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Temporal Variability In The Daytime Green Roof Energy Balance During Drying Periods

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Abstract

Green roofs are a building design element intended to increase evaporative cooling in cities during the summer, which helps alleviate the daytime impacts of heat on human health and energy consumption, and supports mitigation and adaptation to the local effects of climate change. Time varying energy balances were measured on a 0.15 m deep, ~ 60 m² modular green roof with *Sedum spurium* in London, Ontario for the summer of 2014. A lysimetry approach was used to measure latent heat $Q_E$. Net radiation $Q^*$ and ground heat flux $Q_G$ were also measured, with sensible heat flux $Q_H$ derived as a residual. An empirical model of evaporative flux ratio $Q_E/Q^* - Q_G$ by volumetric water content $VWC$ was fit based on experimental data (typical values ranged from 0.2-0.4 and decreased linearly to 0.05 during atypical low $VWC$ below 0.22). Research presented here can inform future optimization of green roof atmospheric cooling performance. Furthermore, this study indicates that green roof atmospheric cooling performance in typical North American mid latitude climates is lower than typical urban greenery such lawns and parks, which has policy implications for sustainable building design and urban planning.

**Keywords:** green roof, energy balance, urban climate, sustainable design, urban heat island, evapotranspiration
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# Contents

Abstract ii

Acknowledgments iii

List of Figures vii

List of Tables xii

List of Appendices xiii

1 Introduction 1

1.1 The Surface Energy Balance ........................................ 5
1.2 The Surface Energy Balance, Surface Temperature, and Air Temperatures 6
1.3 Surface Energy Balance Measurements to Inform Urban Climate Models 7
1.4 Surface Controls on the Surface Energy Balance ...................... 7
1.5 Research Objectives ................................................... 9

2 Site and Methods 11

2.1 Overview .............................................................. 11
2.2 Green Roof Test Array ............................................... 12
2.3 Radiation Budget Measurements .................................... 17
  2.3.1 Solar Radiation and Albedo ....................................... 17
  2.3.2 Longwave Radiation and Surface Temperature ................. 20
  2.3.3 Net Radiation ...................................................... 21
2.4 Ground Heat Flux ......................................................... 23
2.5 Latent Heat Flux ......................................................... 24
2.5.1 Previous Studies Using Lysimeters and Green Roof Lysimeters . . . 25
2.5.2 Limitations of Other Green Roof Latent Heat Flux Measurement Techniques ......................................................... 25
2.5.3 Advantages of Lysimetry on a Modular Green Roof ......................... 26
2.5.4 Errors in Lysimetry on a Modular Green Roof ................................ 26
2.5.5 Noise in Lysimeter Signal ................................................ 27
2.5.6 Systematic Variability in Replicate Lysimeters ..................... 28
2.5.7 Lysimeter Measurement Repeatability through Time ................ 31
2.5.8 Total Module Volumetric Water Content ................................ 31
2.6 Chapter Summary ......................................................... 35

3 Study Results and Discussion: Time Varying Energy Balance Fluxes 36
3.1 2014 Study Period ......................................................... 36
3.2 Plant Growth ......................................................... 40
3.3 Drying Periods ......................................................... 40
3.4 Aggregate Energy Balance Summary .................................. 43
3.4.1 Clear Sky Ensemble Energy Balance .................................. 43
3.4.2 Hourly Daytime Energy Balance .................................... 47
3.4.3 Maximum Daytime Energy Balance .................................. 48
3.4.4 Daytime Integrated Energy Balance .................................. 49
3.4.5 Monthly Daytime Integrated Energy Balance and Flux Ratios ....... 50
3.5 Time Varying Energy Balances During Long Drying Periods ............ 54
3.5.1 Results: Drying Period 1 ................................................ 54
3.5.2 Results: Drying Period 2 ................................................ 57
3.5.3 Results: Drying Period 3 ................................................ 59
3.5.4 Results: Drying Periods 4 and 5 ........................................ 61
List of Figures

1.1 Conceptual schematic of the urban boundary layer (UBL) including its vertical layers (Mixing layer, Surface layer, Inertial sublayer, Roughness sublayer, Urban Canopy layer - UCL) and scales (Mesoscale, Local scale, Microscale). Green roof shown in green within the microscale. Modified from Piringer et al. (2002) .................................................. 4

2.1 Green roof test array setup and instrument configuration. ..................... 14


2.3 Pyranometer correction, TSP-400 to CMA6. Top panel: TSP-400 #1 July 10, 2016 to July 20, 2016 used to correct $K_\downarrow$ during 2014 study; Bottom panel: TSP-400 #2 Aug 5, 2016 to Aug 8, 2016 used to correct $K_\uparrow$ during 2014 study. ................................................................. 19

2.4 Net radiometer empirical correction of REBS Q7 to NRLITE2 from side-by-side inter-comparison from June 17, 2016 to June 22, 2016. Top: relation for positive $Q^*$ values. Bottom: relation for $Q^*<-50$ W m$^{-2}$, also used for $Q^*$ 0 to -50 W m$^{-2}$ .................................................................................. 22

2.5 Departure of latent heat flux of individual lysimeter modules from median against the median latent heat flux by hour of day for London, 2014. N=116 (hourly per lysimeter; days). Thick line indicates slope significantly different from 0 (p<0.05) using robust linear regression .................................................. 30
2.6 Relative standard deviation (RSD) of lysimeter module weight against wind speed and wind direction standard deviation 2016. Data from July 2016, N=8435. Standard deviation of 5 minute data with sampling interval of 1 second. 32

2.7 Lysimeter response to dewfall and freewater evaporation. 33

2.8 Regressions of lysimeter weight to volumetric water content using 4 lysimeter modules and 1 water content probe. Slopes represents rate of change in VWC with a change in lysimeter module weights. NW module was lower weight overall than other lysimeter modules. 34

3.1 Overview of data collection period: April 1, 2014 to October 31, 2014. All values shown are hourly. Water content not shown during rain or drainage. Trend in plant height and plant density interpolated with spline for clarity. DOY shown under plant images. 38

3.2 London 2014 temperature and precipitation compared to climate normals (1981-2010). 39

3.3 Drying periods defined within the study period (London Green Roof, May 21 to September 30, 2014). Red - long drying periods (>7 days). Yellow - short drying periods (2-7 days). Drying periods overlaid on Fig. 3.1. 42

3.4 Clear sky ensemble energy balance. London Green Roof, May 21 to September 30, 2014. Solid lines are means, shaded region are standard deviations. 44

3.5 Daytime integrated EFR and Bowen ratio for clear sky days. Box contains 25% to 75% percentiles, whiskers represent 1.5 × IQR. Number of days = 30. London Green Roof, May 21 to September 30, 2014. 46

3.6 Daytime integrated energy balance fluxes. Box contains 25% to 75% percentiles, whiskers represent 1.5 × IQR. Number of days = 96. London Green Roof, May 21 to September 30, 2014. 49
3.7 Daytime integrated energy balance fluxes by month. Box contains 25% to 75% percentiles, whiskers represent 1.5 \times IQR. Number of days = 96. London Green Roof, May 21 to September 30, 2014.

3.8 Daytime integrated energy balance fluxes ratios by month. Box contains 25% to 75% percentiles, whiskers represent 1.5 \times IQR. Number of days = 96. London Green Roof, May 21 to September 30, 2014.

3.9 Time varying energy balance during drying period 1. London Green Roof May 21 to June 2, 2014. Bottom panel: Solid lines are measured values, \( Q_E \) is the mean of 4 lysimeters, \( Q_H \) is calculated by residual. Shaded regions are estimated uncertainties, \( Q_E \) is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.

3.10 Time varying energy balance during drying period 2. London Green Roof June 3 to June 11, 2014. Bottom panel: Solid lines are measured values, \( Q_E \) is the mean of 4 lysimeters, \( Q_H \) is calculated by residual. Shaded regions are estimated uncertainties, \( Q_E \) is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.

3.11 Time varying energy balance during drying period 3, London Green Roof Aug 22 to Sept 4, 2014. Bottom panel: Solid lines are measured values, \( Q_E \) is the mean of 4 lysimeters, \( Q_H \) is calculated by residual. Shaded regions are estimated uncertainties, \( Q_E \) is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.

3.12 Time varying energy balance during drying period 4. London Green Roof September 13 to Sept 21, 2014. Bottom panel: Solid lines are measured values, \( Q_E \) is the mean of 4 lysimeters, \( Q_H \) is calculated by residual. Shaded regions are estimated uncertainties, \( Q_E \) is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.13 Time varying energy balance during drying period 5. London Green Roof
September 21 to September 30, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.

4.1 Albedo through the growing season for 2013, 2014, and 2016. Albedo values are derived from integrated daytime totals of $K↑$ and $K↓$ with zenith angle>85°.

4.2 Segmented empirical fit of albedo in relation to growing degree days (GDD) for 2013 and 2014. Base temperature for GDD was 10°C.

4.3 Wind rose for all drying periods during hours with $Q^* > 100$ W m$^{-2}$. Long fetch of roof at the same height as the green roof test array highlighted in red.

4.4 Identification of possible advection in hourly EFR when $Q^* > 100$ W m$^{-2}$. See text for a description of each case.

4.5 Hourly EFR $Q_e/(Q^*-Q_G)$ separated into three case studies plotted against water content.

4.6 Hourly EFR $Q_e/(Q^*-Q_G)$ for $Q^* > 500$ W m$^{-2}$ plotted against water content, piecewise linear model. Superimposed models are shown with dashed lines. Thick blue line is a linear piece-wise fit to all drying period points. Thin blue line is a polynomial fit to all drying period points. Thick red line is a linear piece-wise fit to points after second drying period. Thin red line is a polynomial fit to points after second drying period.

4.7 Integrated daytime ($K↓ > 0$ W m$^{-2}$) EFR $Q_e/(Q^*-Q_G)$ plotted against water content for three cases of daily integrated $Q^*$. 
4.8 Daytime EFR $\frac{Q_e}{(Q^* - Q_G)}$ for available energy $>10$ MJ $m^{-2} d^{-1}$ plotted against water content with points separated into different drying periods. Superimposed models are shown with dashed lines. Thick blue line is a linear piece-wise fit to all drying period points. Thin blue line is a polynomial fit to all drying period points. Thin red line is a polynomial fit to points after second drying period.

5.1 Hourly EFR by air temperature for all drying periods with symbols separated into two classes of VWC.

5.2 Green roof evaporative flux ratio (EFR) superimposed on daily EFR from urban to rural by vegetation fraction modified from Oke et al. (2017). Other study points are a few weeks in duration from several different sites in different cities. Boxplot for daytime EFR includes 100 daytime periods from all 20 drying periods. Dashed blue line is the median daytime EFR. Solid blue line is the median daily EFR.

C.1 Procedure used to extract six samples of known volume from green roof media in order to find bulk density.
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Instrumentation used on the London green roof test array.</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Descriptive statistics of daytime ($K \downarrow &gt; 0$) energy balance during all drying periods. London Green Roof, May 21 to September 30, 2014.</td>
<td>47</td>
</tr>
<tr>
<td>3.2</td>
<td>Descriptive statistics of maximum daytime ($K \downarrow &gt; 0$) energy balance during all drying periods. London Green Roof, May 21 to September 30, 2014.</td>
<td>48</td>
</tr>
<tr>
<td>A.1</td>
<td>Pyranometer manufacturer specifications</td>
<td>108</td>
</tr>
<tr>
<td>A.2</td>
<td>Net radiation manufacturer specifications and estimated uncertainty</td>
<td>109</td>
</tr>
<tr>
<td>A.3</td>
<td>Inputs for error in surface temperature $\Delta T_{0gr}$</td>
<td>109</td>
</tr>
<tr>
<td>B.1</td>
<td>Load cell manufacturer specifications and estimated uncertainty. Interface Inc. SPI Platform Scale Load Cell, Single Point 25 lbf to 150 lbf</td>
<td>112</td>
</tr>
<tr>
<td>B.2</td>
<td>Lysimeter calibrations London 2014</td>
<td>113</td>
</tr>
<tr>
<td>B.3</td>
<td>Lysimeter calibrations London 2016</td>
<td>114</td>
</tr>
<tr>
<td>C.1</td>
<td>Bulk Density from sampling of green roof module in 2013</td>
<td>117</td>
</tr>
<tr>
<td>D.1</td>
<td>Error in EC-5 calibration</td>
<td>119</td>
</tr>
<tr>
<td>E.1</td>
<td>Inputs for error in $\Delta Q_{sv}$</td>
<td>121</td>
</tr>
</tbody>
</table>
List of Appendices

Appendix A Radiation Instrument Details ........................................... 107
Appendix B Lysimeter Details .............................................................. 111
Appendix C Bulk Density of Media ...................................................... 115
Appendix D Water Content Details ...................................................... 118
Appendix E Error Analysis of Ground Heat Flux ................................. 120
Chapter 1

Introduction

Climate affects a city’s energy use, the health and comfort of its citizens, and the economy. Urban areas, which include cities with high population density, have a unique climate compared to their rural counterparts. The distinct urban climate arises due to changes in the surface and atmospheric characteristics over cities brought about by urbanization. These changes include: replacement of natural cover with built materials, an increase in impervious surface cover, and a three-dimensional roughening to the surface, along with additions of heat, water vapour and pollutants to the urban atmosphere. The resultant urban climate shows modifications in all characteristics (Oke et al., 1997), the most famous of which is the additional warmth in cities known as the urban heat island.

A green roof is a building rooftop that has a vegetated surface added to its outermost layer. Green roofs have become an important design option for urban building designs in North America to reduce stormwater runoff (VanWoert et al., 2005). Green roofs can also provide a range of other benefits. Research suggests they can reduce urban temperatures (Alexandri and Jones, 2008), cleanse pollutants (Oberndorfer et al., 2007), increase building acoustical performance (Van Renterghem et al., 2014), increase building thermal performance (Niachou et al., 2001; Sailor et al., 2012), increase longevity of building membranes (Kosareo and Ries, 2007), provide urban habitat for insects and birds (Brenneisen, 2006), and add to the aesthetic appeal of a building (Oberndorfer et al., 2007).
The most significant periods for using green roofs as a means of cooling occur during summer days when peak demand on energy grids (e.g., due to air conditioning) and highest pollutant and CO$_2$ emissions from energy demand occur. These times are also most likely to cause human discomfort and increased risk to human health. Green roofs provide a cooling benefit by replacing dry hot roofs with a vegetated surface that provides some evaporative cooling to the overlying urban atmosphere through a reduced surface temperature and sensible heat flux. Evaporative cooling occurs as energy required to evaporate water reduces the surface-air temperature gradient and reduces the amount of heat released into the atmosphere. Advocates of green roofs suggest that they can be effective strategies to both mitigate and adapt to expected climate changes in urban areas during the summer (Demuzere et al., 2014; Santamouris, 2014). These changes are expected to increase the number of hot days that drive large cooling demand and the incidence of high precipitation events that can contribute to urban flooding. Several jurisdictions in Canada and the U.S. have considered green roofs as a strategy to adapt to local climate change and, to some extent, mitigate local emissions that contribute to large-scale climate change. For example, the City of Toronto passed a by-law in 2009 mandating green roofs for new constructions (City of Toronto, 2013). The City of Chicago has progressive policies and incentives to mitigate urban climate impacts through green roofs, which has resulted in the installation of over 500 green roofs in Chicago covering a surface area of over 5.5 million square feet (City of Chicago, 2010). With heightened interest in green roofs to cool cities, it is important to understand the cooling performance of green roofs under real-world conditions, especially in terms of their contribution to cooling the atmosphere.

There are different scales of the urban atmosphere as can be seen in Fig.1.1. Green roofs exist within the microscale at the level of individual buildings. Green roofs are a boundary condition both for the building below and atmosphere above. The influence of green roofs on building-scale climate, including interior building climate and energy demand (Castleton et al., 2010; Jaffal et al., 2012; Santamouris et al., 2007; Fioretti et al., 2010), roof surface temperature (Dvorak and Volder, 2013; DeNardo et al., 2005) and roof-
air temperature (MacIvor et al., 2016; Berardi, 2016)) is well established, but the green roof surface energy balance (SEB) must be known to address the forcing from green roofs on the urban atmosphere. The cumulative impact of green roofs on the urban atmosphere is difficult to measure directly, but it can be quantified through the use of numerical models. These models use the SEB as a boundary condition. The SEB boundary condition must be evaluated with measurement data to ensure that physical processes are adequately captured by the model. Few studies have measured the surface energy balance of green roofs (Takebayashi and Moriyama, 2007; Jim and He, 2010; Coutts et al., 2013; Heusinger and Weber, 2017). Even fewer have studied the surface energy balance over entire summer periods (Jim and He, 2010; Heusinger and Weber, 2017). Fewer yet have studied the surface energy balance of green roofs over summertime periods in a temperate climate (Heusinger and Weber, 2017). Many studies exist for the study of green roof storm-water retention and even evapotranspiration in isolation (Sims et al., 2016; Hill et al., 2017; Marasco et al., 2014), but there is a lack of robust full summer SEB measurements. The objective of this thesis is to help address the gap in long term SEB measurements on green roofs.
Figure 1.1: Conceptual schematic of the urban boundary layer (UBL) including its vertical layers (Mixing layer, Surface layer, Inertial sublayer, Roughness sublayer, Urban Canopy layer - UCL) and scales (Mesoscale, Local scale, Microscale). Green roof shown in green within the microscale. Modified from Piringer et al. (2002)
1.1 The Surface Energy Balance

Exchanges of energy between a surface and the atmosphere are described using the SEB. The SEB is a conservation of energy equation that describes the flows of energy between the surface and the atmosphere. The SEB describes how the net radiative energy surplus or deficit at a surface is balanced by vertical heat transfer through convection and conduction. The simplest form of the SEB for a large flat homogeneous plane is:

\[ Q^* = Q_H + Q_E + Q_G \]  \hspace{1cm} (1.1)

where the net radiative energy at a surface \( Q^* \) is balanced by: convective latent heat transfer to and from the atmosphere \( Q_E \), convective sensible heat transfer to and from the atmosphere \( Q_H \), and conductive sensible heat transfer to and from the substrate \( Q_G \). Positive fluxes are identified as those directed away from the surface. Green roofs can provide benefits to urban climate by increasing \( Q_E \) relative to \( Q_H \), which contributes to reduced urban air temperatures via Eq.1.4.

For more complicated surfaces, such as forests and cities, where a distinct canopy structure exists and where surface inhomogeneity may give rise to horizontal transfers, the volumetric characterization of the energy balance:

\[ Q^* = Q_H + Q_E + \Delta Q_S + \Delta Q_A \]  \hspace{1cm} (1.2)

is more appropriate. Here, \( Q_G \) is replaced with \( \Delta Q_S \), the change in heat storage in the canopy. \( \Delta Q_A \) is advection, the horizontal convergence or divergence of heat into the volume; it is negligible when a surface is extensive and homogeneous, but can enhance \( Q_E \) when a cool wet surface is proximate to hot dry surroundings. A term for heat exchange from plant photosynthetic processes exists but is negligible relative to the size of the other terms, therefore it is ignored here. In this thesis, the flat infinite plane representation of the SEB (Eq.1.1) is used, with \( Q_G \) incorporating the change in heat storage in the canopy along with heat conduction into the surface (detailed in section 2.4). Since \( \Delta Q_A \) was not directly measured, it will be implicit in the other terms, primarily the other convective fluxes \( Q_E \).
and $Q_H$. There are multiple scales at which $\Delta Q_A$ can occur: the local roof scale and larger urban scale. The green roof used in this thesis is a patch situated on a larger roof (see section 2.2). This could result in local scale advection from the surrounding roof that may be uncharacteristic of a larger green roof that is not a patch on a larger roof.

It is also useful to partition the energy balance fluxes $Q_E$, $Q_H$, and $Q_G$ by $Q^*$, as is often done to allow comparisons to other surfaces (Oke, 1987). For assessing convective fluxes in comparisons to other surfaces, expressing convective fluxes as a Bowen ratio $\beta = \frac{Q_H}{Q_E}$ or as a ratio of available energy ($Q^* - Q_G$) may be more appropriate. In this thesis, since each of $Q_E$, $Q^*$ and $Q_G$ was directly measured, $\frac{Q_E}{Q^* - Q_G}$, the ratio of available energy partitioned into $Q_E$ is used as a metric climate performance and is referred to as the evaporative flux ratio, EFR.

### 1.2 The Surface Energy Balance, Surface Temperature, and Air Temperatures

The heating or cooling of a surface $\frac{\partial T_0}{\partial t}$ of thickness $z$ and heat capacity $C_0$ is related to the energy balance of a surface by:

$$C_0 \frac{\partial T_0}{\partial t} z = Q^* - Q_H - Q_E - Q_G$$

(1.3)

Another common metric used to describe urban climate is air temperature, again for its simplicity and ease of measurement. Air temperature change in the urban atmosphere is also linked to the SEB. The heating and cooling of air $\frac{\partial T_a}{\partial t}$ with heat capacity $C_a$, near a vast homogeneous flat surface is related to the vertical divergence of the net radiation $\frac{\partial Q^*}{\partial z}$ and sensible heat flux $\frac{\partial Q_H}{\partial z}$, such that

$$C_a \frac{\partial T_a}{\partial t} z = \frac{\partial Q^*}{\partial z} + \frac{\partial Q_H}{\partial z}$$

(1.4)

In most situations, sensible heat flux divergence $\frac{\partial Q_H}{\partial z}$ is the main determinant of air temperature change. Hot urban air temperatures can negatively influence human health (Kovats
and Hajat, 2008) and also drive increased energy use for cooling in the warm season. Given the dependence of the surface and air temperatures on the surface energy balance, an understanding of the green roof energy balance – rather than surface and air temperatures alone – is required to determine the effect of green roofs on urban climate.

### 1.3 Surface Energy Balance Measurements to Inform Urban Climate Models

The SEB of a green roof describes green roof surface-atmospheric energetic exchanges. The SEB more directly represents the surface energetics than does use of the surface temperature and air temperature above green roofs, which both result from the SEB exchanges. In order to understand and forecast the effects of surface modifications such as addition of green roofs on urban climate, urban climate models such as Masson (2000) are used to simulate the complex dynamics between surface and atmospheric exchange. However, these models are only useful if their outputs agree with reality, and thus observational studies are critical to evaluating numerical models. Green roof additions to urban climate models need to be evaluated for agreement with measurements at multiple time scales. Green roof additions to urban climate models, such as de Munck et al. (2013) and Sun et al. (2013), use an energy balance framework, therefore having energy balance measurements at multiple time scales is needed for their evaluating their performance. A characterization of the time varying daytime energy balance at the diurnal, multi-day, and monthly scales at an hourly and daily resolution is needed to obtain data for model evaluation at different time scales.

### 1.4 Surface Controls on the Surface Energy Balance

The net radiation $Q^*$ absorbed by a surface is the driver of the SEB. The net radiation is a measure of the total absorbed radiation by a surface. It consists of incoming longwave $L_\downarrow$ and shortwave $K_\downarrow$ radiation, less the outgoing longwave $L_\uparrow$ radiation emitted and reflected...
by the surface and shortwave radiation $K\uparrow$ reflected by the surface, such that:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$  \hspace{1cm} (1.5)

The surface property that describes the shortwave reflectivity of the surface is albedo $\alpha$ ($\alpha = K\uparrow / K\downarrow$). Albedo plays an important role in determining $Q^*$, as evident when Eq.1.5 is rewritten such that:

$$Q^* = K\downarrow - \alpha K\downarrow + L\downarrow - L\uparrow$$  \hspace{1cm} (1.6)

Surfaces with a high albedo have lower daytime $Q^*$ than surfaces with lower albedo. All else being equal, this translates to a cooler surface and less heating of the urban atmosphere. Albedo varies drastically for different roof surfaces; for example, Coutts et al. (2013) found albedos of 0.1 for a growing media, 0.15 for a green roof, 0.21 for a steel roof, and 0.71 for a white or cool roof. The albedo of green roofs was also found to vary by plant type as highlighted in Lundholm et al. (2015), where albedo ranged from 0.16 to 0.26, with *Sedum spurium* having an albedo of 0.21. In another study by Monteiro et al. (2017), albedo of different plants ranged from 0.14 to 0.27, with *Sedum spurium* having an albedo of 0.19 but dropping to 0.17 the following year. The second study shows a decrease in green roof albedo between years but both studies are limited to a few days of albedo measurements.

From the existing green roof literature, irrigation was found to be an important control as it influenced the moisture content, measured as volumetric water content $VWC$, of green roofs. Irrigation was found to decrease air temperature above a green roof (MacIvor et al., 2016), especially for *Sedum* compared to other vegetation. Irrigation was also found to increase the latent heat flux $Q_E$ (Coutts et al., 2013). Even without irrigation, a higher water content from natural rainfall as measured through a long term eddy covariance study was yet again found to increase $Q_E$ (Heusinger and Weber, 2017). Both studies highlighted the importance of water content as a control on $Q_E$ and therefore the energy balance and atmospheric cooling from a green roof. In the latter study, a nearly linear relationship between water content and $Q_E$ was reported, but the range of water contents were limited to the conditions of the study which took place in Germany. It was also highlighted that
1.5 Research Objectives

The purpose of this thesis is to assess the temporal variability in the daytime green roof SEB during summer using long term direct measurements on a green roof. SEB measurements are needed to characterize the forcing from green roofs on urban atmosphere in different climates and can be used to evaluate numerical models that are used to assess the impact of green roofs at the urban scale. Specifically, this thesis addresses the following questions:

1. How does daytime green roof SEB vary during sustained drying periods at a range of temporal scales? For a more complete assessment of the nature of the summer time green roof SEB during drying periods rather than assessment of isolated days within drying periods, the SEB change through the following temporal scales are required: diurnally, through multi-day drying periods, and through the summer. An hourly frequency incorporates diurnal changes while daytime integrations allow assessment of longer time scale changes.

2. Given that albedo is a strong control on available energy, how does green roof albedo vary with time? *Sedum spurium* undergoes phenological changes throughout the growing season, including changes in color, structure, and density, each of which impacts albedo. The magnitude of these changes through time on albedo and therefore $Q^*$ and the SEB is not well understood.

3. To what extent might advection influence the green roof SEB? All green roofs are
patches that are potentially subject to advection. However, our green roof test array (section 2.2) is a vegetated patch within a larger bare roof that could potentially experience advection due to the surrounding bare roof. An assessment of advective effects is important to characterizing the ability of the green roof SEB data to represent a full scale green roof and to provide appropriate model evaluation data.

4. What is the relationship between daytime summer green roof evaporative flux ratio $Q_E/(Q_T - Q_G)$ and water content for sustained drying periods? It is expected that EFR should exhibit a near-linear decrease with water content during sustained drying periods.
Chapter 2

Site and Methods

This chapter describes the study site and detailed methods used to determine the green roof energy balance terms. Specifically, this chapter includes a description of the setup of the green roof site; measurements of the radiation budget terms, including: solar radiation, albedo, and applied corrections; net radiation measurement and its correction; and finally, the ground heat flux measurement and assumptions used in its calculation. This chapter also provides an in-depth analysis of latent heat flux measurement using lysimeters, including advantages over other methods of measuring latent heat flux, and an evaluation of their performance. Finally, an estimation of volumetric water content $VWC$ from a water content probe and multiple lysimeter weight measurements is presented.

2.1 Overview

A lysimetry approach to the surface energy balance (SEB) was taken, wherein the latent heat flux was derived from continuous measurements from four miniature custom lysimeters; the ground heat flux $Q_G$ was derived from measured subsurface soil heat flux and use of soil and canopy temperatures to quantify the correction for stored heat; and the net radiation $Q^*$ was measured using a pyrradiometer (net radiometer). No measurements of the sensible heat flux $Q_H$ were made; it was derived as a residual from the energy balance.
(1.1). This approach allows for direct measurement of $Q_E$ for any size of green roof and when used with a modular green roof setup permits multiple measurements to assess the replicability and potential spatial variability of $Q_E$.

The long term SEB measurements of the green roof described here were made within the context of a larger study to assess the green roof performance in terms of climate, hydrology, and biology in Canadian climates. The project used three test sites set up in London, Ontario; Calgary, Alberta; and Halifax, Nova Scotia. Climate performance was measured by the energy balance, where a better performance was characterized by a high portioning of net radiation or available energy into the latent heat flux. Three plant types were included in the study: *Sedum spurium*, *Aquilegia canadensis*, and *Sporobolus heterolepis*. Only *Sedum spurium* at the more heavily instrumented London site in 2014 is considered in the current study.

### 2.2 Green Roof Test Array

The green roof plot consisted of interlocking modules 0.3 m × 0.3 m in area with 0.15 m or 0.1 m depth) that contained growing media and plants. A central elevated array with *Sedum spurium* was used to obtain energy balance measurements using a lysimetry approach. The central array was surrounded by a downward sloping and flat array consisting of 0.15 m and 0.1 m depth modules of *Sedum spurium*, *Aquilegia canadensis*, *Sporobolus heterolepis*, and a mixed planting of the three species. The growth media consisted of roughly half coarse material by weight, mainly expanded shale, and 10% fines, consisting predominately of limestone (Perelli, 2014). This elevated central array construction allowed for the lysimetry approach to the energy balance. The lysimeters, consisted of 22.5 kg capacity load cells mounted between two aluminum plates, covered by plastic protective covers. The lysimeters were placed and leveled on cement slabs on the roof surface. Each lysimeter carried a single standard green roof module with *Sedum spurium* canopy so that the level of the
soil and plant canopy was even with that of the surrounding modules in the array. The lysimeters measured the change in weight of the module through time and thereby allowed calculation of the latent heat flux $Q_E$ via Eq. 2.20. A separate module (heat flux module) was built with an embedded heat flux sensor as well as a multiple junction averaging thermocouple and water content sensor in order to measure the ground heat flux $Q_G$. There were four replicate lysimeters with two replicates placed adjacent to one another towards the western and eastern portion of the central elevated array (Fig. 2.1). The heat flux module was placed adjacent to the replicate lysimeters on the eastern side. A net radiometer was placed at a height no lower than 25 cm above the green roof canopy in order to maximize the view factor of the green roof and minimize shadow effects. The net radiometer was mounted with its arm extending southward to reduce shadows from the instrument and mounting equipment influencing the measurements. Meteorological variables of air temperature, relative humidity, wind speed, and wind direction were collected at a height of 2 m from a separate tower mounted off the test array to the north (Fig. 2.1) in order to characterize the roof scale and ambient condition. Incoming solar radiation was measured using a pyranometer, mounted above the array to maximize its sky view factor. Reflected solar radiation was measured above the green roof to find albedo. Surface temperatures of the green roof, bare media, and roof membrane were taken using infrared radiometers. Precipitation was measured using tipping bucket rain gauges. One set was embedded in the green roof array so that the gauge opening was at the same height as the upper plant canopy. Another rain gauge was also mounted on the conventional roof membrane adjacent to the green roof test array. Data was sampled at a 1 second interval and averages recorded at a resolution of at least 5 minutes using Campbell Scientific CR3000 dataloggers. Instrument details are given in Table 2.1.

The green roof test site was constructed on top of Talbot College at The University of Western Ontario in London, Ontario (Fig. 2.2). The existing roof was a modified bitumen roof membrane with a degraded slope around roof drains such that ponding of rainwater occurred.
Figure 2.1: Green roof test array setup and instrument configuration.
Table 2.1: Instrumentation used on the London green roof test array.

<table>
<thead>
<tr>
<th>Measured Variables</th>
<th>Symbol</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature, Relative Humidity</td>
<td>$T_a$, $RH$</td>
<td>T&amp;RH HC3-S3</td>
</tr>
<tr>
<td>Net Radiation</td>
<td>$Q^*$</td>
<td>Net Radiometer REBS Q7.1</td>
</tr>
<tr>
<td>Incoming Solar Radiation</td>
<td>$K\downarrow$</td>
<td>Pyranometer YES TSP-400</td>
</tr>
<tr>
<td>Reflected Solar Radiation</td>
<td>$K\uparrow$</td>
<td>Pyrgeometer Epply PIR</td>
</tr>
<tr>
<td>Incoming Longwave Radiation</td>
<td>$L\downarrow$</td>
<td>IRT Apogee SI-121</td>
</tr>
<tr>
<td>Outgoing Longwave Radiation</td>
<td>$L\uparrow$</td>
<td>IRT Apogee SI-111</td>
</tr>
<tr>
<td>Green Roof Surface Temperature</td>
<td>$T_{G_0}$</td>
<td>3 junction averaging thermocouples</td>
</tr>
<tr>
<td>Bare Roof Surface Temperature</td>
<td>$T_{B_0}$</td>
<td>Omega Type T /Custom Thermistor</td>
</tr>
<tr>
<td>Subsurface Temperature</td>
<td>$T_{z_1}$</td>
<td>Fine wire thermocouple Omega Type E</td>
</tr>
<tr>
<td>Air Temperature Above Roof Membrane</td>
<td>$T_{B_1}$, $T_{B_2}$</td>
<td>Anemometer/Wind Vane</td>
</tr>
<tr>
<td>Air Temperature Above Green Roof Canopy</td>
<td>$T_{G_1}$, $T_{G_2}$</td>
<td>R.M. Young 3102 Wind Sentry Set</td>
</tr>
<tr>
<td>Leaf Wetness Sensor</td>
<td>LWS</td>
<td>Leaf wetness sensor CS LWS</td>
</tr>
<tr>
<td>Wind Speed, Wind Direction</td>
<td>$WS$, $WD$</td>
<td>Custom using tipping bucket</td>
</tr>
<tr>
<td>Drainage</td>
<td>$D$</td>
<td>Rain Gauge Texas</td>
</tr>
<tr>
<td>Precipitation</td>
<td>$P$</td>
<td>Electronics Tipping bucket TE525WS</td>
</tr>
</tbody>
</table>
Figure 2.2: Photograph of green roof test array, Talbot College, London, Ontario. July 2014.
2.3 Radiation Budget Measurements

Incoming solar radiation $K_{\downarrow}$ and reflected solar radiation $K_{\uparrow}$ were measured using upward and downward facing pyranometers. Incoming longwave radiation $L_{\downarrow}$ and outgoing longwave radiation $L_{\uparrow}$ were measured using a pyrgeometer and infrared radiometer (IRT). Net radiation $Q^*$ was measured directly using a pyrradiometer (net radiometer) and calculated from the individually measured components ($K_{\downarrow}, K_{\uparrow}, L_{\downarrow}, L_{\uparrow}$).

2.3.1 Solar Radiation and Albedo

Yankee Environmental Systems TSP-400 pyranometers were used for both $K_{\downarrow}$ and $K_{\uparrow}$ measurements. The TSP-400s were used for albedo measurements throughout the main 2014 study period and also during an additional albedo study undertaken in 2016. An inter-comparison was conducted in 2016 and the TSP-400s were corrected to a Kipp & Zonen CMA6 that was re-calibrated by the manufacturer in 2016 (Fig. 2.3). The inter-comparison was conducted predominantly under clear sky conditions in July and August for periods of 3 to 10 days. Error in measurements of $K_{\downarrow}$, $K_{\uparrow}$, and consequently $\alpha$ were assumed to be a combination of the errors in the CMA6 and those associated with the empirical fit in the correction of the TSP-400s. $\delta K_{\downarrow\text{fit}}$ is the error in the empirical fit for the TSP-400 that was used to measure $K_{\downarrow}$ in the 2014 and 2016 studies. Similarly, $\delta K_{\uparrow\text{fit}}$ is the error in the empirical fit for the TSP-400 that was used to measure $K_{\uparrow}$ in the 2014 and 2016 studies. $\delta \text{CMA6}$ is the error associated with measurements from the CMA6. Assuming average incoming solar radiation $K_{\downarrow} \approx 350$ W m$^{-2}$ and average outgoing solar radiation $K_{\uparrow} \approx 50$ W m$^{-2}$, the individual errors (see Table 2.3 and A.1) were estimated as

\begin{equation}
\delta K_{\downarrow\text{fit}} = 6.11 \text{ W m}^{-2}, \text{ or } \frac{\delta K_{\downarrow\text{fit}}}{K_{\downarrow}} = 1.7\%; \tag{2.1}
\end{equation}

\begin{equation}
\delta K_{\uparrow\text{fit}} = 7.53 \text{ W m}^{-2}, \text{ or } \frac{\delta K_{\uparrow\text{fit}}}{K_{\uparrow}} = 15.1\%; \tag{2.2}
\end{equation}

\begin{equation}
\frac{\delta K_{\text{CMA6}}}{K_{\text{CMA6}}} = 5\%, \delta K_{\downarrow\text{CMA6}} \approx 17.5 \text{ W m}^{-2}, \delta K_{\uparrow\text{CMA6}} \approx 2.5 \text{ W m}^{-2}. \tag{2.3}
\end{equation}
The relative error of the CMA6 was provided by the manufacturer (Table A.1); it was assumed to be constant at all irradiance values, hence $\delta K_{\downarrow_{\text{CMA6}}}$ and $\delta K_{\uparrow_{\text{CMA6}}}$ values correspond with $K_{\downarrow}$ and $K_{\uparrow}$. The combined error in the incoming solar radiation measurements $\delta K_{\downarrow}$, and the combined error in the albedo measurement $\delta \alpha$ was estimated by adding the error and relative error in quadrature such that

$$\delta K_{\downarrow} \approx \left( (\delta K_{\downarrow_{\text{fit}}}^2 + (\delta K_{\downarrow_{\text{CMA6}}})^2) \right)^{0.5} = 18.5 \text{ W m}^{-2} \text{ or } \frac{\delta K_{\downarrow}}{K_{\downarrow}} = 5.3\% \text{ at } K_{\downarrow} \approx 350 \text{ W m}^{-2}$$

(2.4)

$$\delta K_{\uparrow} \approx \left( (\delta K_{\uparrow_{\text{fit}}}^2 + (\delta K_{\uparrow_{\text{CMA6}}})^2) \right)^{0.5} = 7.5 \text{ W m}^{-2} \text{ or } \frac{\delta K_{\uparrow}}{K_{\uparrow}} = 15.9\% \text{ at } K_{\uparrow} \approx 350 \text{ W m}^{-2}$$

(2.5)

$$\frac{\delta \alpha}{\alpha} \approx \left( \left( \frac{\delta K_{\downarrow}}{K_{\downarrow}} \right)^2 + \left( \frac{\delta K_{\uparrow}}{K_{\uparrow}} \right)^2 \right)^{0.5} = 16.7\%, \text{ or } 0.025 \text{ at } \alpha \approx 0.15$$

(2.6)
2.3. Radiation Budget Measurements

Figure 2.3: Pyranometer correction, TSP-400 to CMA6. Top panel: TSP-400 #1 July 10, 2016 to July 20, 2016 used to correct $K_\downarrow$ during 2014 study; Bottom panel: TSP-400 #2 Aug 5, 2016 to Aug 8, 2016 used to correct $K_\uparrow$ during 2014 study.
2.3.2 Longwave Radiation and Surface Temperature

Longwave radiation was measured using a pyrgeometer for incoming $L_\downarrow$ and an infrared radiometer (IRT) for outgoing $L_\uparrow$. The IRT radiative surface temperature, $T_{rad}$ in K, was used to find $L_\uparrow$ by applying the Stefan-Boltzmann equation:

$$L_\uparrow = \sigma T_{rad}^4$$  \hspace{1cm} (2.7)

where $\sigma$ is the Stefan-Boltzmann constant $5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$. $T_{rad}$ incorporates both the longwave surface emission and reflection. This is appropriate for use in the calculation of the upward longwave radiation, however, the IRT was also used to measure surface temperature. An emissivity correction was required for calculation of the true surface temperature to account for reflected longwave included in the brightness temperature. Surface temperature was calculated using

$$T_{surface} = \left(\frac{\sigma T_{rad}^4 - (1 - \varepsilon)L_\downarrow\varepsilon}{\varepsilon\sigma}\right)^{0.25}$$  \hspace{1cm} (2.8)

where $\varepsilon$ is the emissivity of the surface. Emissivity values of natural surfaces are typically 0.82-0.99 (Oke, 1987). Emissivities of crops are typically 0.97 (Chen, 2015). Emissivity specifically for a Sedum roof was reported as 0.995 by Hirano and Ichinose (2006) and 1.0 for Sedum lineare by Feng et al. (2010). Emissivity of soils is typically lower than that of plants, around 0.93 (Wittich, 1997). However, for green roof growth media, emissivity was found to be 0.96 and varied little between several types (Sailor et al., 2008). The high emissivity of Sedum and growing media suggests that the combined emissivity of soil and plants assumed for models; for instance, values of 0.94 (Alexandri and Jones, 2008), or 0.95 (Sun et al., 2014; Tabares-Velasco and Srebric, 2009), were too low. To convert the radiative surface temperature to a kinetic surface temperature, an emissivity of 0.98 was assumed for the plant and media combination in a vegetated module. Instrument error in surface temperature was a maximum of 0.5°C according to manufacturer specifications.
2.3. Radiation Budget Measurements

2.3.3 Net Radiation

Net radiation $Q^*$ was measured directly using a REBS Q7 net radiometer. The wind corrected REBS Q7 values (Eq. A.1) from 2014 were corrected using a comparison to a newly calibrated NR LITE2 in 2016. Positive and negative values were assessed separately since a different calibration factor and wind correction were required for each in the REBS Q7. Error in the net radiation $\delta Q^*$ was assumed to be a combination of error in the NR LITE2 $\delta Q_{\text{NRLITE2}}^*$ to which the measured values were corrected (Table A.2), and error in the fit $\delta Q_{\text{fit}}^*$ (Fig. 2.4). Assuming $Q^* \sim 275$ W m$^{-2}$ if $Q^* > 0$ and $Q^* \approx 30$ W m$^{-2}$ if $Q^* < 0$,

$$\delta Q_{\text{fit}}^* = \begin{cases} 
9.54 \text{ W m}^{-2} & \frac{\delta Q_{\text{fit}}^*}{Q^*} = 3.5\% \quad \text{if } Q_{\text{fit}}^* > 0 \\
1.45 \text{ W m}^{-2} & \frac{\delta Q_{\text{fit}}^*}{Q^*} = 4.8\% \quad \text{if } Q_{\text{fit}}^* < 0 
\end{cases} \tag{2.9}$$

$$\frac{\delta Q_{\text{NRLITE2}}^*}{Q_{\text{NRLITE2}}^*} = 8\%, \text{ or } \delta Q_{\text{NRLITE2}}^* = \begin{cases} 
22 \text{ W m}^{-2} & \text{if } Q^* > 0 \\
2.4 \text{ W m}^{-2} & \text{if } Q^* < 0 
\end{cases} \tag{2.10}$$

Error in net radiation was assumed to be error in the NR LITE2 estimated based on the manufacturer specifications (Table A.2), and the fit error $\delta Q_{\text{fit}}^*$ combined such that

$$\delta Q^* \approx \left( (\delta Q_{\text{fit}}^*)^2 + (\delta Q_{\text{NRLITE2}}^*)^2 \right)^{0.5} = \begin{cases} 
14.6 \text{ W m}^{-2} & \frac{\delta Q^*}{Q^*} = 8.7\% \quad \text{if } Q^* > 0 \\
2.9 \text{ W m}^{-2} & \frac{\delta Q^*}{Q^*} = 9.3\% \quad \text{if } Q^* < 0 
\end{cases} \tag{2.11}$$
Figure 2.4: Net radiometer empirical correction of REBS Q7 to NRLITE2 from side-by-side inter-comparison from June 17, 2016 to June 22, 2016. Top: relation for positive $Q^*$ values. Bottom: relation for $Q^* < -50$ W m$^{-2}$, also used for $Q^* 0$ to $-50$ W m$^{-2}$
2.4 Ground Heat Flux

The ground heat flux at the surface $Q_G$ was obtained using a heat flux plate placed at a depth below the surface of a module in conjunction with an averaging thermocouple above the heat flux plate and knowledge of green roof media properties. $Q_G$ (in $W\,m^{-2}$) was determined using:

$$Q_G = Q_G_z + \Delta Q_{S_m} + \Delta Q_{S_v}$$ (2.12)

$$\Delta Q_{S_m} = C_{V_m} \frac{\Delta T}{\Delta t} z_m$$ (2.13)

where $Q_G$ is the conductive heat flux into the ground at the surface in $W\,m^{-2}$, $Q_G_z$ is the change the ground heat flux at depth of the heat flux plate $z_m$ in m, $\Delta Q_{S_m}$ is the change in heat storage in the green roof media layer above the heat flux plate in $W\,m^{-2}$, $\Delta Q_{S_v}$ is the change in heat storage in the vegetation canopy in $W\,m^{-2}$, $C_{V_m}$ is the volumetric heat capacity of the green roof media in $J\,m^{-3}\,K^{-1}$, $\Delta T$ is the change in temperature through time in the layer between the surface and depth $z$ in K, $\Delta t$ is the time step in s. $C_{V_m}$ was calculated as detailed in Abu-Hamdeh (2003) as

$$C_{V_m} = \rho_b (c_d + wc_w)$$ (2.14)

$$w = \frac{\theta \rho_b}{\rho_w}$$ (2.15)

where $\theta$ is the volumetric water content as measured using an EC-5 moisture probe (refer to Appendix D), $\rho_w$ is the density of water and $\rho_b$ is the dry bulk density of the media. Through destructive sampling of a green roof module in 2013, it was found that $\rho_b = 639 \pm 155$ (refer to Appendix C). The change in heat storage of the vegetation canopy layer $Q_{S_v}$ was adapted from the equation presented in Gay et al. (1996) and detailed in Gay (1998) as

$$Q_{S_v} = K_v \Delta T_c$$ (2.16)

$$K_v = \rho_v c_v \frac{z_v}{\Delta t}$$ (2.17)
where $\rho_v$ is density of the vegetation; $c_v$ is the specific heat of the vegetation, assumed to be that of water; $z_v$ is the canopy depth; and $\Delta T_c$ is change in air temperature in the canopy with time interval $\Delta t$. Since

$$\rho_v = \frac{m_v}{z_v A} \quad (2.18)$$

where $m_v$ is the mass of vegetation and $A$ is area, Eq. 2.16, Eq. 2.17 and Eq. 2.18 were simplified to

$$Q_{S_v} = \frac{m_v c_v \Delta T}{A \Delta t} \quad (2.19)$$

The mass of vegetation was estimated as be 0.09153 kg based on destructive sampling in 2013. The error in $Q_G$ was estimated to be $\approx 45\%$, attributed primarily to uncertainty in soil temperature measurements. While this error is high, the magnitude of $Q_G$ is typically low and therefore does not greatly impact the SEB.

### 2.5 Latent Heat Flux

The latent heat flux was found through the use of four continuously weighing lysimeters. A lysimeter is an instrument that monitors weight changes of a representative sample of soil in a container, in this case, a green roof module. Continuous measurements were made using lysimeters similar to that described in Grimmond et al. (1992). These lysimeters consisted of a load cell mounted between two rectangular metal plates and a rectangular plastic cover the same size as a green roof module. The latent heat flux $Q_E$ was calculated as:

$$Q_E = \frac{\Delta W L_v}{\Delta t A} \quad (2.20)$$

where $\Delta W$ is the change in weight of the lysimeter module in kg, $\Delta t$ is the time step in between measurements in s, and $A$ is the evaporating surface area of the lysimeter module in $m^2$. $L_v$ is the latent heat of vaporization for water in $J kg^{-1}$. An average of $Q_E$ from the 4 lysimeters was used.

$$L_v = 1.91846 \times 10^6 \left( \frac{T_a}{T_a - 33.91} \right)^2 \quad (2.21)$$
where $T_a$ is air temperature in K. This approach is restricted to periods in which there is no input of water from rainfall or output of water from drainage.

### 2.5.1 Previous Studies Using Lysimeters and Green Roof Lysimeters

Lysimeters are a common means of measuring $Q_E$ and have been deployed in previous studies such as those quantifying $Q_E$ in urban parks (Spronken-Smith et al., 2000). Lysimeters have also been used in previous green roof studies, such as a green roof study in New York (DiGiovanni et al., 2010). An important distinction between the urban park and green roof study is that lysimeters at the park were integrated into the soil so that the soil vegetation monolith measured was flush with the surrounding surface, ensuring it was under the same atmospheric boundary conditions as the surroundings. This is a challenge for green roofs where it is not usually possible to recess the lysimeter into the roof structure. Implementation of a lysimeter approach on a green roof thus necessitates raising all or part of the green roof modules. Where only a portion of the modules are raised, such as in DiGiovanni et al. (2010), inhomogeneity is created relative to the surroundings. A more sound approach would be to raise the entire green roof and have a low slope symmetrical surrounding portion with vegetation transitioning to a lower green roof.

### 2.5.2 Limitations of Other Green Roof Latent Heat Flux Measurement Techniques

Other techniques to measure green roof $Q_E$ include eddy covariance (Heusinger and Weber, 2017), chamber methods (Coutts et al., 2013), soil moisture approximations (Takebayashi and Moriyama, 2007) and Bowen ratio methods (Jim and He, 2010). Each of these has their limitations. Both eddy covariance and Bowen ratio techniques are limited to large extensive areas which would limit their application to large green roofs such as in Heusinger and Weber (2017). Soil moisture approximations have an underlying assumption that moisture loss from a point measurements is only due to surface losses and that no redistribution
of water occurs in the subsurface. Chamber methods require isolating the measurement surface from the overlying atmosphere and are often limited to short term measurements. As shown in the following sections, for continuous, long-term (months) $Q_E$ measurements of a modular green roof, lysimetry is a suitable approach.

### 2.5.3 Advantages of Lysimetry on a Modular Green Roof

Previous studies using lysimetry on green roofs that used a separate fully exposed tray above the roof (e.g., DiGiovanni et al., 2010) have had limitations on representativeness because the lysimeters do not experience the same atmospheric boundary conditions as the surrounding green roof. The current study eliminates this issue by using an elevated array and placing the lysimeter system beneath the green roof such that measured module is at the same elevation as that of those in the surrounding green roof test array (Fig. 2.2). Another general limitation with small lysimeters is that isolating substrate and plants might induce drying out of the container greater than that of the surroundings, thus limiting the ability to make long term measurements (Spronken-Smith et al., 2000). For a modular green roof, this is not an issue since the substrate is already separated into containers by design.

### 2.5.4 Errors in Lysimetry on a Modular Green Roof

Previous quantification of measurement error from lysimeters for determining the latent heat flux have identified the following as sources of measurement error: (1) evaporation is not representative of surroundings, (2) lysimeter surface area is different from the evaporating plant canopy, (3) the gap between lysimeter and surrounds increases turbulence (and therefore latent heat flux), and (4) mechanics and electronics (Grimmond et al., 1992). Here, the modular design leads to lysimeter modules being similar to the surroundings. To ensure a representative evaporative area, vegetation growth on lysimeters and adjacent modules were manually trimmed. This also ensured that interaction with sur-
rounding plants did not interfere with weight measurements and did not impede vertical growth, which remained similar to the surrounding green roof. A gap of <2 cm between the lysimeter module and surroundings was found to be sufficient to prevent interaction between plants while minimizing the surface discontinuity.

Error from lysimeters used in this study was primarily attributed to mechanics and electronics of the weighing system, including sensitivity of the lysimeter to the environmental effects of wind, vibrations and temperature variations on the weighing system. An estimate of the error based on manufacturer specifications for the load cell suggest an error in $Q_E$ of 39 W m$^{-2}$. This is similar to the measurement error for the lysimeter setup calculated in Grimmond et al. (1992) using an Interface Inc. SPI 50 Load Cell.

2.5.5 Noise in Lysimeter Signal

Lysimeter data exhibited noise at resolutions of 1 min and 5 min, likely due to mechanical turbulence induced by wind (Fig. 2.6) and roof vibrations; the latter was observed in tests where the lysimeter output was monitored while a researcher deliberately walked around the roof. Turbulence is approximately random and can be averaged at time scales of 30 min to 1 hour (Stull, 1988). Previous studies utilizing continuously weighed mini lysimeters have used 1 hour averages, presumably to average out the sensitivity of load cells in the environment to the random mechanical forces exerted from wind (i.e. turbulence). Using wind speed and wind direction standard deviation (SD) as an indication of turbulence, it can be seen that there is a relation of both wind speed and wind direction SD to the lysimeter noise (Fig. 2.6). Lysimeter noise was characterized with relative standard error (RSE). Regression techniques were not employed to quantify the relationships since these wind speed and wind direction SD are only rough indications and not direct measures of surface level turbulence. Additional noise may arise due to vibrations from the roof itself. Explicit testing could quantify the noise that can be attributed to turbulence instead of other variables such as roof vibrations; however, all roof level processes influencing the lysimeter were expected to be high frequency and approximately random in nature, and assumed to
not influence an hourly average. An exception is transient forces from wildlife or debris in the wind that may cause unbalanced extreme readings that incorrectly bias an average, and must therefore be removed. The use of robust methods automatically aggregate data without the influence of extreme values. The current study utilized a second order robust local regression to achieve this via the *rloess* function in MATLAB (2016). Dewfall and freewater evaporation are $Q_E$ phenomena of interest that occur at the shortest time scales and were therefore used as a measure of the resolution capability of using hourly lysimeter values. Both dewfall and freewater evaporation could clearly be observed using hourly lysimeter values (Fig. 2.7). As expected during dewfall (negative $Q_E$), all four replicates showed a negative value only when the leaf wetness sensor LWS increased, indicating the onset of dewfall. Decline in the LWS value, indicated evaporation of the dew. Since evaporation occurs from free water suspended on the sensor and plants, this is referred to as freewater evaporation. Three of the four replicates showed an increased $Q_E$ value during freewater evaporation and a subsequent leveling off as the LWS indicated the end of free water evaporation. The variability seen in the lysimeters highlights the importance of having replicate measurements in order to represent the processes of the entire green roof. This variability is explored in the subsequent sections.

### 2.5.6 Systematic Variability in Replicate Lysimeters

Lysimetry is a point measurement. To increase spatial representativeness and assess long term random variability in the measurement system, four replicate lysimeters were used at different positions on the green roof (Fig. 2.1). Replicate lysimeters show systematic diurnal differences (>10%) throughout the entire dataset (Fig. 2.5), suggesting that either there are long term systematic deviations in the lysimeter measurement system between replicates, or that sample modules behave differently from one another and are therefore inherently different. The former is unlikely since an assessment of long term calibration repeatability (detailed in the following section) revealed only small differences in slope (<1%) that could not account for the larger variability (>10%) seen between replicates.
This suggests that the systematic differences in $Q_E$ seen between lysimeter modules result from differences in the individual modules on the green roof.
Figure 2.5: Departure of latent heat flux of individual lysimeter modules from median against the median latent heat flux by hour of day for London, 2014. N=116 (hourly per lysimeter; days). Thick line indicates slope significantly different from 0 (p<0.05) using robust linear regression.
2.5.7 Lysimeter Measurement Repeatability through Time

The measurement repeatability of the lysimeter systems was assessed by taking the average of multiple calibrations throughout the measurement period. Additional calibrations were performed in 2016 to assess the long term performance of lysimeters. For a detailed list of calibrations, refer to Appendix B. In the calculation of $Q_E$ (refer to Eq. 2.20) only the change in weight— and not the absolute magnitude— is important, thus only the slope is relevant for consideration for assessing measurement in $Q_E$. The relative standard error of the slope from the applied mean was 0.3% to 0.5%, indicating consistency of the measurement system through time. This corresponds to a measurement system error of 2.5 W m$^{-2}$ if taken as the error from the measurement system alone over an hour near the expected upper limit of $Q_E$ of 500 W m$^{-2}$.

2.5.8 Total Module Volumetric Water Content

For comparison with other studies—such as Heusinger and Weber (2017)—and to generalize measurements from the four lysimeters to the entire green roof, it was desirable to express the weight of the four modules in terms of a total water content. A soil moisture probe placed inside the same module as the heat flux plate was used to correlate the weight measurements to volumetric water content. There was a strong linear relationship (Fig. 2.8) between the lysimeter weights and volumetric water content from the soil moisture probe. Hysteretic behaviour in the regression was observed, likely due to the fact that the soil moisture probe captures a point measurement of diurnal changes in local water content in the vicinity of the probe. Overall, there is a good linear fit for all four lysimeter modules. Notably, module NW had a much lower weight than the other three but still had a relationship to the water content measurement consistent with the other three modules. This fit was used in all subsequent analysis, and all lysimeter weights were expressed as total module volumetric water content.
Figure 2.6: Relative standard deviation (RSD) of lysimeter module weight against wind speed and wind direction standard deviation 2016. Data from July 2016, N=8435. Standard deviation of 5 minute data with sampling interval of 1 second.
2.5. **Latent Heat Flux**

Figure 2.7: Lysimeter response to dewfall and freewater evaporation.

LWS—leaf wetness sensor, increase from baseline value indicates dewfall, decrease from peak indicates freewater evaporation. London 2014.
Figure 2.8: Regressions of lysimeter weight to volumetric water content using 4 lysimeter modules and 1 water content probe. Slopes represent rate of change in VWC with a change in lysimeter module weights. NW module was lower weight overall than other lysimeter modules.
2.6 Chapter Summary

This chapter presented the green roof setup and the methods used to determine each of the radiation and SEB fluxes. Estimates of their errors were also provided. It was established that lysimeters were a logical and effective technique for $Q_E$ measurement on a typical size green roof, and their performance was quantified. An average of $Q_E$ from the four lysimeters was taken. Significant differences were found in $Q_E$ between the four green roof modules measured, indicating a potential for improving green roof design to maximize $Q_E$. The next chapter used the SEB method to assess the temporal variations in SEB during summer drying periods.
Chapter 3

Study Results and Discussion: Time Varying Energy Balance Fluxes

This chapter presents one of the key study results: the time varying energy balance of the green roof test array during the 2014 growing season in London, Ontario. The chapter begins with a description of the weather, plants through the growing season, and the definition of drying periods. This is followed by aggregate summaries of datasets describing the energy balance during these drying periods, and then by a detailed look at the time varying energy balance of five long drying periods and their relation to water content. The aggregate summaries presented include: the diurnal clear sky ensemble energy balance, the daytime integrated evaporative flux ratio (EFR) and Bowen ratio ($\beta = \frac{Q_E}{Q^* - Q_G}$), the daytime and maximum daytime descriptive statistics of the hourly green roof SEB fluxes, the daytime integrated energy balances by month, and the daytime integrated relative SEB fluxes by month.

3.1 2014 Study Period

The study period extends from the beginning of April to the end of October, 2014. The general climate, moisture and plant conditions for the study period is shown in Fig. 3.1.
Temperatures sometimes dipped below freezing and frost was observed in the early morning periods for some days in April and May and near freezing temperatures occurred at the end of September. Sub-zero temperatures and frost complicate energy balance measurements by affecting the instrumentation and methods used. More importantly, these conditions were not the focus of this study, and therefore all periods where air, surface, or substrate temperatures dropped below 0°C were excluded from analysis. For the analysis of time varying energy balances, the effective study period examined drying periods from mid-May to the end of September. In 2014, daily temperature and monthly precipitation totals for London were fairly close to the 30-year climate normals for April, May June, July and October. However, August and September were atypical. In August, precipitation was lower than normal, while September was characterized by lower temperatures and much higher than normal rainfall.
Figure 3.1: Overview of data collection period: April 1, 2014 to October 31, 2014. All values shown are hourly. Water content not shown during rain or drainage. Trend in plant height and plant density interpolated with spline for clarity. DOY shown under plant images.
3.1. **2014 Study Period**

Figure 3.2: London 2014 temperature and precipitation compared to climate normals (1981-2010).
3.2 Plant Growth

The height and density of *Sedum spurium* was estimated through manual measurements and samples as detailed in Lundholm et al. (2014). There is no direct physical basis for plant height and plant growth to be related to transpiration which occurs through leaves. Because of this inability to relate the plant growth to the physically intuitive leaf area index (LAI), measures of plant growth were limited descriptive use and were not used for quantitative analysis. Through April (DOY 91 to 120), the *Sedum spurium* canopy was beginning to come out of winter dormancy and grow. Plant density continued to increase through May (DOY 121-152), reaching their maximum density near the end of May. In June (DOY 153-185), the *Sedum spurium* canopy began to flower, during which the plant density decreased but the height increased, with the maximum height being reached in late-June. The flowered state persisted through July (DOY 182-212) but began to transition to a state where the flowers died while remaining a part of the plant as a brown mass. Through August (DOY 213-243) the dead flower mass persisted while the *Sedum spurium* leaf growth increased at the beginning of August and then declined through the rest of the month. In September (DOY 244-273) and October (DOY 274-304), the plant height and density continued to decline. By the end of October, the plant density had decreased to a level comparable to the start of the season, but the plant height had only decreased to a level comparable to that of early-June since the dead flowering stocks had still largely persisted.

3.3 Drying Periods

Periods of drying are of interest because under clear weather conditions, the energy balance terms are higher in magnitude and changes in the relative partitioning of energy among the terms of the energy balance are expected to take place. Of particular interest are periods of extended drying when water becomes limiting over time. These periods allow the influence of water content on the surface energy balance to be assessed. The season was classified into drying periods of different length based on consecutive hours with less than 2 mm of
3.3. **Drying Periods**

Rain. Short drying periods were classified as 2 to 7 days in length and long drying periods were classified as more than 7 days. Energy balances were not calculated during rainy periods. Radiation measurements are subject to errors while instrument domes are wet and lysimeter measurements must take into account drainage from the module, the uncertainty for which is too large to be considered viable at hourly time scales. Energy balances during rain are generally known to be low in magnitude and therefore of little interest in the context of green roof cooling. Drying periods of different length are identified in Fig.3.3. Five long drying periods occur during the study period: two in late-May to early-June and the others at the end of August and September. Each of these five long drying periods started with high water content that declined over several days with only small amounts of intermittent rain. Importantly, the first long drying period was extreme in both its starting and ending water content, and the second drying period reached the driest growing media conditions of the season.
Figure 3.3: Drying periods defined within the study period (London Green Roof, May 21 to September 30, 2014). Red - long drying periods (>7 days). Yellow - short drying periods (2-7 days). Drying periods overlaid on Fig. 3.1.
3.4 Aggregate Energy Balance Summary

In this section, the green roof energy balance is summarized on different temporal scales. These summaries utilize days from all of the drying periods. Summaries begin with the diurnal clear sky energy balance and the associated aggregated clear sky daytime integrated EFR and flux ratios. This provides an overall picture of the expected green roof energy balance under conditions when the radiative forcing is greatest and thus individual SEB components and their flux ratios are most easily distinguished. This is followed by summaries of hourly flux density (units of W m$^{-2}$) and aggregated daytime integrated totals, which are then further grouped into integrated totals and the monthly ratios thereof. These summaries serve as a useful tool to evaluate green roof energy balance models. General insights from the summaries are drawn and comparisons are made to other studies where possible.

3.4.1 Clear Sky Ensemble Energy Balance

The hourly ensemble energy balance for clear sky days is shown in Fig. 3.4. Clear sky days were defined as days with integrated incoming solar radiation $K_\downarrow$ within 2 MJ m$^{-2}$ d$^{-1}$ of $K_\downarrow$ from the Bird and Hulstrom (1981) clear sky model. The maximum of $Q_G$ lags that of $Q^*$ and has little variability. This lagged response in maximum $Q_G$ relative to maximum $Q^*$ is similar to the pattern observed for urban lawn surfaces in Oke (1979) and Suckling (1980). $Q_E$ – and by virtue of being a residual – $Q_H$, have more variability, but in general $Q_E$ is flatter through the mid-day period with substantial variability depending on the day. Considering just the ensemble means, $Q_E$ increases earlier and decreases later than $Q_H$, and $Q_H$ overtakes $Q_E$ at 8 EST and falls below $Q_E$ at 18 EST. The consistent maintenance of positive $Q_E$ from 19 to 22 EST when $Q^*$ is most negative is similar to the results for an urban park (Oke, 1979) and suburban lawn (Suckling, 1980). Since $Q_G$ during these times is low in magnitude, the energy supplied for this process is drawn from a negative $Q_H$. A similar pattern was noted in a direct measurement of convective fluxes through eddy
covariance on a green roof (Heusinger and Weber, 2017).

Figure 3.4: Clear sky ensemble energy balance. London Green Roof, May 21 to September 30, 2014. Solid lines are means, shaded region are standard deviations.
The daytime integrated EFR and Bowen ratio for the 30 clear sky days from all of the drying periods are summarized in Fig. 3.5. The EFR $\frac{Q_e}{(Q_r - Q_c)}$ median value for clear sky days was found to be $\sim 0.33$; or in other words, about a third of the available energy was partitioned into the latent heat flux. This corresponds to a median $\beta$ of $\sim 2$. The first and third quartiles for EFR were $\sim 0.26$ to $0.38$, respectively. The corresponding $\beta$ for the first and third quartile was $\sim 1.8$ to $2.9$, respectively. $\beta$ values $<1$, which indicates more latent heating than sensible heating, are rare, and accounted for less than a quarter of the dataset. The wide variability in extremes is exemplified in the outlying values in which daytime EFR of greater than $0.6$ ($\beta < 0.7$), as well as $\beta$ above $5$ were observed. These are daytime integrated values that provide information about the total effect over a daytime period; however, it is important to note that individual hours could vary. The values for $\beta$ reported here are lower than those found in Heusinger and Weber (2017), who found a mean daytime $\beta$ of $2$, which rose to $10$ for hot days. The difference might be explained by their drying periods almost always having a volumetric water content $VWC$ below $0.2$ and usually below $0.15$, in stark contrast to the minimum $VWC$ of $0.16$ in the present study. This again reaffirms that regional context of studies must be considered when using aggregate energy balance summaries.
Figure 3.5: Daytime integrated EFR and Bowen ratio for clear sky days. Box contains 25% to 75% percentiles, whiskers represent $1.5 \times$ IQR. Number of days = 30. London Green Roof, May 21 to September 30, 2014.
3.4. Aggregate Energy Balance Summary

3.4.2 Hourly Daytime Energy Balance

The hourly daytime energy balance fluxes during all drying periods, short and long, are summarized with descriptive statistics in Table 3.1. Daytime $Q^\ast$ for the drying periods ranged from $-68 \text{ W m}^{-2}$ to $764 \text{ W m}^{-2}$ with an hourly average over all daytime drying periods of $308 \text{ W m}^{-2}$. This is similar to the summertime daytime average found by Heusinger and Weber (2017). Unlike their study, however, the mean $Q_E$ in the current study was $114 \text{ W m}^{-2}$, over twice as high as their summertime $Q_E$. The maximum observed $Q_E$ was also over 70% larger in the current study compared to that reported in Heusinger and Weber (2017), which illustrates the importance of location to variability in $Q_E$ and shows that the current study has higher experimental variability despite being a smaller dataset. $Q_G$ was low with an average of $15 \text{ W m}^{-2}$ and a maximum of $71 \text{ W m}^{-2}$. Water content was variable, ranging from 0.16 to 0.32 with an average of 0.24.

Table 3.1: Descriptive statistics of daytime ($K \downarrow > 0$) energy balance during all drying periods. London Green Roof, May 21 to September 30, 2014.

<table>
<thead>
<tr>
<th></th>
<th>$Q^\ast$ (W m$^{-2}$)</th>
<th>$Q_E$ (W m$^{-2}$)</th>
<th>$Q_H$ (W m$^{-2}$)</th>
<th>$Q_G$ (W m$^{-2}$)</th>
<th>VWC (m$^3$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-68</td>
<td>-13</td>
<td>-97</td>
<td>-25</td>
<td>0.16</td>
</tr>
<tr>
<td>Median</td>
<td>308</td>
<td>105</td>
<td>157</td>
<td>12</td>
<td>0.25</td>
</tr>
<tr>
<td>Mean</td>
<td>307</td>
<td>114</td>
<td>178</td>
<td>15</td>
<td>0.24</td>
</tr>
<tr>
<td>Max</td>
<td>764</td>
<td>502</td>
<td>589</td>
<td>71</td>
<td>0.32</td>
</tr>
<tr>
<td>SD</td>
<td>232</td>
<td>80</td>
<td>168</td>
<td>20</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Sample size=1199
3.4.3 Maximum Daytime Energy Balance

A summary of the daytime maximum SEB values (based on hourly values) for all drying periods is provided in Table 3.2. Maximum SEB values complement the hourly summaries provided in Table 3.1 by capturing only variation between days. Considering the average of daytime maximum SEB values over the study period (n=100 days): $Q^*$ was $617 \pm 103 \text{ W m}^{-2}$, $Q_E$ was $192 \pm 79 \text{ W m}^{-2}$, $Q_H$ was $406 \pm 103 \text{ W m}^{-2}$, and $Q_G$ was $42 \pm 14 \text{ W m}^{-2}$. The the average of daytime maximum volumetric water content $VWC$ during this time was 0.25. These averages for $Q^*$, $Q_E$, $Q_H$, and $Q_G$ were 310 W m$^{-2}$ or 101%, 78 W m$^{-2}$ or 68%, 228 W m$^{-2}$ or 128%, and 27 W m$^{-2}$ or 180% greater than the mean hourly values respectively. The smaller difference between the hourly daytime average and daytime maximum values for $Q_E$ relative to the other SEB fluxes is indicative of a less pronounced maximum value, as observed in Fig. 3.4 for clear sky periods.

Table 3.2: Descriptive statistics of maximum daytime ($K \downarrow > 0$) energy balance during all drying periods. London Green Roof, May 21 to September 30, 2014.

<table>
<thead>
<tr>
<th></th>
<th>$Q^*$ (W m$^{-2}$)</th>
<th>$Q_E$ (W m$^{-2}$)</th>
<th>$Q_H$ (W m$^{-2}$)</th>
<th>$Q_G$ (W m$^{-2}$)</th>
<th>$VWC$ (m$^3$ m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>245</td>
<td>55</td>
<td>119</td>
<td>11</td>
<td>0.16</td>
</tr>
<tr>
<td>Median</td>
<td>637</td>
<td>183</td>
<td>411</td>
<td>44</td>
<td>0.26</td>
</tr>
<tr>
<td>Mean</td>
<td>617</td>
<td>192</td>
<td>406</td>
<td>42</td>
<td>0.25</td>
</tr>
<tr>
<td>Max</td>
<td>764</td>
<td>502</td>
<td>589</td>
<td>71</td>
<td>0.32</td>
</tr>
<tr>
<td>SD</td>
<td>103</td>
<td>79</td>
<td>103</td>
<td>14</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Sample size=100
3.4. Aggregate Energy Balance Summary

3.4.4 Daytime Integrated Energy Balance

The daytime integrated energy balance for all drying periods is presented in Fig. 3.6. This provides a summary of the typical total for SEB fluxes over daytime periods in a growing season and their variability. This information is valuable for modelers to evaluate model outputs of daytime green roof energy balance performance over a growing season, especially for temperate mid-latitudes climates similar to the climate of this study. Fig. 3.7 shows a median $Q^*$ of $< 15 \text{ MJ m}^{-2} \text{ d}^{-1}$, $Q_E$ of $\sim 5 \text{ MJ m}^{-2} \text{ d}^{-1}$, $Q_H$ of $\sim 8 \text{ MJ m}^{-2} \text{ d}^{-1}$ and $Q_G$ of $\sim 2 \text{ MJ m}^{-2} \text{ d}^{-1}$. As with the summaries in the previous section, the $Q_E$ is less than $Q_H$ with $Q_G$ being low and nearly invariant.

Figure 3.6: Daytime integrated energy balance fluxes. Box contains 25% to 75% percentiles, whiskers represent $1.5 \times \text{IQR}$. Number of days = 96. London Green Roof, May 21 to September 30, 2014.
In order to statistically compare the daytime integrated flux density of the three energy balance terms ($Q_E$, $Q_H$, and $Q_G$), the statistical software R (R Core Team, 2016) was used to perform a bootstrap one-way 20% trimmed mean ANOVA using the function `t1waybt` in the package Mair et al. (2016), as detailed in Wilcox (2012a). This test was to account for variability in the distribution of the SEB data that invalidated a classical one-way ANOVA. There was a significant difference among the three fluxes ($p<0.01$). A post hoc pairwise comparison performed using the `mcppb20` function in Mair et al. (2016) revealed a significant difference ($p<0.01$) in integrated daytime energy flux density between all pairwise comparisons of $Q_E$, $Q_H$, and $Q_G$ such that $Q_H > Q_E > Q_G$.

### 3.4.5 Monthly Daytime Integrated Energy Balance and Flux Ratios

Monthly daytime integrated flux are shown in Fig.3.7. Monthly integrated fluxes ratios, normalized by $Q^*$, are shown in Fig. 3.8. $Q^*$ is site-specific and limits the generalization of the flux magnitudes to sites with similar weather conditions. In fact, all of the energy balance terms in Fig.3.7 are absolute values and are therefore site-specific. This is important to consider when applying these results in a model evaluation framework or comparing between studies. For example, $Q^*$ in Heusinger and Weber (2017) is one-third less than that observed in London during the summer of 2014, and $Q_G$ is generally a small fraction for vegetated surfaces. $Q^*$ is nevertheless an important component of the energy balance. Fig. 3.7 provides an overview of the typical values and variability of the SEB terms by month and through time between months.

Fig. 3.7 shows that median $Q^*$ decreased from 18 MJ m$^{-2}$ d$^{-1}$ in May to $<15$ MJ m$^{-2}$ d$^{-1}$ in September with July and August values being closer to September values and June values being closer to May values. As seen in all previous metrics, $Q_G$ is small, and it is also relatively invariant through time. An interesting pattern is observed in the relationship between $Q_E$ and $Q_H$: in May, they were of similar magnitude, but diverge thereafter, with $Q_H$ increasing relative to $Q_E$. A similar trend can be observed in the relative integrated fluxes shown in Fig. 3.8.
3.4. Aggregate Energy Balance Summary

In order to statistically test if there was a correlation in the daytime integrated flux density of each energy balance term ($Q^*$, $Q_E$, $Q_H$, $Q_G$) and the month of the growing season (May, June, July, Aug, Sept), a robust correlation procedure, the percentage bend correlation described in Wilcox (2012b), was implemented in R (R Core Team, 2016) using the `pball` function in the package by Mair et al. (2016). This procedure was used instead of a standard Pearson correlation since it better accounted for influential points present in the data. A significant correlation was found for $Q^*$ ($p<0.01$) and $Q_E$ ($p<0.01$), but not for $Q_G$ ($p>0.9$) or $Q_H$ ($p>0.2$). A slope of $\sim-0.3$ for $Q^*$ and $\sim-0.1$ for $Q_E$ indicated an overall decrease in $Q^*$ by month in the growing season and a slower decrease in $Q_E$. Repeating the procedure for the relative fluxes ($Q_E/Q^*$, $Q_H/Q^*$, $Q_G/Q^*$) yielded a significant correlation for each of the relative fluxes with time. The slopes of each of $Q_E/Q^*$, $Q_H/Q^*$, and $Q_G/Q^*$ were less than $\sim-0.23$, $\sim0.19$, and $\sim0.23$. Here $Q_E/Q^*$ decreased significantly through the growing season at a rate of 22% per month. $Q_G/Q^*$ and $Q_H/Q^*$ increased significantly through the growing season. It is important to note that the magnitude of $Q_G/Q^*$ remained an order of magnitude lower than the other relative fluxes. To normalize the influence of $Q_G$ in addition to $Q^*$, $Q_E$ and $Q_H$ were expressed as a fraction of the available energy ($Q^*-Q_G$). Repeating the correlation significance testing procedure once more, we see that $Q_E/(Q^*-Q_G)$ decreases significantly ($p<0.01$) through the growing season and a significant ($p<0.01$) increase in $Q_H$. From visual inspection of Fig. 3.7 and 3.8 it appears that $Q_E$, $Q_H$ and their respective relative fluxes are more different in May than for the other months. Excluding May from the previous analysis yielded a significant decrease in $Q_H$ through the growing season and no significant difference in $Q_E/Q^*$, $Q_H/Q^*$, $Q_E/(Q^*-Q_G)$, or $Q_H/(Q^*-Q_G)$ through the growing season on a monthly basis. This analysis suggests that the SEB values in May were atypical. This uncharacteristic period is further explored in the next section.
Figure 3.7: Daytime integrated energy balance fluxes by month. Box contains 25% to 75% percentiles, whiskers represent $1.5 \times$ IQR. Number of days = 96. London Green Roof, May 21 to September 30, 2014.
3.4. Aggregate Energy Balance Summary

Figure 3.8: Daytime integrated energy balance fluxes ratios by month. Box contains 25% to 75% percentiles, whiskers represent 1.5 × IQR. Number of days = 96. London Green Roof, May 21 to September 30, 2014.
3.5 Time Varying Energy Balances During Long Drying Periods

There were five drying periods of seven or more consecutive days with less than 2mm of rain. The objective of this section is to identify patterns in the evolution of the energy balance as the green roof dries for extended periods of time after a large rain event. It was expected that as water content decreased in a drying period, the $Q_E$ would also decrease. The energy balance during each of these drying periods and the influence of water content are presented here. In addition to water content, the nuances of dew and rain on the green roof energy balance are also discussed. The drying periods are presented sequentially with a description and discussion, followed by an overall discussion of all drying periods.

3.5.1 Results: Drying Period 1

Drying period 1 refers to the May 21 to June 2 (DOY 141 to 153) period inclusive, which occurred early in the growing season. Water content during the drying period starts high (>0.3) and declined throughout the drying period (low of 0.16). The ground heat flux $Q_G$ remained low throughout the drying period (<100 W m$^{-2}$ on an hourly basis). The first three days were cloudy and water content changed little. The latent heat $Q_E$ accounted for approximately half of net radiation $Q^*$ during the first three days. For the remainder of the drying period, daily maximum $Q^*$ remained high at up to or greater than 700 W m$^{-2}$. From DOY 144 to 146 inclusive, daily maximum $Q_E$ was high (>400 W m$^{-2}$) and increased even further (>500 W m$^{-2}$), an increase from ~ 50% to ~ 70% of the partitioned $Q^*$. Water content during these three days decreased rapidly from ~ 0.3% to ~ 0.23% m$^{-3}$. The two days that followed, DOY 147 to 148 inclusive, were cloudy; daily maximum $Q_E$ during these two days dropped slightly to ~ 350 W m$^{-2}$ while water content dropped to ~ 0.2. For the remaining five days, DOY 149 to DOY 153, maximum $Q_E$ was low (~ 200 W m$^{-2}$) at the start of the five day period and decreased throughout to ~ 50 W m$^{-2}$. The daily maximum $Q_E$ during these last five days of the drying period preceded the time
of maximum $K_\downarrow$ and decreased thereafter with mid-day values of $< 100$ W m$^{-2}$. The water content during the last 5 days decreased from $\sim 0.2$ to $\sim 0.16$.

There was dew or light rain during 8 of the 12 nights (on nights of DOY 142, 143, 144, 145, 147, 148, 150, and 150).

The occurrence of maximum $Q_E$ prior to mid-day on the last five days of the drying period occurred irrespective of night-time dew or rain. This suggests that the maximum is not a result of free-water evaporation and during these dry, low $Q_E$ periods the maximum $Q_E$ occurred prior to mid-day for other reasons. A possible explanation could be control from the plants during water limited conditions in bringing water to the surface for transpiration.

To effectively compare $Q_E$ in relation to the other SEB fluxes and between days, the hourly EFR $Q_E/(Q^* - Q_G)$ was compared to $VWC$. For clarity, only periods with $(Q^* - Q_G)$ of at least 100 W m$^{-2}$ were used since smaller values of available energy introduce too much noise in the fraction and are not practically meaningful as a measure of green roof climate performance.
Figure 3.9: Time varying energy balance during drying period 1. London Green Roof May 21 to June 2, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.5.2 Results: Drying Period 2

Drying period 2 was early in the growing season from June 3 to June 11 (DOY 154 to 162) inclusive and immediately followed drying period 1. A rain event replenished water content from \( \sim 0.16 \text{ m}^3 \text{ m}^{-3} \) at the end of the previous drying event to \( \sim 0.23 \text{ m}^3 \text{ m}^{-3} \). Rain or dew occurred during the night-time of DOY 155, 156, 158, 160, 161, and 162. DOY 154, 156, 157, 158, 160, and 161 had high maximum \( Q^* \), up to and greater than 700 W m\(^{-2}\). DOY 155, 159, and 162 were cloudy with mean \( Q^* \) less than 400 W m\(^{-2}\). For the first day (DOY 154), maximum \( Q_E \) was high, with peak values just under 400 W m\(^{-2}\), nearly half of \( Q^* \). On the second day (DOY 155) \( Q_E \) was < 200 W m\(^{-2}\) and represented the majority of the partitioned \( Q^* \). \( Q_E \) on the third day of the drying period (DOY 156) was similar to the previous day and water content decreased from \( \sim 0.19 \) to \( \sim 0.18 \). DOY 157 to 158 inclusive had maximum \( Q_E \) of > 100 W m\(^{-2}\) prior to mid-day that decreased thereafter to < 100 W m\(^{-2}\). DOY 159 had mid-day drizzle, and water content by the end of the day was less than 0.17. \( Q_E \) on DOY 160 and 161 was less than 100 W m\(^{-2}\) with the maximum occurring prior to mid-day and decreasing thereafter. Rain occurred the night of DOY 162 and daytime \( Q_E \) peaked at greater than 100 W m\(^{-2}\) prior to mid-day then decreased to less than 50 W m\(^{-2}\).
Figure 3.10: Time varying energy balance during drying period 2. London Green Roof June 3 to June 11, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.5.3 Results: Drying Period 3

Drying period 3 was late in the growing season from Aug 22 to Sept 4 (DOY 234 to 244) inclusive. DOY 237, 239, 240, 241 and 242 were clear sky or mostly clear sky with up to 700 W m$^{-2}$ and a consistent $Q_E$ of $\sim$ 200. DOY 235, 236 and 244 were cloudy with mean low zenith $Q^*$ of 400 to 500 W m$^{-2}$ and maximum $Q_E$ of 150 W m$^{-2}$ or greater. Maximum $Q_E$ was aligned with those of $Q^*$. The water content deceased from $\sim$ 0.28 to $\sim$ 0.21. A small rain event during DOY 238 replenished the night-time water content on DOY 239 to a level approximately equivalent to the night prior. Nighttime rain or dew occurred on DOY 235, 236, 237, 238, 240, 241, and 244.

The relative partitioning of $Q^*$ into $Q_E$ was fairly consistent throughout the drying period despite water content continually decreasing.
Figure 3.11: Time varying energy balance during drying period 3, London Green Roof Aug 22 to Sept 4, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.5.4 Results: Drying Periods 4 and 5

Drying periods 4 and 5 occurred towards the end of the growing season from September 13 to Sept 21 (DOY 256 to 264) for drying period 4 and from September 21 to September 30 (DOY 264 to 273) for drying period 5. DOY 259 to 263 inclusive had maximum $Q^*$ of $\sim 600$ W m$^{-2}$ and mid-day $Q_E$ of 150 W m$^{-2}$ to greater than 200 W m$^{-2}$. DOY 257 had $Q^*$ of less than 500 W m$^{-2}$ with $Q_E$ greater than 100 W m$^{-2}$. DOY 258 was rainy and the water content at the start of DOY 259 rose to a level approximately equivalent to that at the start of the drying period. The water content during the drying period decreased from $\sim 0.31$ to $\sim 0.27$. The relative partitioning of $Q^*$ into $Q_E$ remained fairly constant throughout the drying period. For drying period 5, DOY 266 to 273 had $Q^*$ 500 to 600 W m$^{-2}$ with $Q_E$ greater than 150 W m$^{-2}$. DOY 264 had a high maximum $Q^*$ of approximately 700 W m$^{-2}$ and $Q_E$ was less than 200 W m$^{-2}$. DOY 265 was cloudy with mean mid-day $Q^*$ less than 300 W m$^{-2}$. The $Q_E$ was slightly higher immediately following rain at the start of the drying period compared to other days of the drying period with equivalent $Q^*$. Water content decreased from approximately 0.29 to 0.24. $Q_E$ was relatively consistent throughout the drying period on the mostly clear sky days past DOY 266. This consistency persisted even with declining $Q^*$ from DOY 270 to DOY 272. The partitioning of $Q^*$ into $Q_E$ remained a large portion, roughly a quarter to a third, despite decreasing moisture content.
Figure 3.12: Time varying energy balance during drying period 4. London Green Roof September 13 to Sept 21, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.5. Time Varying Energy Balances During Long Drying Periods

Figure 3.13: Time varying energy balance during drying period 5. London Green Roof September 21 to September 30, 2014. Bottom panel: Solid lines are measured values, $Q_E$ is the mean of 4 lysimeters, $Q_H$ is calculated by residual. Shaded regions are estimated uncertainties, $Q_E$ is the standard deviation of 4 lysimeters. Top panel: Line is LWS output, bars are periods of increase.
3.5.5 All Long Drying Periods: Time Varying Energy Balances During Drying Periods

From visual inspection, drying periods 1 and 2 exhibited similar evolution in that $Q_E$ during high $Q^*$ decreased with time and roughly covaried with water content. Drying periods 3, 4, and 5 exhibited similar evolution to each other but different from those of drying periods 1 and 2; maximum $Q_E$ remained largely stable throughout and differences roughly covaried with differences in $Q^*$, independent of water content. A multiple linear regression model of $Q_E$ as a function of $Q^*$ and VWC for the first two drying periods revealed both $Q^*$ and VWC to be significant (p<0.01). The model had an adjusted $R^2$ of 0.92. However, a multiple linear regression model of $Q_E$ as a function of $Q^*$ and VWC for the third, fourth, and fifth drying periods revealed only $Q^*$ to be significant (p<0.01); VWC for these drying periods was not significant (p>0.1). The model had an adjusted $R^2$ of 0.71. The $Q_E$ and $Q^*$ terms in the models were daytime integrated values, while VWC was a daytime average. The \textit{lm} function in R (R Core Team 2016) was used to fit the linear models.

\begin{equation}
\text{Daytime integrated } X = \int_{\text{sunrise}}^{\text{sunset}} X dt \tag{3.1}
\end{equation}

where $X$ is each of $Q_E$ and $Q^*$. The same interval is used for daytime averages.

The model for the first two drying periods was

\begin{equation}
Q_E = 0.473 + 13.5VWC - 9.32VWC^2 + 0.35Q^* \tag{3.2}
\end{equation}

The model for the third to fifth drying periods was

\begin{equation}
Q_E = -0.0365 - 0.45VWC + 0.316Q^* \tag{3.3}
\end{equation}

A simple model could not adequately fit the data from all five drying periods. The presence of two different models for $Q_E$ with very different levels of contributions from VWC for the first two and last three long drying periods confirm what was evident from visual inspection, that the dependence of $Q_E$ is not consistent. This is explored further in section 4.3.
During very dry days that were reached in drying periods 1 and 2, a distinct recurring pattern was observed in which $Q_E$ peaked in the morning and leveled off thereafter. Initially, this pattern appeared to be concurrent with freewater evaporation after night-time dew or rain, however, with closer inspection, the occurrence of this phenomenon was found to occur even in the absence of night-time dew. A multiple linear regression of the $Q_E$ maximum hour as a function of VWC and presence of night-time dew or rain revealed a significant ($p<0.01$) contribution from VWC, but no significant contribution from the presence of night-time dew or rain ($p>0.1$). The model serves as a test of significance, not as a predictive tool. Put another way, the shift in maximum $Q_E$ is an early decrease in $Q_E$ only when VWC is low: from visual inspection of each of the five drying periods, when VWC was less than $\sim 0.22 \text{ m}^3 \text{ m}^{-3}$. This pattern indicates a threshold below which moisture transport to the surface from the subsurface becomes limited or regulated by a plant process. The exact mechanism for the occurrence of this threshold is an area for future research. Water content is discussed further section 4.3 where a relationship is drawn to EFR. The earlier decrease in $Q_E$ prior to noon has implication for urban cooling. Maximum energy demand in the summertime occurs in the late morning to early evening as it is typically the hottest and requires the most energy to cool buildings. These results suggest that if there has been sustained drying to reduce water content below, $\sim 0.18 \text{ m}^3 \text{ m}^{-3}$, green roof cooling would be less effective than usual at the time periods when it is most required for reducing energy use from air conditioning.

### 3.6 Chapter Summary

This chapter summarizes the daytime energy balance during drying periods of a green roof in aggregate form at the following time scales: diurnally, monthly, and for the full summer period using hourly values and daytime integrations of the green roof energy balance fluxes. The mean daytime $Q_E$ was 114 W m$^{-2}$ and the mean daytime maximum for $Q_E$ was 192 W m$^{-2}$. $Q_E$ in the early morning and afternoon was found to be positive even
when $Q^*$ was low or negative. Considering daytime integrations for all drying periods, $Q_H$ was significantly greater than $Q_E$ and both were greater than $Q_G$. Daytime integrated flux ratios were invariant on a monthly basis when excluding the May period. Case studies of specific long drying periods revealed an expected pattern of $Q_E$ decrease in concert with VWC at the beginning of the growing season but an unexpected stability in $Q_E$ for other drying periods. The relationship between VWC and green roof cooling for all drying periods is explored in the following chapter. In spring, during very dry periods with low water content, the diurnal maximum of latent heat occurred in the morning rather than near noon. This behaviour was found to be independent of freewater evaporation after rain or dew, indicating a vegetation restriction of $Q_E$ rather than morning enhancement due to free water evaporation of dew or intercepted rainwater on leaves.
Chapter 4

Surface Controls on Energy Balance Fluxes

This chapter addresses questions 2, 3 and 4; surface controls expected to influence the green roof energy balance, including, albedo, advection, and water content. First the effect of albedo on net radiation is presented using two supplemental years of measurements in addition to the 2014 study period. Next, the possible influence of advection on enhancing $Q_E$, including local advection specific to the current study, is explored. The chapter concludes with an assessment of the influence of water content on green roof cooling using the metric of EFR.

4.1 Albedo

This section addresses the second research question by evaluating the albedo through the growing season using daily integrated albedo measurements over the *Sedum spurium* test array for multiple years. The variability in albedo through time was quantified through its relation to growing degree days. Additional data from 2013 and 2016 were used here along with the 2014 data set.

Albedo is an important determinant of the surface energy balance because it exerts a
strong daytime control on the net shortwave radiation, which is the primary control on daytime net radiation $Q^*$. An increase in albedo increases the reflected shortwave radiation and reduces the net absorbed shortwave radiation $K^*$. The dominance of $K^*$ in daytime $Q^*$ thus results in a decrease of $Q^*$. In contrast, a decrease in albedo increases $Q^*$. Changes to $Q^*$ provide affect the available energy to be partitioned into the other energy balance terms. Energy balance based models of green roof performance (e.g., de Munck et al., 2013) often assume a constant albedo, but a green roof is a dynamic surface that changes its surface properties as the plants undergo changes to their life-cycle stages.
Figure 4.1: Albedo through the growing season for 2013, 2014, and 2016. Albedo values are derived from integrated daytime totals of $K^\uparrow$ and $K^\downarrow$ with zenith angle $>85^\circ$. 
The time series of green roof albedo (Fig. 4.1) show a similar trend in albedo for 2013 and 2014, with 2014 consistently lower during the beginning and end of the growing season. The timing of the highest albedos in all three years is similar and coincides with the flowering of *Sedum spurium*. The range of albedo values observed encompass the values for *Sedum* observed in other studies Lundholm et al. (2015), Monteiro et al. (2017). As found in Monteiro et al. (2017), the albedo decreased overall from one year to the next when considering 2013 and 2014. There was also a difference in the pattern of albedo change near the start and end of the growing season between 2013 and 2014. Albedo in 2013 remained high for the period DOY 140-190 then decreased sharply after flowering, followed by a slight increase towards the end of the growing season (DOY >240). In contrast, albedo in 2014 increased from the beginning of measurements (DOY 100) and exhibits a slight decrease following the steep decline that coincides with the end of the flowering stage. This may be related to the increased height and density of the Sedum spurium canopy in 2014, which results in greater multiple reflections and an increase in canopy shortwave radiation absorption. The increase in plant coverage area also exposes less bare media, which may have also contributed to the deceased albedo, because bare media typically had a higher albedo than *Sedum spurium*.

Albedo measurements in 2016 began later in the growing season (at approximately the time of flowering) and thereafter declined, but at a much slower rate than was observed in 2013 or 2014. Qualitative assessment of the *Sedum spurium* cover and growth in 2016 suggest that canopy coverage and height were less than in the previous years. A lower flowering density and less subsequent brown coloured dead flowering material in the plant canopy, allowed for more exposed green leaves and a less complex canopy with lower multiple reflections. Field observations also noted gaps in *Sedum spurium* coverage that replaced vegetation with higher soil media albedo in the composite measured value.

Albedo values over all years range from ~0.1 to 0.25; a constant albedo value of 0.2 translates into a ~35 W m$^{-2}$ to 65 W m$^{-2}$ error in the calculation of $Q^*$ with an incoming solar radiation range of 500 W m$^{-2}$ to 900 W m$^{-2}$. This should serve as a caution to those
running green roof energy balance models. These results suggest that a time varying albedo may be more appropriate than use of a constant value. The change in overall pattern in 2016 compared to 2013 and 2014 shows that major changes to canopy characteristics can affect the seasonal evolution of the green roof albedo, which may not be consistent between years.

Figure 4.2: Segmented empirical fit of albedo in relation to growing degree days (GDD) for 2013 and 2014. Base temperature for GDD was 10°C.
A segmented linear regression model was fit for albedo in relation to growing degree days for 2013 and 2014, shown in Fig 4.2. Data from 2016 were excluded since it was an anomalous year for plant growth. Growing degree days was defined as:

\[ GDD = \frac{(T_{\text{max}} + T_{\text{min}})}{2} - 10^\circ C \]  

(4.1)
This empirical fit (Fig. 4.2) captures the differences observed through visual inspection for albedo from 2013 to 2014. Assuming conditions similar to this study, this relationship would be representative of green roofs almost a full year following installation (2013) and almost 2 years after installation (2014). The albedo decreases sharply by \( \sim 0.08 \) in both years, from a starting value of \( \sim 0.23 \) in 2013 and \( \sim 0.21 \) in 2014. It can be seen that this sharp decrease occurs from \( \sim 400 \) to \( \sim 700 \) GDDs.

4.2 Advection

This section assesses the potential influence of advectively assisted \( Q_E \) using simple metrics for potential advection. In particular, local advection specific to the siting of the green roof in this study is assessed.

The advection term \( \Delta Q_A \) in the SEB arises as horizontal airflow adjusts to a new set of boundary conditions from spatial heterogeneities in surface characteristics. Urban areas in general are subject to substantial microadvection due to the patchy nature of the urban surface, for example, hot asphalt road that borders an irrigated grass lawn. Any green roof is subject to advection given that it is a ‘new’ surface with likely different surfaces upwind. The green roof used in this study might have further been subject to local roof scale advection because it was a patch within the roofs on which it was situated. That is, the green roof test array did not cover the full extent of the roof surface on which it was constructed. If enhancement of \( Q_E \) occurs due to advection of warmer, drier air from the upwind conventional roof due to the leading edge effect (Oke, 1987), similar to that identified in irrigated urban parks (Spronken-Smith et al., 2000), this might limit the representativeness of the SEB estimates presented in this thesis from those that would be expected for a full green roof.

Fig. 4.3 presents a wind rose for all drying periods during hours with \( Q^* > 100 \text{ W m}^{-2} \) when advection forcing due to strong temperature or moisture differences between the conventional and green roof are expected to be largest. The sector of the wind rose that rep-
represents the longest fetch over the conventional roof that surrounds the green roof test array is highlighted in red. Winds from this sector present the greatest concern for local advection because they have the potential to enhance QE beyond that expected for a green roof covering the entire building roof. Less than 6% of all wind originated from this sector, suggesting the potential for advective enhancement of $Q_E$ is fairly small. To this is added the observation that the conventional roof also often stores significant water following a rain event, which would help mitigate advection of hot dry air over the green roof test array.

![Wind rose for all drying periods during hours with $Q^* > 100$ W m$^{-2}$. Long fetch of roof at the same height as the green roof test array highlighted in red.](image)

Figure 4.3: Wind rose for all drying periods during hours with $Q^* > 100$ W m$^{-2}$. Long fetch of roof at the same height as the green roof test array highlighted in red.
4.2. Advection

Figure 4.4: Identification of possible advection in hourly EFR when $Q^* > 100 \text{ W m}^{-2}$. See text for a description of each case.
Since $\Delta Q_A$ was not measured directly, an assessment of advection was made using four cases when it was likely to occur.

**Case 1** These are times when $\frac{Q_E}{Q^* - Q_G}$ (discussed in more detail in the next section), was greater than 1. In these instances $Q_E$ surpasses the available energy. Since the energy for this enhanced $Q_E$ must come from somewhere, it implies a supply of convective sensible heat $Q_H$ from the atmosphere. Such conditions strongly indicate advection but does not specify local roof level advection from the long fetch of conventional roof.

**Case 2** This case specifies the additional constraint of a near surface temperature inversion, as indicated from near-surface vertical temperature profile measurements using fine-wire thermocouples, to the $\frac{Q_E}{Q^* - Q_G} > 1$ condition of case 1. This provides further evidence for a downward $Q_H$ which would occur to supply energy to the enhanced $Q_E$. This case provides even stronger evidence for advectively enhanced $Q_E$ but, as with Case 1, does not specifically identify local roof scale advection due to the long fetch of conventional roof.

**Case 3** This case identifies periods when winds, as measured from the on-roof anemometer, were from the SSW, the sector containing the long fetch of conventional roof. The criteria for this case was a dry roof along the long fetch of conventional roof, a conventional roof surface temperature $5^\circ$C warmer than the green roof surface temperature, and light wind speeds (less than 3 m s$^{-1}$). The temperature difference between the conventional roof and green roof is of interest since it is under these conditions that a long fetch of conventional roof would likely increase air temperatures beyond the typical surroundings. This could result in a temperature inversion over the green roof and a downward sensible heat flux $Q_H$ on the green roof as hot dry air passes over the relatively cool green roof surface. When the air passing over the green roof is also dry, as it should be when it has passed over the long dry fetch of conventional roof, it also provides a higher moisture gradient. These are favourable conditions
for enhanced $Q_E$. Local roof advection from the long fetch of conventional roof is directly specified in this case.

**Case 4** This case has the same criteria as Case 3 but specifies a roof temperature 20°C higher than the green roof to represent maximum forcing of sensible heating of the upwind air. These are conditions when the conditions for $Q_E$ enhancement from local roof advection are extremely favourable.

Case 1 and Case 2 identify some conditions when an enhancement of $Q_E$ is likely, either from the long fetch of conventional roof or any other wind direction. Case 2 in particular provides strong evidence for enhanced $Q_E$, while Case 1 could contain false identification as a result of small $Q_E$ fluxes. Note that Case 1 and 2 indicate some, but not all times when $Q_E$ was likely enhanced by advection. In contrast, Cases 3 and 4 assess all times when advectively enhanced $Q_E$ was likely, but specifically as a result of the long fetch of conventional roof. All four cases are presented in Fig. 4.4.

It can be seen in Fig. 4.4 that there is little overlap between cases 1 or 2 and cases 3 or 4. As alluded to earlier, all values identified in case 1 or 2 are in the morning or evening and correspond with periods with lower available energy and low magnitudes of $Q_E$. Case 2 provides the most convincing evidence of advection since there is a temperature inversion to support a downward $Q_H$. There is also a slightly higher proportion of possible advection due specifically to the green roof setup, cases 3 and 4, early in the season. This could in part explain the higher $Q_E$ partitioning observed in the previous chapter.

Periods of possible advection were identified with a potential influence on 2.8% of the data evaluated in the following section, from all drying periods and $Q^* > 100 \text{ W m}^{-2}$. There is strong evidence of advection for 1.2% of the data, all in the morning and evening periods with advection enhanced $Q_E$. 
4.3 Water Content

This section addresses objective #5, finding a relationship between EFR and water content. A relationship is found at both the hourly and daytime scale. Three different cases are considered for both the hourly and daytime scale. These cases were chosen since the first two long drying periods were unique as discussed in the previous Chapter, section 3.5.5. $Q^*$ was also found to be an important control on $Q_E$ (Section 3.5.5), so the cases of low and high $Q^*$ are considered in this section, with an emphasis on high $Q^*$.

For the long drying periods at the beginning of the growing season, it was observed that $Q_E$ exhibited a downward trend as time progressed and the green roof became drier. It was also observed that this decrease in $Q_E$ with drying was not the case for the three long drying periods at the end of the growing season. The long drying periods, used as case studies in the previous chapter, occur in the beginning or end of the season with many short drying periods in between. This section includes all of the shorter drying periods as well. In Fig. 4.5, EFR is compared in relation to volumetric water content $VWC$. EFR is the fraction of available energy $Q(E)/(Q^* - Q_G)$ that is partitioned into $Q_E$ and is a measure of green roof climate performance. EFR can be thought of as cooling relative to a hypothetical dry reference surface of identical $Q^*$, in which all available energy is partitioned into $Q_H$. While an exact match of $Q^*$ between the green roof and an associated conventional roof is unlikely, many conventional roofs have daytime $Q^*$ not vastly different from that of a green roof and do not retain water, unless immediately following rain or with dysfunctional roof drainage, and therefore has practically no $Q_E$. $Q^*$ of asphalt, grass, and concrete in study by Santillán-Soto et al. (2015) was found to be similar within $\sim 100$ W m$^{-2}$. A study of $Q^*$ for a "lawn roof" and tar roof was also found to be similar to $\sim 1$ MJ d$^{-1}$ (Jones and Suckling, 1983), and estimated to be within the previously mentioned range on shorter time scales. As noted in section 4.1, the variation in albedo could influence $Q^*$ up to 65 W m$^{-2}$ while $Q^*$ of a conventional roof would be constant. While not perfect, the hypothetical reference roof framework is a reasonable estimate of general daytime relative cooling performance of a green roof over a typical roof. Three subsections of data are specified on Fig. 4.5:
available energy from 100 to 500 W m\(^{-2}\), 500 W m\(^{-2}\) or greater but only for the first two long drying periods, and available energy greater than 500 W m\(^{-2}\) after the second drying period. First, with all hours in which available energy ranges from 100 to 500 W m\(^{-2}\), a pattern emerges in which an increase in VWC is associated with an increase in EFR at low water content but levels off at higher water contents. If we consider only hours with \(Q^*\) greater than 500 W m\(^{-2}\), the scatter in the previous case diminishes and a much clearer relationship is observed between EFR and VWC, at least for dryer conditions. From the previous chapter the first two drying periods showed much higher \(Q_E\) values than the other long drying periods. By subsetting the hourly data greater than 500 W m\(^{-2}\) in Fig. 4.5 into hours after the second drying period, it is evident that drying periods 1 and 2 have uniquely high evaporative cooling capacities at higher water content. There are some hours where the EFR exceeds one, but these all occur when \(Q^*\) is less than 500 W m\(^{-2}\) which coincides with times when cooling may not be of as much importance, and of lower absolute magnitude. This relationship was quantified using both a piece-wise linear regression and second order polynomial regression of EFR by VWC for periods of high \(Q^*\) (greater than 500 W m\(^{-2}\)). For brevity, the distinction between all drying periods and those excluding the first two drying periods shall be referred to hereafter as DP\(_{\text{All}}\) and DP\(_{\text{x1,2}}\) respectively. Similarly, the distinction between piecewise regression and polynomial regression models shall be referred to as M1 and M2 respectively. M1 and M2 for DP\(_{\text{All}}\) and DP\(_{\text{x1,2}}\) correspond for data with \(Q^* > 500\) W m\(^{-2}\). In Fig. 4.6 M1 for DP\(_{\text{All}}\) is visualized as the thick blue dashed line, M2 for DP\(_{\text{All}}\) as the thin blue dashed line, M1 for DP\(_{\text{x1,2}}\) as the thick red dashed line, and M2 for DP\(_{\text{x1,2}}\) as the thin red dashed line. M1 for DP\(_{\text{All}}\) and M1 for DP\(_{\text{x1,2}}\) both had a significant breakpoint (p<0.15) as determined using the Davies test (Davies, 2002) as implemented in the segmented package (Muggeo, 2008) in R (R Core Team, 2016). In other words the addition of a break point significant over a strictly linear model. M2 for DP\(_{\text{All}}\) and M2 for DP\(_{\text{x1,2}}\) performed slightly worse than the corresponding M1. From visual inspection of just the first two drying periods there is an apparent increasing EFR to a critical VWC and a subsequent decrease, as previously described. A model for these
drying periods was provided in the previous chapter for $Q_E$ as a function of $Q^*$ and VWC, and are not shown here for the EFR. The M1 for DP_{All}, M2 for DP_{All}, M1 for DP_{x1,2}, and M2 for DP_{x1,2} for EFR as a function of VWC are provided in Eq. 4.2, Eq. 4.3, Eq. 4.4, and Eq. 4.5 respectively.

\[
\frac{Q_E}{Q^* - Q_G} = \begin{cases} 
-1.1610 + 7.396VWC & \text{for } 0.16 \leq VWC \leq 0.216 \\
0.7378 - 1.406VWC & \text{for } 0.216 \leq VWC \leq 0.32 
\end{cases}
\] (4.2)

\[
\frac{Q_E}{Q^* - Q_G} = -2.597 + 24.332VWC - 49.265VWC^2 \quad \text{for } 0.16 \leq VWC \leq 0.32
\] (4.3)

\[
\frac{Q_E}{Q^* - Q_G} = \begin{cases} 
-0.7126 + 4.890VWC & \text{for } 0.16 \leq VWC \leq 0.223 \\
0.6133 - 1.062VWC & \text{for } 0.223 \leq VWC \leq 0.32
\end{cases}
\] (4.4)

\[
\frac{Q_E}{Q^* - Q_G} = -2.597 + 24.332VWC - 49.265VWC^2 \quad \text{for } 0.16 \leq VWC \leq 0.32
\] (4.5)

These results do not contradict the findings of previous studies such as Coutts et al. (2013) and Heusinger and Weber (2017), but do change the narrative they propose. Coutts et al. (2013) identified that low water contents resulted in lower $Q_E$ and higher water contents in higher $Q_E$, while Heusinger and Weber (2017) offered a relationship of the form $Q_E \propto VWC^{0.94}$ applicable during periods of high solar radiation $K \downarrow > 500$ W m$^{-2}$, which is essentially linear. Heusinger and Weber (2017) contributes to the findings of Coutts et al. (2013), but is bound to the constraints of their study in which VWC for their drying periods was rarely above 0.2 and often below 0.1.

This pattern in evaporative cooling has very clear implications for green roof management and suitability as a cooling mechanism in urban design. The VWC of a green roof is closely tied to its cooling performance but in a non linear fashion. Fig. 4.6 suggests that EFR when it is required most (when available energy is high) does not increase as VWC increases beyond a critical VWC value of $\approx 0.22$. This would suggest that for irrigated
green roofs, over-irrigation, in addition to the obvious diminishing of stormwater retention capacity, would provide no additional benefit to summertime climate performance. Note that the slight decrease in EFR at high VWC may be a result of pooling of water on the roof beneath the green roof and is not expected to be characteristic of all green roofs.

The daytime EFR in relation to daytime mean VWC is shown in Fig. 4.7. The daytime EFR was defined such that

\[
\text{Daytime} \frac{Q_E}{(Q^* - Q_G)} = \frac{\int_{\text{sunset}}^{\text{sunrise}} Q_E dt}{\int_{\text{sunset}}^{\text{sunrise}} (Q^* - Q_G) dt}
\]

A subsectioning similar to that in Fig. 4.5 is performed with: daytime integrated available energy 10 MJ d^{-1} or less, daytime integrated available energy greater than 10 MJ d^{-1} for only drying periods 1 and 2, and daytime integrated available energy greater than 10 MJ d^{-1} for drying periods past the second one. In Fig. 4.7 a similar pattern to Fig. 4.5 can be seen. In Fig. 4.7 for the daytime total case, as with the hourly case; there is scatter when daytime total available energy is lower, there is a consistent visual linear relationship between VWC and the daytime total EFR at lower VWC, and the first and second drying period have a higher daytime total EFR at higher VWC while other drying periods have a lower daytime total EFR. There was more scatter, even for the higher available total daytime energy, when considering the daytime total than with the hourly; this is due to the inclusion of particular hours with high evaporative cooling capacities concurrent with lower hourly available energy being included in daytime totals which overall have a high available energy. Despite this increased scatter, the daytime EFR showed a similar decrease following the increase with VWC.
Figure 4.5: Hourly EFR $Q_E/(Q^* - Q_G)$ separated into three case studies plotted against water content.
Figure 4.6: Hourly EFR $\frac{Q_e}{Q^* - Q_G}$ for $Q^* > 500 \text{ W m}^{-2}$ plotted against water content, piece-wise linear model. Superimposed models are shown with dashed lines. Thick blue line is a linear piece-wise fit to all drying period points. Thin blue line is a polynomial fit to all drying period points. Thick red line is a linear piece-wise fit to points after second drying period. Thin red line is a polynomial fit to points after second drying period.
Chapter 4. Surface Controls on Energy Balance Fluxes

Figure 4.7: Integrated daytime ($K \downarrow > 0$ W m$^{-2}$) EFR $Q_E/(Q^*-Q_G)$ plotted against water content for three cases of daily integrated $Q^*$. 
The relationship was quantified in a similar manner to the hourly data. In Fig. 4.8, model 1 is visualized as the thick blue dashed line with the corresponding polynomial as the thin blue dashed line; both incorporate all drying periods. Model 2 in polynomial form was also visualized in Fig. 4.8 as the thin red dashed line and incorporated data only after the second drying period. A piecewise regression for model 2 data (not shown) revealed an insignificant \((p>0.15)\) breakpoint due to the lack of lower \(VWC\) data. As with the hourly data, the significance of the breakpoints were determined using the Davies test (Davies, 2002) as implemented in the \textit{segmented} package (Muggeo, 2008) in R (R Core Team, 2016). The breakpoint of model 1 with inclusion of all data including high \(VWC\) from the first two drying periods was significant \((p<0.15)\). Model 1 captured the general trend best with an adjusted \(R^2\) higher than the corresponding polynomial; 0.318 for the former and 0.248 for the latter. The polynomial for model 2 was not able to capture the trend at lower \(VWC\) with an overall poor fit at an adjusted R of only 0.073.
Figure 4.8: Daytime EFR $Q_E/(Q^*-Q_G)$ for available energy $>10$ MJ m$^{-2}$ d$^{-1}$ plotted against water content with points separated into different drying periods. Superimposed models are shown with dashed lines. Thick blue line is a linear piece-wise fit to all drying period points. Thin blue line is a polynomial fit to all drying period points. Thin red line is a polynomial fit to points after second drying period.
The models are provided in Eq. 4.7, Eq. 4.8, and Eq. 4.9 respectively in the following order: model 1 piecewise regression, corresponding polynomial for model 1, polynomial for model 2. Models 1 and the corresponding polynomial contain data points with $Q^* > 500 \text{ W m}^{-2}$ for all drying periods, while the model 2 polynomial contain data points $Q^*> 500 \text{ W m}^{-2}$ only after the second drying period.

$$Q_{E}/(Q^*-Q_G) = \begin{cases} -0.956 + 6.643VWC & \text{for } 0.16 \leq VWC \leq 0.217 \\ 0.824 - 1.558VWC & \text{for } 0.217 \leq VWC \leq 0.32 \end{cases}$$ (4.7)

$$Q_{E}/(Q^*-Q_G) = -2.004 + 19.793VWC - 40.009VWC^2 \text{ for } 0.16 \leq VWC \leq 0.32$$ (4.8)

$$Q_{E}/(Q^*-Q_G) = -0.870 + 9.979VWC - 19.684VWC^2 \text{ for } 0.16 \leq VWC \leq 0.32$$ (4.9)

### 4.4 Chapter Summary

The controls from albedo, advection, and water content were explored in this chapter. Albedo was found to vary throughout the growing season with two years exhibiting a sharp decline of $\sim 0.08$ following the flowering of *Sedum spurium*. The pattern prior to, and subsequent to, the peak differed slightly for the two years and was likely due to a sparser plant coverage during those times in the earlier year. The overall effect of assuming a constant albedo was estimated to be an error in $Q^*$ estimation of 35-65 W m$^{-2}$. A segmented fit for albedo in relation to growing degree day (GDD) with a base of 10°C accounted for differences in temperature between the two years. This revealed the sharp decrease in albedo to occur between $\sim 400$ to $\sim 700$ GDDs. Up to 2.8% of the data were possibly influenced by advection specific to the current study. There was strong evidence for 1.2% of the data, all in the morning and evening periods with advection enhanced $Q_E$. A relationship was identified between EFR and $VWC$ in which a significant breakpoint was identified at a $VWC$ of approximately 0.22 for hours when $Q^*$ was high ($> 500 \text{ W m}^{-2}$), in which a linear increase in EFR occurs prior to the breakpoint. A similar pattern was observed when integrated over a daytime period when all drying periods were considered.
Chapter 5

Conclusions

5.1 Summary of Findings

In order to assess how effectively green roofs cool cities during summer days, measurements of the summer daytime energy balance on green roofs are required. This thesis used a lysimetry approach to measuring the SEB. The custom-built lysimeters exhibited noise at high frequency intervals due to the effect of direct wind loading on the modules. However, $Q_E$ could successfully be measured using the lysimetry approach at an hourly timescale when the signal was averaged over multiple modules. The questions this thesis sought to answer were:

1. How does daytime green roof SEB vary during sustained drying periods at a range of temporal scales?

2. Given that albedo is a strong control on available energy, how does green roof albedo vary with time?

3. To what extent does advection influence the green roof SEB?

4. What is the relationship between summer daytime green roof EFR and water content for sustained drying periods?
5.1. Summary of Findings

To address the first question, the energy balance was characterized for multiple time scales at hourly and daytime frequencies. It was found that diurnally, $Q_E$ in the early morning and afternoon was positive even when $Q^*$ was low or negative. A Bowen ratio ($\beta$) of $\sim 2$ was observed for clear sky days and slightly less when all conditions were included. These values are lower than typical vegetated surfaces which have $\beta < 1$. The mean integrated flux ratios from June to September were: 0.36 for $Q_E/Q^*$, 0.6 for $Q_H/Q^*$, and 0.03 for $Q_G/Q^*$, with no significant differences from month-to-month. There was a significant difference in the month of May relative to the summer months (June to September) for all three relative fluxes. It was also found that $Q_E$ decreased sharply prior to noon for low water contents (below $\sim 0.18 \text{ m}^3\text{ m}^{-3}$). This sometimes coincided with the time when urban temperatures became hottest and urban cooling would have been most beneficial (see Fig. 5.1). Two multiple linear regression models of $Q_E$ for the five longest sustained drying periods (greater than 7 days of drying) found $Q^*$ and VWC to be significant predictors, with $Q^*$ being the predominant determinant of $Q_E$ in both models. The first model was for drying periods primarily in May and the second model was for primarily the summer months (June - September), with predicted $Q_E$ over 10% greater in the first model than the second model.

To address the second question, the temporal evolution of daily integrated green roof albedo was assessed for three different years. Albedo was found to vary within and between years, however there was a consistent pattern between two of the years. Data from 2016 exhibited a different temporal evolution that is explained by poor plant growth compared to the two earlier (2013, 2014) years. The most notable feature of the change in albedo through time was a sharp decrease following the Sedum spurium flowering stage, when the albedo decreased by a value of $\sim 0.08$ from starting values of $\sim 0.23$ for 2013 (one year after installation) and $\sim 0.21$ for 2014 (two years after installation). By modeling the temporal trend of albedo as a function of growing degree days, the decrease was approximated as occurring between $\sim 400$ and $\sim 700$ growing degree days using a base temperature of $10^\circ\text{C}$. Taking this notable decrease in albedo into account would provide a more robust
determinant of $Q^*$ than assuming a constant value, with an estimated implication to $Q^*$ of 35-65 W m$^{-2}$ for $K_\downarrow$ values of 700-900 W m$^{-2}$.

To address the third question, periods when conditions were favourable to local roof scale advection within the summer of the study were identified. It was found that advection likely had little influence on the results of this study, since less than 3% of the data were measured under conditions favourable for advection at roof scale specific to the roof scale of the green roof in this study. This is important because it provides some assurance that the green roof test array in this study, which did not cover the entire roof on which it was located, was not unduly impacted by advection and can be used to represent the conditions expected on full green roof installations.

To address fourth question, a non-linear model was fit for EFR by volumetric water content $VWC$. For hours with high $Q^*$, EFR was 0.2-0.4 with peak performance at a $VWC$ of 0.22m$^3$ m$^{-3}$, a sharp linear decrease in performance below, and no increase above this threshold. This was found to be true when excluding the higher $Q_E$ period in May.

### 5.2 Research Implications

Green roof cooling would be most beneficial when air temperatures are high. As shown in Fig. 5.1, EFR from a green roof is sustained at a modest level, above 0.3, provided that $VWC$ is above 0.22.
Figure 5.1: Hourly EFR by air temperature for all drying periods with symbols separated into two classes of VWC.
The identification of relatively constant cooling performance under most soil moisture conditions and the identification of a critical water content is readily useful for policy makers and green roof manufacturers interested in optimizing the ability of green roofs to cool. The EFR, unlike surface or air temperature comparisons, also provides a scalable metric for the ability of green roofs to cool.

The presence of an optimal VWC also suggests that irrigation would be an effective strategy for cooling if closely monitored to ensure that over irrigation does not take place. This is because the results of this study demonstrate that at high VWC (>0.22 m$^3$ m$^{-3}$), an increase in VWC was not associated with an additional increase in EFR. However, excessive VWC would decrease water retention capacity, and be a wasted expense, thus reducing the multi-functional benefits from green roofs. Irrigation would be beneficial to EFR only in low VWC (<0.22 m$^3$ m$^{-3}$) situations. For this study in London, Ontario for 2014, low water conditions were observed primarily in May and were infrequent for the summer period (June - September). These results also provide direct support for the importance of incorporating a two phase evaporation model in green roof models to capture the threshold dependence of VWC on EFR. Green roof manufacturers and researchers could also focus on finding substrate and plant combinations that reduce the VWC threshold to maintain a higher EFR for a wider range of conditions.

This study has direct implications for urban design and green infrastructure planning. For urban areas across multiple types and geographical regions, there is a consistent linear relationship between EFR and the vegetation fraction in the urban area, with rural areas having the highest EFR. Fig. 5.2 shows this relationship. The results of this study are also superimposed onto Fig. 5.2 with the assumption that the SEB results are equivalent to having 100% vegetation cover.

If it is assumed there is a linear scaling between an urban area with no vegetation fraction and full green roof cover, the resultant line would be the hypothetical EFR of the urban area as the fraction of green roof cover increased. Under these assumptions, it can be seen there is a lower EFR per increase in vegetative fraction in the hypothetical green roof
case than is actually observed for cities with characteristic ground level and tree canopy vegetation cover. Put another way, this suggests that green roofs would not be sufficient to offset the EFR penalty from a new development that displaces standard vegetation.

The hypothetical case of complete green roof cover is equivalent to the observed EFR in urban areas with a vegetative fraction of 45%. Standard vegetation such as parks, trees, and lawns account for the typical vegetative fraction of urban areas. This suggests that increasing vegetation fraction of a city using green roofs would not result in a lower EFR compared to standard vegetation (parks, trees, lawns).
Figure 5.2: Green roof evaporative flux ratio (EFR) superimposed on daily EFR from urban to rural by vegetation fraction modified from Oke et al. (2017). Other study points are a few weeks in duration from several different sites in different cities. Boxplot for daytime EFR includes 100 daytime periods from all 20 drying periods. Dashed blue line is the median daytime EFR. Solid blue line is the median daily EFR.
This research may be applied to validate the energy balance output from climate models incorporating green roofs to assess their overall cooling impact. The energy balance dataset summarized in this thesis is valuable for numerical model evaluation since a full growing season of data (May - September) is used under drying periods when green roof cooling is most relevant. The energy balance data presented in this thesis can guide numerical models to correctly incorporate the energy balance from green roofs in a modeling environment to find their urban scale influence.

5.3 Limitations and Future Research

This research is based on a single green roof site for 100 days during the summer of 2014 using a lysimetry approach on a roof that allows for pooling of water. The study is limited to a single year duration and one site because of the practical constraints of processing data available from other less instrumented sites.

5.3.1 Instrumentation

The most uncertain term of the SEB measured in this study was $Q_H$ since it was calculated as a residual of the other terms. The scale of the green roof limited direct measurement of $Q_H$. Development of new micrometerological methodology or evaluation of emerging methodologies for measurement of $Q_H$ for small scale setups would provide greater certainty in the full SEB of green roofs. Traditional direct measurements of $Q_H$ from established techniques such as eddy covariance are only possible on large scale roof setups, such as in Heusinger and Weber (2017).

Maintenance of the lysimeter setup was required to ensure plants of modules adjacent to the lysimeter modules did not touch plants of the lysimeter module. The integrity of lysimetry data on an hourly basis was also dependent on the ability to discern completely dry periods from light rain periods. Lysimetry was found to be sensitive to small rain events that could not be detected by tipping bucket rain gauges, but could be identified using by
a leaf wetness sensor. Careful processing of data was required in order to find hourly $Q_E$ values or daytime integrations of hourly $Q_E$ values. The overhead of obtaining useful data limited the scope of this thesis to a single year at the London green roof site for which small rain event data was available through the leaf wetness sensor. Data for two other green roof study sites exist: Calgary, Alberta and Halifax, Nova Scotia. Processing of lysimeters from these sites to obtain hourly and daytime integrated $Q_E$ values would require information on small rain events not identified from tipping bucket raingauges. In addition $Q_E$ measured from individual modules was found to differ significantly and since the Calgary and Halifax sites had two lysimeters instead of four as in London, their representativity could not be assured. This significant difference between modules may however provide an opportunity for optimization of green roof design. It would be useful for future research to explore reasons for individual module differences and find the properties, times, and conditions that lead to some modules having higher $Q_E$ in order to inform design on how to maximize $Q_E$. Lysimetry could also be used to better quantify both local scale advection and roof scale advection depending on the test setup in a manner similar to how lysimeters were used to quantify local advection for urban parks by Spronken-Smith et al. (2000).

5.3.2 Time Scales

As this research is focused on a single year, future study of multiple years could verify the presence of a distinct period with higher evapotranspirational cooling in May that was identified in this study. Future study of multiple years could also confirm the fairly consistent summertime energy balance identified in this study. Since albedo was different in 2016 compared to other years due to a diminished canopy height as a result of green roof age and sequence of weather for that season, EFR during that time might have also been different. Future study of EFR for 2016 London data would identify how different year-to-year variation in EFR is and how much the underlying relationship to VWC changes as a result of a diminished Sedum canopy. More generally, the relationship between EFR and VWC and the identification of an optimal VWC could be assessed at study sites in Calgary.
and Halifax for which project data exist. This would allow confirmation of the relationship and an assessment of whether it is region specific or if it is true in general regardless of the sequence of weather events.

A more comprehensive model of albedo could also be developed in future research with quantification of plant growth through several growing seasons. Confirmation of the form of the albedo change relationship with GDD in future studies with different types of Sedum would provide greater evidence for its general applicability.

Since this study focused on daytime performance, an assessment of energy balances for the nighttime period would also be useful in future research to more comprehensively relate green roofs to the urban heat island.

### 5.3.3 Study Site

The current study was situated on a roof with improper roof drainage which allowed water to pool on the roof. The presence of water beneath the elevated portion of the green roof might have reduced EFR during periods of high water content relative to moderate water contents when water pooling did not occur. Future research on a roof without water pooling could confirm that the slight decrease in EFR observed in this study at higher VWC was characteristic of the roof and not controlled by plant or media properties. Because the roof pooled water, this limited the ability to assess air and surface temperature cooling on a green roof using the conventional roof as a reference for typical roof conditions.

### 5.4 Main Contributions to Green Roof SEB Literature

This research builds upon the body of existing green roof SEB measurements (Takebayashi and Moriyama, 2007; Jim and He, 2010; Coutts et al., 2013; Heusinger and Weber, 2017) and identifies the need for full season SEB measurements, instead of a few days (Takebayashi and Moriyama, 2007; Coutts et al., 2013). Measurements should also be taken using robust measurement techniques appropriate for the scale of study. For small scale green
roof setups, on the order of 60m$^2$, lysimetry with an elevated green roof design should be used, instead of flux gradient methods such as Bowen ratio (Jim and He, 2010) for which a theoretical basis does not exist for the complex aerodynamic conditions of a typical rooftop. SEB measurements should also be taken under a range of substrate water content conditions during drying periods. This research builds upon existing summer-long, robust, SEB measurement research (Heusinger and Weber, 2017), by measuring a wider range of substrate $VWC$ to identify an optimal $VWC$ threshold beyond which further $VWC$ increase yields no atmospheric cooling benefit. The finding of a stable partitioning of available energy into latent heat during conditions in which drying periods occur beyond the threshold $VWC$ is novel in the existing body of SEB measurement literature. This matters because it identifies a limit to green roof atmospheric cooling under typical conditions which is lower than that for conventional ground level vegetation in cities. Policy makers and researchers alike should carefully consider how effective green roofs are as a strategy for cooling cities. Green roofs clearly provide cooling benefit compared to dry conventional roofs and unlike highly reflective cool roofs, they are multi-functional and provide multiple other benefits as well. However, in terms of their daytime climate performance in cities, this research suggests that green roofs are not a direct substitute for conventional urban vegetation and should be considered as supplemental to other urban greening or green space preservation techniques.
References


Davies, R., 2002: Hypothesis testing when a nuisance parameter is present only under the alternative: Linear model case. Biometrika, 89 (2), 484–489.


Mair, P., F. Schoenbrodt, and R. Wilcox, 2016: WRS2: *Wilcox robust estimation and testing*. 0.9-1.


Appendix A

Radiation Instrument Details

REBS Q7 wind corrections provided by manufacturer:

\[
Q^* = \begin{cases} 
\frac{Q^*_\text{raw}}{1 - 0.059(1 - 2.8^{-WS}) - \frac{0.0096(WS)}{0.216 + WS^3}} & \text{if } Q^*_\text{raw} > 0 \\
Q^*_\text{raw} & \text{if } Q^*_\text{raw} < 0 \\
1.01 - 0.021(101.45^{-WS}) - \frac{2^{-7WS}}{100} & \text{if } Q^*_\text{raw} < 0
\end{cases}
\]  

(A.1)

where WS is wind speed and \(Q^*_\text{raw}\) is the is net radiation prior to applying wind corrections.

\(L_\downarrow\) error using pyrgeometer measurements was assumed to be 10%. Pyrgeometers are known to overestimate by up to 10 W m\(^{-2}\) or \(\approx 3\%\) and up to 10\% when unshaded compared to a shaded pyrgeometer (Meloni et al., 2012). As per Meloni et al. (2012), the dome correction formula from Albrecht and Cox (1977) (Eq. A.2) was applied with coefficients from Philipona et al. (2001) as \(k_2 = 1\) and \(k_3 = 4\).

\[
L_\downarrow = L_\downarrow\text{thermopile} + k_2\sigma T^4_{\text{case}} - k_3\sigma(T^4_{\text{dome}} - T^4_{\text{case}}) 
\]  

(A.2)

\(L_\downarrow\) is the corrected incident longwave, \(L_\downarrow\text{thermopile}\) is longwave output from the main thermopile sensor, \(\sigma\) is the Stefan-Boltzmann constant, and \(T^4_{\text{case}}\) temperature of the case, \(T^4_{\text{dome}}\) is the temperature of the dome, and \(k_2\) and \(k_3\) are empirical coefficients.
Table A.1: Pyranometer manufacturer specifications

<table>
<thead>
<tr>
<th></th>
<th>TSP-400</th>
<th>CMA6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Response:</td>
<td>0.3 to 3 nm</td>
<td>285-2800 nm</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1 W m(^{-2})</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>~ 48 µV/(W m(^{-2})) output impedance</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity:</td>
<td>&lt;300 , 40 mVdc nominal (60 mVdc max FS)</td>
<td>5 to 20 µV/(W m(^{-2}))</td>
</tr>
<tr>
<td>Cosine Response:</td>
<td>Better than 1% for a 75 SZA; better than 2%</td>
<td>&lt;20 W m(^{-2})</td>
</tr>
<tr>
<td></td>
<td>for a 85 SZA (up to 80° with 1000 W m(^{-2}) beam)</td>
<td>-</td>
</tr>
<tr>
<td>Temperature Dependence:</td>
<td>&lt;1% of F.S. over 50°C ambient</td>
<td>±4% (-10 to +40°C)</td>
</tr>
<tr>
<td></td>
<td>temperature range</td>
<td></td>
</tr>
<tr>
<td>Response Time:</td>
<td>12 sec (I/O response to a step change in incident irradiance)</td>
<td>&lt;18 s</td>
</tr>
<tr>
<td>Linearity:</td>
<td>0.5% (0-1400 W m(^{-2}))</td>
<td>&lt;1% (0 to 1000 W m(^{-2}))</td>
</tr>
<tr>
<td>Axial Asymmetry:</td>
<td>&lt;0.1%</td>
<td>-</td>
</tr>
<tr>
<td>Expected Daily Uncertainty</td>
<td>-</td>
<td>&lt;5%</td>
</tr>
</tbody>
</table>
Table A.2: Net radiation manufacturer specifications and estimated uncertainty

<table>
<thead>
<tr>
<th>Error</th>
<th>Reported Error</th>
<th>Error estimate</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directional Error</td>
<td>&lt;30 W m(^{-2}) @ 1000 W m(^{-2})</td>
<td>3%</td>
<td>Consistent at other irradiances</td>
</tr>
<tr>
<td>Sensor Asymmetry</td>
<td>5% (10% worst case)</td>
<td>5%</td>
<td>Daytime bottom sensor half of net radiation</td>
</tr>
<tr>
<td>Cosine Response Error</td>
<td>2-5% @ Zenith 20-60</td>
<td>5%</td>
<td>Same as typical radiometer value</td>
</tr>
<tr>
<td>Temperature Dependence</td>
<td>0.12%/°C</td>
<td>3%</td>
<td>25°C deviation from 22°C (calibration temperature)</td>
</tr>
<tr>
<td>Combined Error Estimate</td>
<td></td>
<td>8%</td>
<td></td>
</tr>
</tbody>
</table>

Combined error estimated by assuming individual errors add in quadrature.

Table A.3: Inputs for error in surface temperature $\Delta T_{0GR}$

<table>
<thead>
<tr>
<th>$T_{sens}$[K]</th>
<th>$\varepsilon$</th>
<th>$L\downarrow$[W m(^{-2})]</th>
<th>The</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate</td>
<td>29.5</td>
<td>0.98</td>
<td>356</td>
</tr>
<tr>
<td>Error</td>
<td>0.5</td>
<td>0.02</td>
<td>36</td>
</tr>
</tbody>
</table>

$T_{sens}$ estimate was taken as the mean of the daytime peak values. $\varepsilon$ was assumed (for details see 2.3.2). $L\downarrow$ estimate was taken as mean $L\downarrow$ coincident with daytime peak values of $T_{sens}$. $T_{sens}$ error was given by the manufacturer specifications.
With the estimate values in Table A.3, $T_{surf}$ is $303\,\text{K} \pm 0.4$ or $29.9\,\text{°C} \pm 0.4$, corrected from a $T_{sens}$ value of $29.5\,\text{°C}$. The largest source of uncertainty is in the emissivity $\varepsilon$ of the green roof. The magnitude of the correction is within the uncertainty range itself, but both are relatively small at $\approx 0.4\,\text{K}$.

$$
\delta T_{sens} \rightarrow \delta T_{surf} = \frac{\partial T_{surf}}{\partial T_{sens}} \delta T_{sens} = \frac{T_{sens}^3}{\varepsilon \left( \frac{T_{sens}^4 \sigma - (1 - \varepsilon)L_{\downarrow}}{\varepsilon \sigma} \right)^{3/4}} \delta T_{sens} = 0.0508 \tag{A.3}
$$

$$
\delta \varepsilon \rightarrow \delta T_{surf} = \frac{\partial T_{surf}}{\partial \varepsilon} \delta \varepsilon = \frac{1/4L_{\downarrow} - 1/4T_{sens}^4 \sigma}{\varepsilon^2 \sigma \left( \frac{T_{sens}^4 \sigma + (\varepsilon - 1)L_{\downarrow}}{\varepsilon \sigma} \right)^{3/4}} \delta \varepsilon = -0.3950 \tag{A.4}
$$

$$
\delta L_{\downarrow} \rightarrow \delta T_{surf} = \frac{\partial T_{surf}}{\partial L_{\downarrow}} \delta L_{\downarrow} = \frac{1/4(\varepsilon - 1)}{\varepsilon \sigma \left( \frac{T_{sens}^4 \sigma + (\varepsilon - 1)L_{\downarrow}}{\varepsilon \sigma} \right)^{3/4}} \delta L_{\downarrow} = -0.1164 \tag{A.5}
$$

$$
\delta T_{surf} = 0.415 \tag{A.6}
$$
Appendix B

Lysimeter Details

This appendix describes lysimeter calibrations, load cell specifications, and error calculations. The lysimeters were calibrated multiple times throughout the measurement periods. Calibrations were performed by placing standard weights of known mass onto the lysimeters then removing them. The slope was found through linear regression of the lysimeter output and known weights added. The intercept or offset was derived by carefully lifting the module from the lysimeter and weighing it using a hand-held scale.
Table B.1: Load cell manufacturer specifications and estimated uncertainty. Interface Inc. SPI Platform Scale Load Cell, Single Point 25 lbf to 150 lbf

<table>
<thead>
<tr>
<th></th>
<th>Errors ± % FS</th>
<th>$W(kg)$</th>
<th>$Q_{E_{eqv}} \text{ W m}^{-2}$</th>
<th>Time Dependent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non linearity</td>
<td>0.02</td>
<td>0.0032</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.02</td>
<td>0.0032</td>
<td>23</td>
<td>x</td>
</tr>
<tr>
<td>Non-repeatability</td>
<td>0.01</td>
<td>0.0016</td>
<td>12</td>
<td>x</td>
</tr>
<tr>
<td>Creep in 20 min</td>
<td>0.025</td>
<td>0.004</td>
<td>29</td>
<td>x</td>
</tr>
<tr>
<td>Eccentric Load Sensitivity/Inch</td>
<td>0.002</td>
<td>0.00032</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Temperature Dependence</td>
<td>0.002</td>
<td>0.00032</td>
<td>2</td>
<td>x</td>
</tr>
<tr>
<td>Combined Time Dependent</td>
<td></td>
<td></td>
<td>0.0054</td>
<td>39</td>
</tr>
</tbody>
</table>

Errors are ± % FS listed from manufacturer. Weight $W$ estimated for $\bar{W} \approx 16 \text{ kg}$ assuming full scale error $\approx \bar{W}$. Latent heat flux equivalent $Q_{E_{eqv}}$ for 1 hour estimated assuming $T_a = 25^\circ\text{C}$, $A = 0.093 \text{ m}^2$ via Eq. 2.20. Combined error is estimated by assuming individual errors add in quadrature.
Table B.2: Lysimeter calibrations London 2014

<table>
<thead>
<tr>
<th>DOY</th>
<th>m</th>
<th>b</th>
<th>DOY</th>
<th>m</th>
<th>b</th>
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<tbody>
<tr>
<td>NE</td>
<td>90</td>
<td>3.303</td>
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<tr>
<td>&quot;</td>
<td>92</td>
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<td>&quot;</td>
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<td>3.327</td>
<td>-3.996</td>
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<td>315</td>
<td>3.324</td>
<td>-</td>
<td>&quot;</td>
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<tr>
<td>NW</td>
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<td>SW</td>
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<td>&quot;</td>
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<td>315</td>
<td>7.003</td>
<td>-</td>
<td>&quot;</td>
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m - slope, b – intercept. Italics indicate 50lb capacity load cell
Table B.3: Lysimeter calibrations London 2016

<table>
<thead>
<tr>
<th>DOY</th>
<th>m</th>
<th>b</th>
<th>DOY</th>
<th>m</th>
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<td>&quot;</td>
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<td>&quot;</td>
<td>310</td>
<td>7.1131</td>
<td>-1.8442</td>
<td>&quot;</td>
<td>310</td>
</tr>
</tbody>
</table>

m - slope, b – intercept. Italics indicate 50lb capacity load cell
Appendix C

Bulk Density of Green Roof Media

The bulk density $\rho_b$ (Eq. C.1) of the green roof media was found through destructive sampling of a green roof module in 2013. Six samples were made within the module using sampling tins of known volume (see Fig. C.1) and oven dried at 80°C for 24 hours. The individual and mean $\rho_b$ are shown in Table C.1.

$$\rho_b = \frac{\text{dry media mass}}{\text{sample volume}}$$  \hspace{1cm} (C.1)
Figure C.1: Procedure used to extract six samples of known volume from green roof media in order to find bulk density.
Table C.1: Bulk Density from sampling of green roof module in 2013

<table>
<thead>
<tr>
<th>Sample Position</th>
<th>Bulk Density kg m$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Left</td>
<td>724</td>
</tr>
<tr>
<td>Top Middle</td>
<td>403</td>
</tr>
<tr>
<td>Top Right</td>
<td>502</td>
</tr>
<tr>
<td>Bottom Left</td>
<td>732</td>
</tr>
<tr>
<td>Bottom Middle</td>
<td>753</td>
</tr>
<tr>
<td>Bottom Right</td>
<td>718</td>
</tr>
<tr>
<td>Mean</td>
<td>639</td>
</tr>
<tr>
<td>Error</td>
<td>155</td>
</tr>
</tbody>
</table>

Error is margin of error for 95% confidence interval. Sampling positions correspond to section of extracted media outlined in Fig. C.1.
Appendix D

Water Content Details

The EC-5 (Decagon Devices) was used to directly measure the volumetric water content \( \theta \) using the method of Sakaki et al. (2008) as detailed in Perelli (2014)

\[
\theta = \frac{ADC^\alpha - ADC^\alpha_{dry}}{ADC^\alpha_{sat} - ADC^\alpha_{dry}} \phi
\]

where \( ADC^\alpha_{dry} \) and \( ADC^\alpha_{sat} \) were determined under dry and saturated conditions for the green roof media used in the current study by Perelli (2014).

\[
ADC^\alpha = (EC5 \text{ mV output } \times 1.3661)^{2.5}
\]

There is an implicit assumption that the variability of calibrations done by Perelli (2014) in a lab column experiment apply in the field. The nominal values and variability of each term volumetric water content \( \theta \) (see Eq.D.1) are shown below.

The error in \( \theta \) due to each input was found as detailed in Darmofal (2010).
### Table D.1: Error in EC-5 calibration

<table>
<thead>
<tr>
<th></th>
<th>$ADC^\alpha$</th>
<th>$ADC_{dry}^\alpha$</th>
<th>$ADC_{sat}^\alpha$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$1.5449 \times 10^7$</td>
<td>$3.7362 \times 10^6$</td>
<td>$2.2908 \times 10^7$</td>
<td>0.43</td>
</tr>
<tr>
<td>Error</td>
<td>$8.3060 \times 10^3$</td>
<td>$3.5082 \times 10^5$</td>
<td>$1.7488 \times 10^6$</td>
<td>0.02</td>
</tr>
<tr>
<td>n</td>
<td>-</td>
<td>24</td>
<td>24</td>
<td>-</td>
</tr>
</tbody>
</table>

Error is standard error for all quantities except $\phi$ which was estimated from a range presented in Perelli (2014). Source data for all quantities except $ADC^\alpha$ was Perelli (2014). $ADC^\alpha$ was estimated as the median of the standard error in hourly averages from 5 minute data during the 2014 study period.

\[
\theta = \frac{ADC^\alpha - ADC_{dry}^\alpha}{ADC_{sat}^\alpha - ADC_{dry}^\alpha} \phi = 0.2627 \quad (D.3)
\]

\[
\delta ADC^\alpha \rightarrow \delta \theta = \frac{\partial \theta}{\partial ADC^\alpha} \delta ADC^\alpha = \frac{\phi}{ADC_{sat}^\alpha - ADC_{dry}^\alpha} \delta ADC^\alpha = 1.8630 \times 10^{-4} \quad (D.4)
\]

\[
\delta ADC_{dry}^\alpha \rightarrow \delta \theta = \frac{\partial \theta}{\partial ADC_{dry}^\alpha} \delta ADC_{dry}^\alpha = \frac{-\phi}{ADC_{sat}^\alpha - ADC_{dry}^\alpha} \delta ADC_{dry}^\alpha = -0.0079 \quad (D.5)
\]

\[
\delta ADC_{sat}^\alpha \rightarrow \delta \theta = \frac{\partial \theta}{\partial ADC_{sat}^\alpha} \delta ADC_{sat}^\alpha = \frac{ADC_{dry}^\alpha - ADC^\alpha}{(ADC_{sat}^\alpha - ADC_{dry}^\alpha)^2} \delta ADC_{sat}^\alpha = -0.0557 \quad (D.6)
\]

\[
\delta \phi \rightarrow \delta \theta = \frac{\partial \theta}{\partial \phi} \delta \phi = \frac{ADC^\alpha - ADC_{dry}^\alpha}{ADC_{sat}^\alpha - ADC_{dry}^\alpha} \delta \phi = 0.0122 \quad (D.7)
\]

\[
\delta \theta = 0.0576 \quad (D.8)
\]
Appendix E

Error Analysis of Ground Heat Flux

The error in volumetric heat capacity of the soil due to each input was found via

$$C_{vm} = \rho_b \left( c_d + \theta \frac{\rho_b}{\rho_w} c_w \right) = 1.0875 \times 10^6$$  \hspace{1cm} (E.1)

$$\delta \rho_b \rightarrow \delta C_{vm} = \frac{\partial C_{vm}}{\partial \rho_b} \delta \rho_b = c_d + \frac{2 \theta \rho_b c_w}{\rho_w} \delta \rho_b = 2.1859 \times 10^5$$  \hspace{1cm} (E.2)

$$\delta c_d \rightarrow \delta C_{vm} = \frac{\partial C_{vm}}{\partial c_d} \delta c_d = \rho_b \delta c_d = 5.112 \times 10^4$$  \hspace{1cm} (E.3)

$$\delta \theta \rightarrow \delta C_{vm} = \frac{\partial C_{vm}}{\partial \theta} \delta \theta = \rho_b \delta \theta = \frac{\rho_b^2 c_w}{\rho_w} \delta \theta = 9.8331 \times 10^4$$  \hspace{1cm} (E.4)

$$\delta C_{vm} = 2.4508 \times 10^5$$  \hspace{1cm} (E.5)

The error in $\Delta Q_{sm}$ W m$^{-2}$ was found via

$$\Delta Q_{sm} = C_{vm} \frac{\Delta T}{\Delta t} z = 18.2923$$  \hspace{1cm} (E.6)

$$\delta C_{vm} \rightarrow \delta Q_{sm} = \frac{\partial Q_{sm}}{\partial C_{vm}} \delta C_{vm} = \frac{\Delta T_1 z_m}{\Delta T} \delta C_{vm} = 4.1223$$  \hspace{1cm} (E.7)

$$\delta \Delta T_1 \rightarrow \delta Q_{sm} = \frac{\partial Q_{sm}}{\partial \Delta T_1} \delta \Delta T_1 = \frac{C_{vm} z_m}{\Delta t} \delta \Delta T_1 = 14.9205$$  \hspace{1cm} (E.8)

$$\delta Q_{sm} = 15.4795$$  \hspace{1cm} (E.9)

$\Delta T_1$ was taken as the daily average of five hours centered about the daily peak during 2014, and its error 0.7071$^\circ$C was taken as the manufacturer error added in quadrature; the error provided by the manufacturer was 0.5$^\circ$C.
Table E.1: Inputs for error in $\Delta Q_{sv}$

<table>
<thead>
<tr>
<th>$m_v$</th>
<th>$\Delta T_c$</th>
<th>$c_v$</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate</td>
<td>0.1831</td>
<td>1.1166</td>
<td>4181</td>
</tr>
<tr>
<td>Error</td>
<td>0.5492</td>
<td>0.1414</td>
<td>-</td>
</tr>
</tbody>
</table>

The mass of vegetation $m_v$ was found through destructive sampling in lab conditions. Since it is expected that the field mass was higher, an estimated mass of twice the lab measurement was used and a factor of three error was assumed. The specific heat of vegetation was assumed to be that of water. $\Delta T_a$ was taken as the daytime average of 2014 data. Error for $\Delta T_c$ was taken as error from the manufacturer 0.5°C added in quadrature.

The error in $\Delta Q_{sv}$ was found via

$$\Delta Q_{sv} = \frac{m_v c_v \Delta T}{A \Delta t} = 2.5555 \quad (E.10)$$

$$\delta m_v \rightarrow \delta \Delta Q_{sv} = \frac{\partial \Delta Q_{sv}}{\partial m_v} \delta m_v = \frac{c_v \Delta T_c}{A \Delta t} \delta m_v = 7.6666 \quad (E.11)$$

$$\delta \Delta T_c \rightarrow \delta \Delta Q_{sv} = \frac{\partial \Delta Q_{sv}}{\partial \Delta T_c} \delta \Delta T_c = \frac{m_v c_v}{A \Delta t} \delta c_v = 0.3237 \quad (E.12)$$

$$\delta \Delta Q_{sv} = 7.6735 \quad (E.13)$$

The total error in $Q_G$ was found as

$$Q_G = Q_{G_i} + \Delta Q_{sm} + \Delta Q_{sv} = 38.3478 \quad (E.14)$$

$$\delta Q_{G_i} \rightarrow \delta Q_G = 0.8750 \quad (E.15)$$

$$\delta Q_{sm} \rightarrow \delta Q_G = 15.4990 \quad (E.16)$$

$$\delta Q_{sv} \rightarrow \delta Q_G = 7.8356 \quad (E.17)$$

$$\delta Q_G = 17.3717 \quad (E.18)$$

$Q_{G_i}$ was estimated as the approximate daily peak of 17.5 W m$^{-2}$. Error in $Q_{G_i}$ was estimated using manufacturer accuracy of 5%.
Curriculum Vitae

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The University of Western Ontario
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