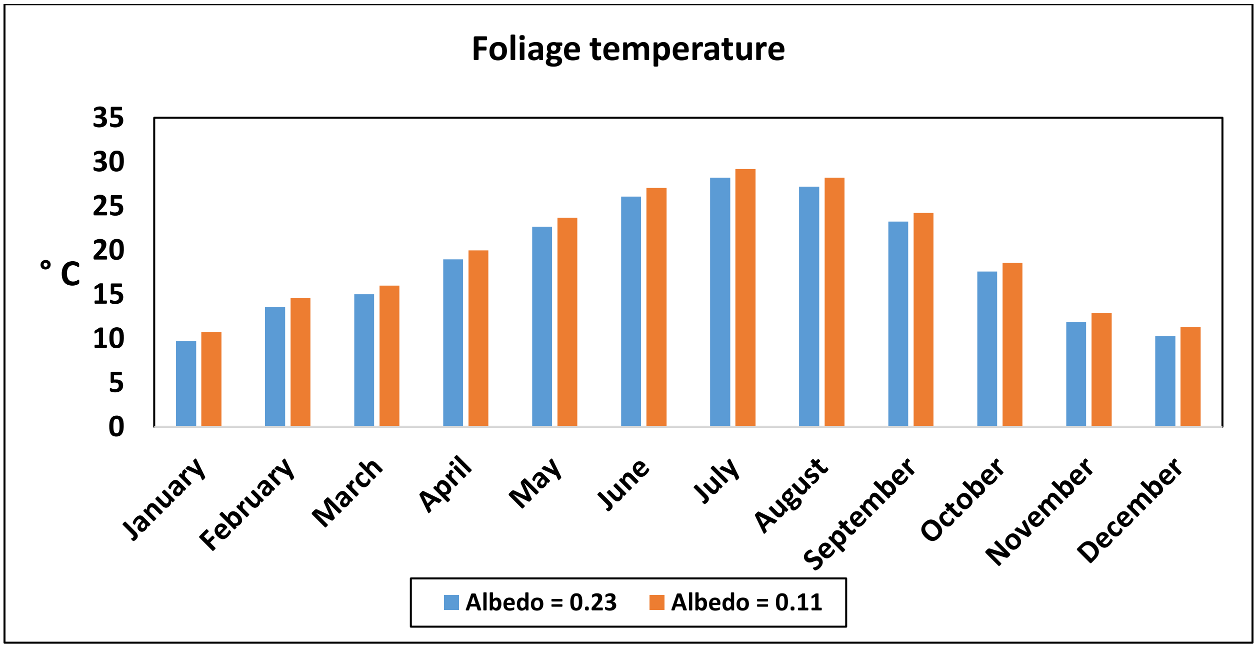

Figure 51. Monthly variations of foliage temperature with plant albedo in Las Vegas.

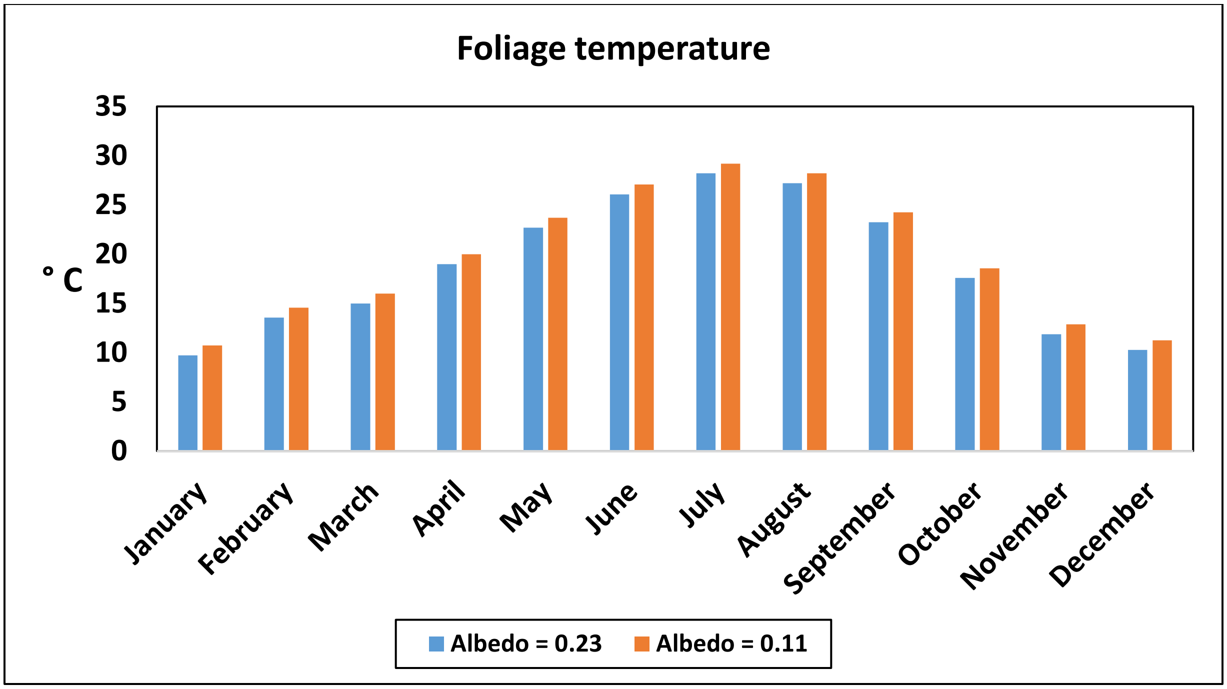

Figure 52. Monthly variations of foliage temperature with plant albedo in Miami.

Appendix J (Foliage temperature vs. LAI)

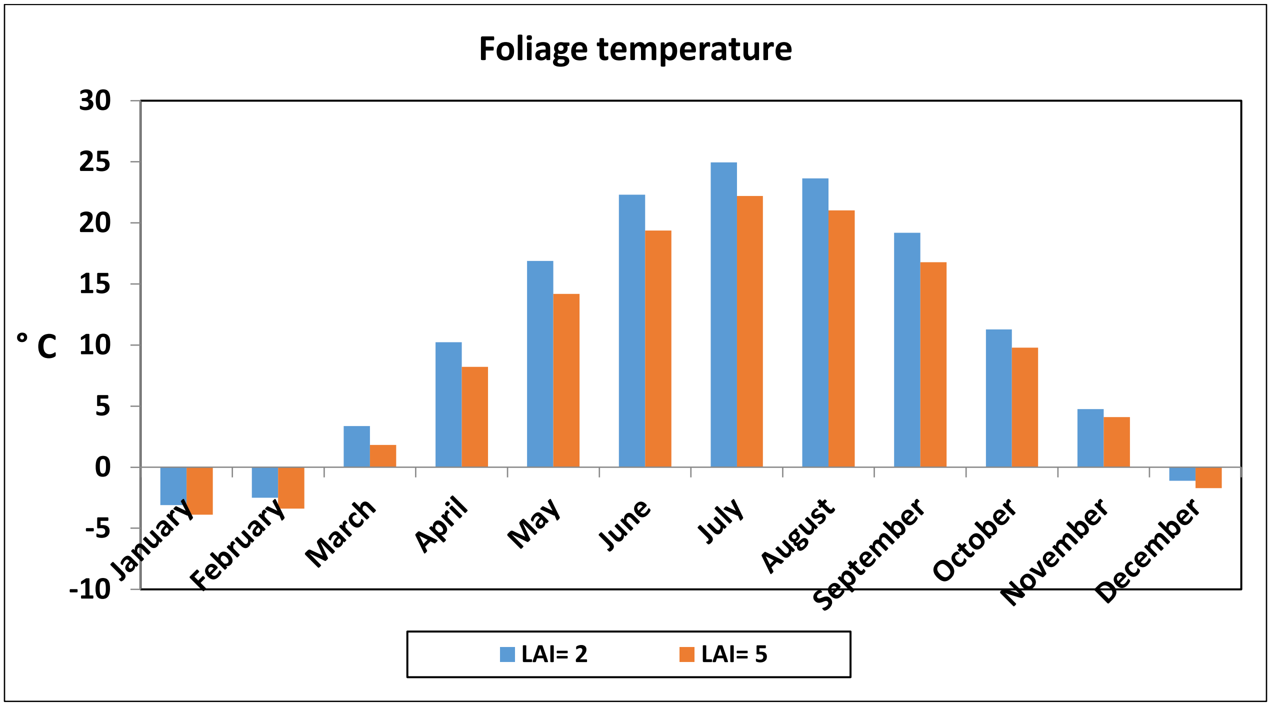

Figure 53. Monthly variations of foliage temperature with leaf area index (LAI) in Toronto.

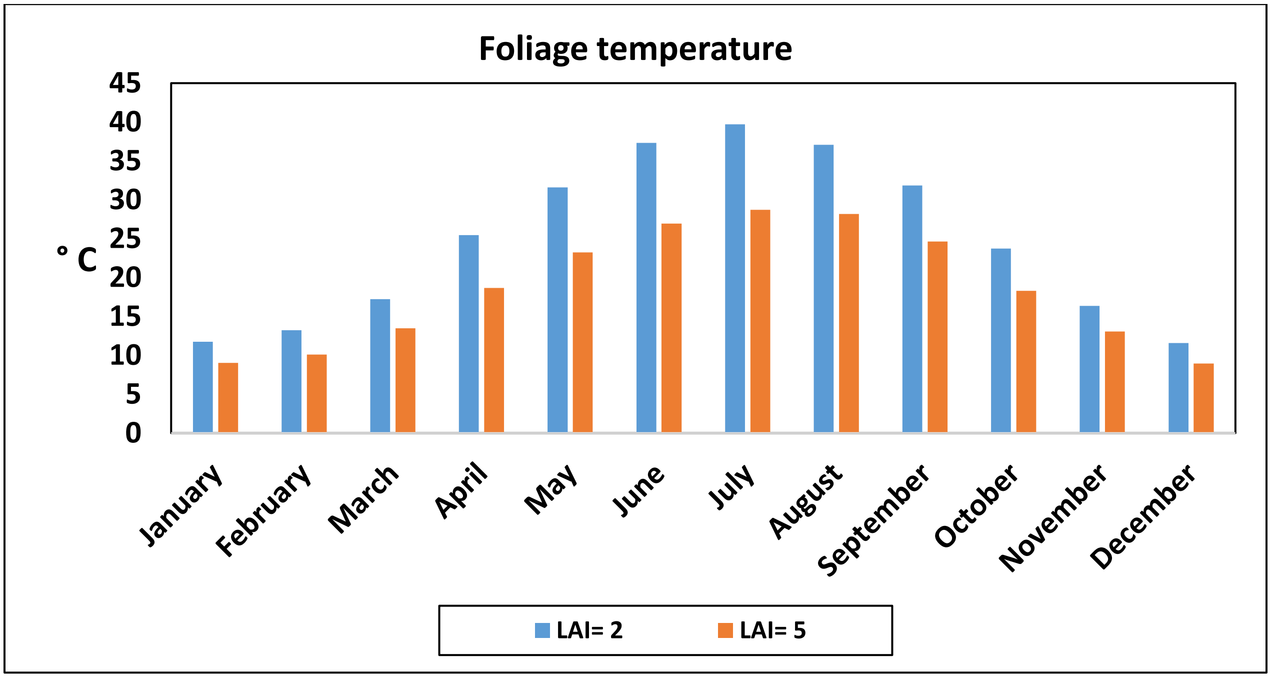

Figure 54. Monthly variations of foliage temperature with leaf area index (LAI) in Las Vegas.

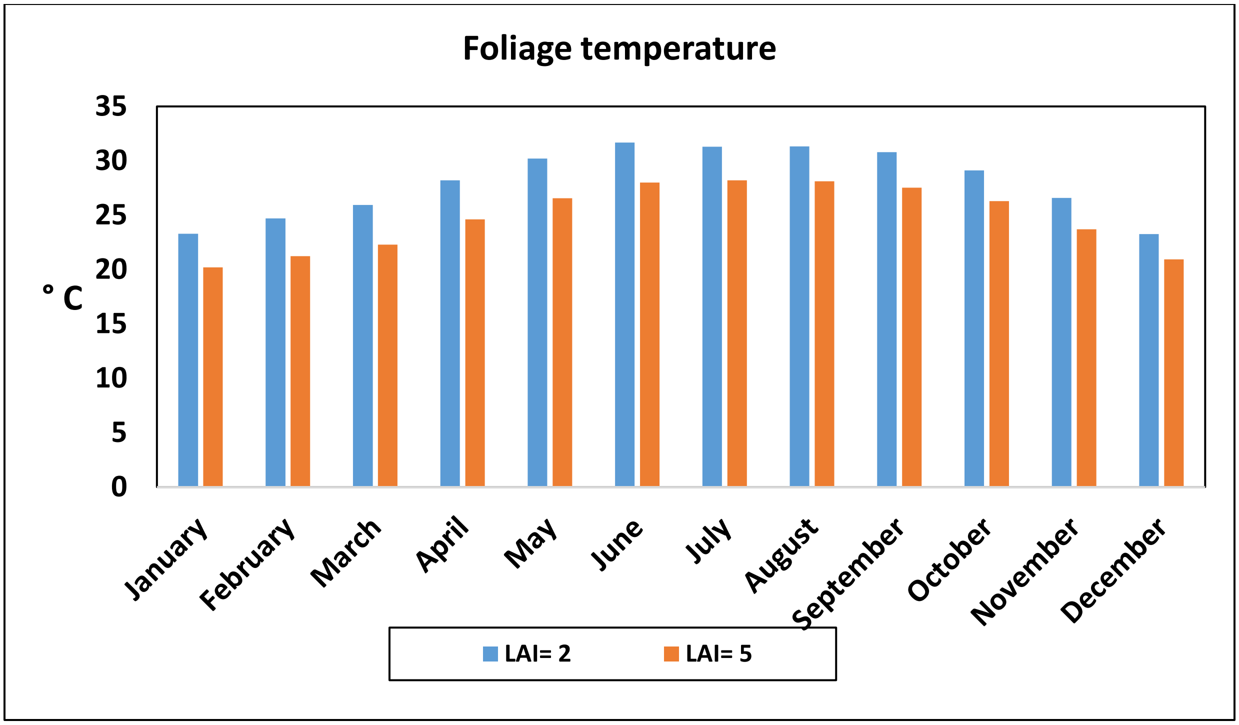

Figure 55. Monthly variations of foliage temperature with leaf area index (LAI) in Miami.

Appendix K (Latent heat flux vs. Plant height)

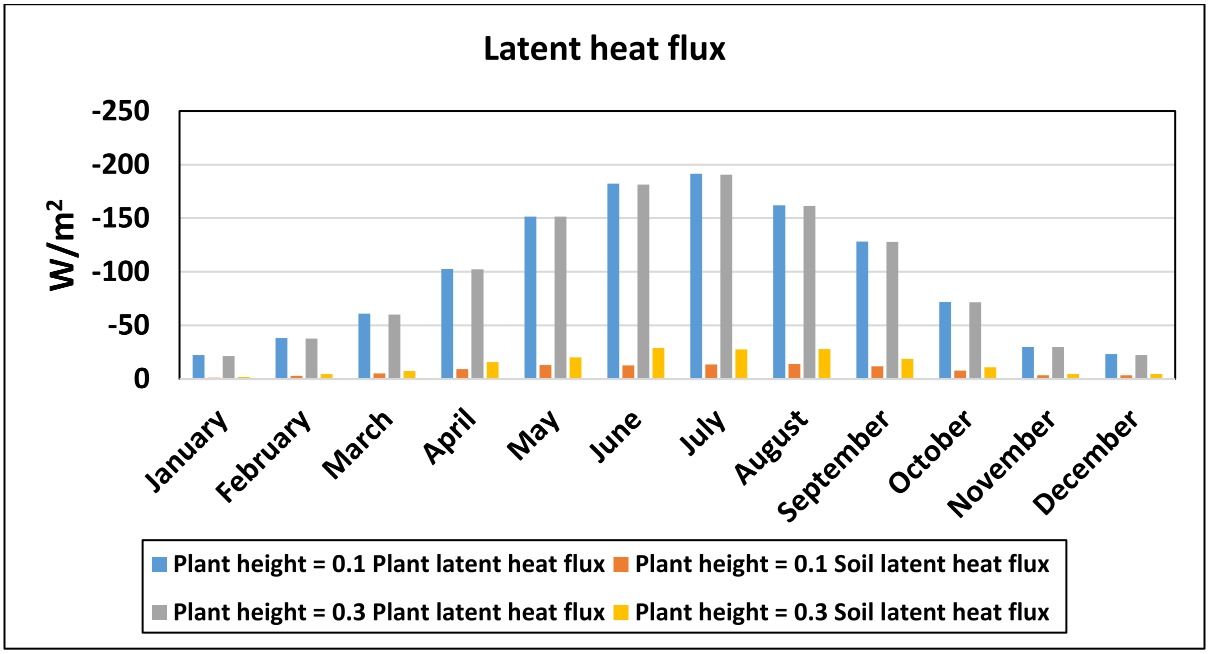

Figure 56. Monthly variations of latent heat flux of soil and plant with plan height in Toronto.

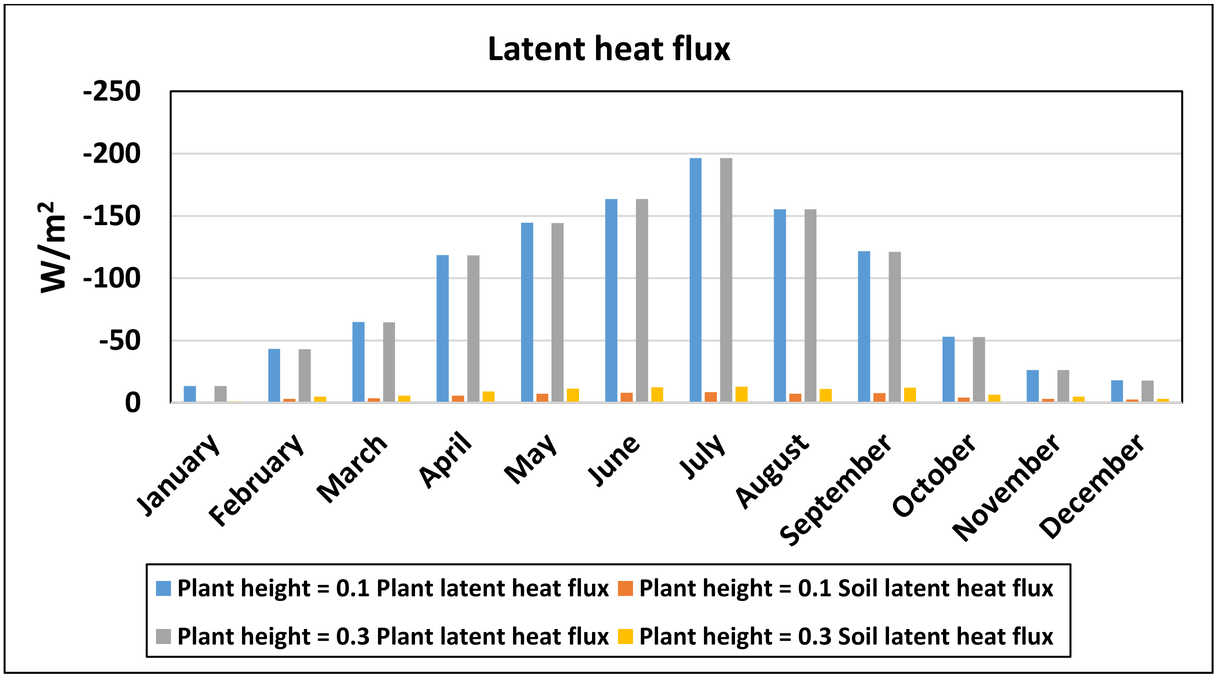

Figure 57. Monthly variations of latent heat flux of soil and plant with plan height in Vancouver.

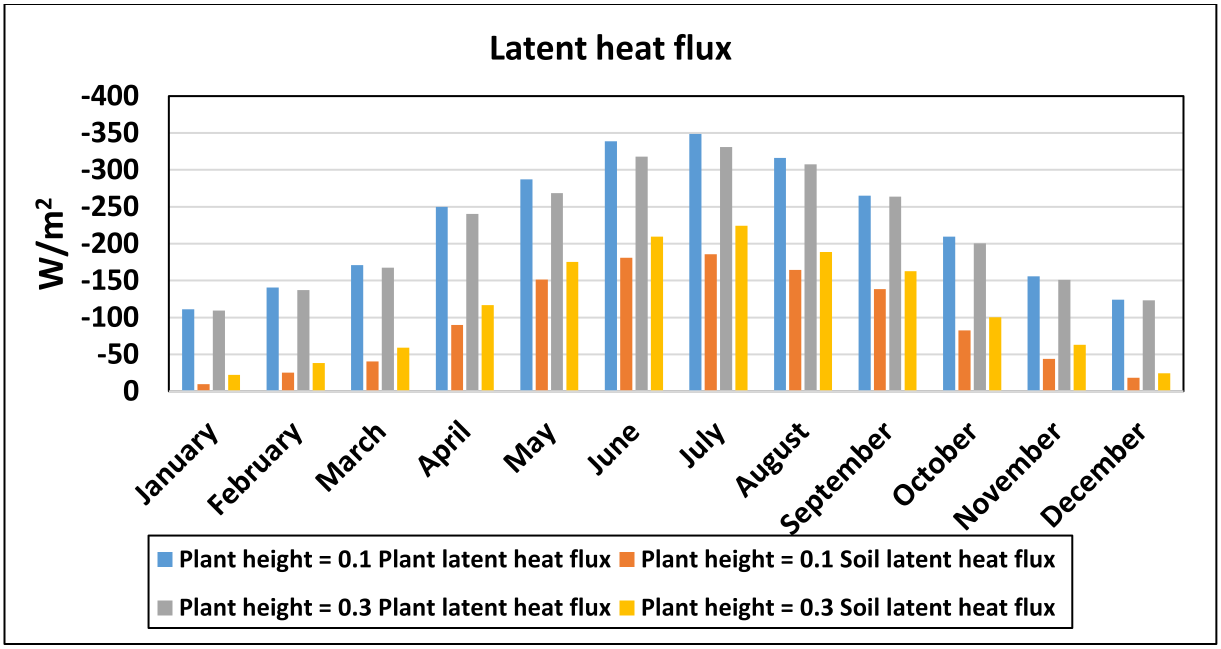

Figure 58. Monthly variations of latent heat flux of soil and plant with plan height in Las Vegas.

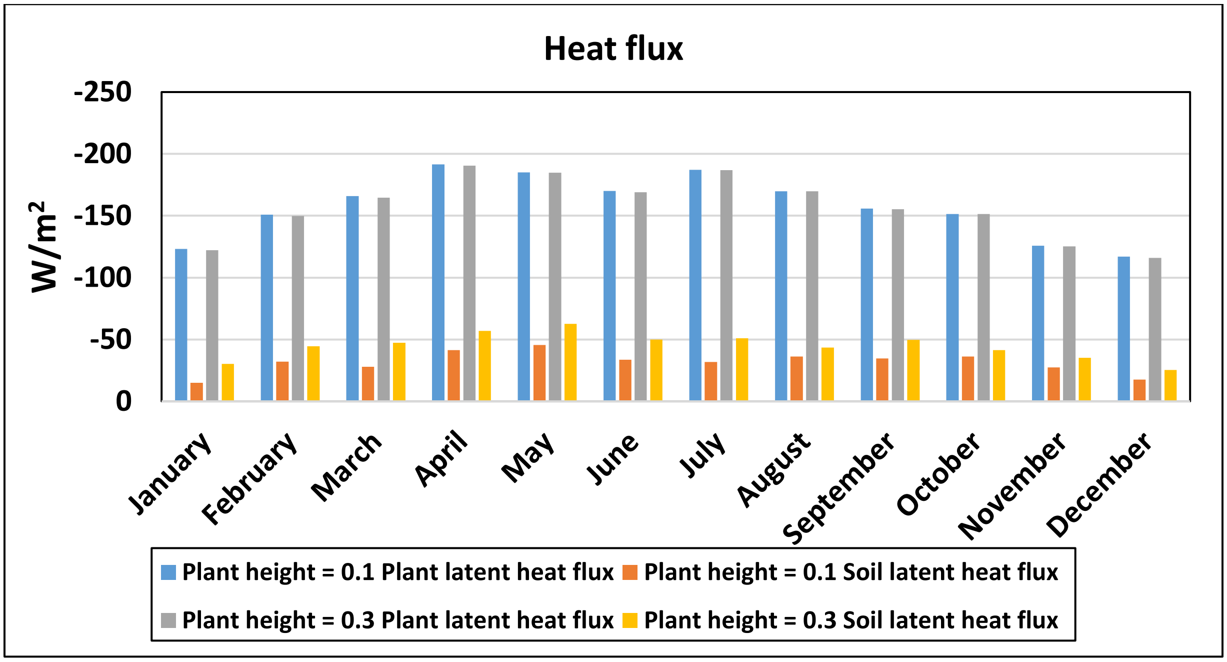

Figure 59. Monthly variations of latent heat flux of soil and plant with plan height in Miami.