Measurements of the Green Roof Energy Balance in Three Canadian Cities

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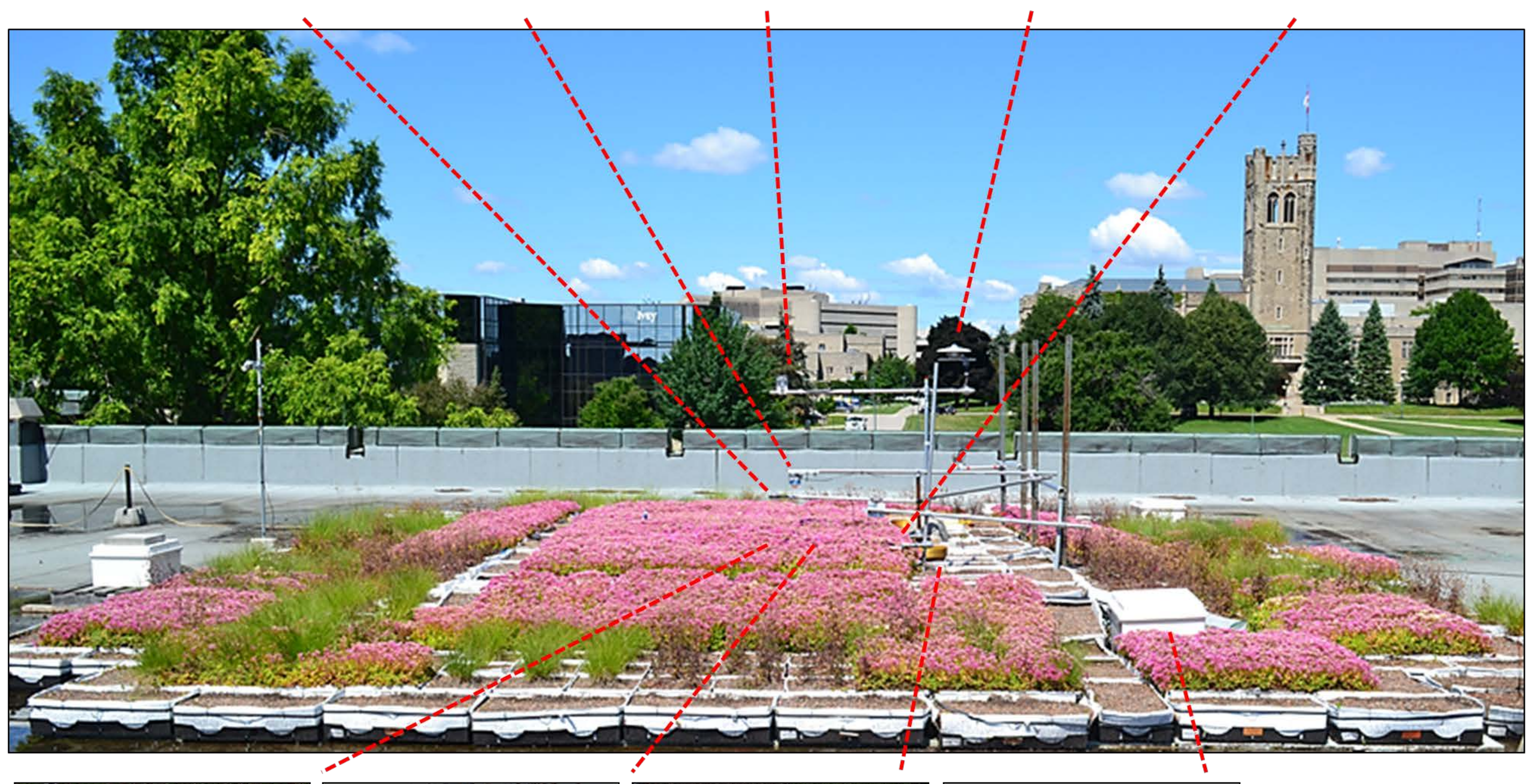
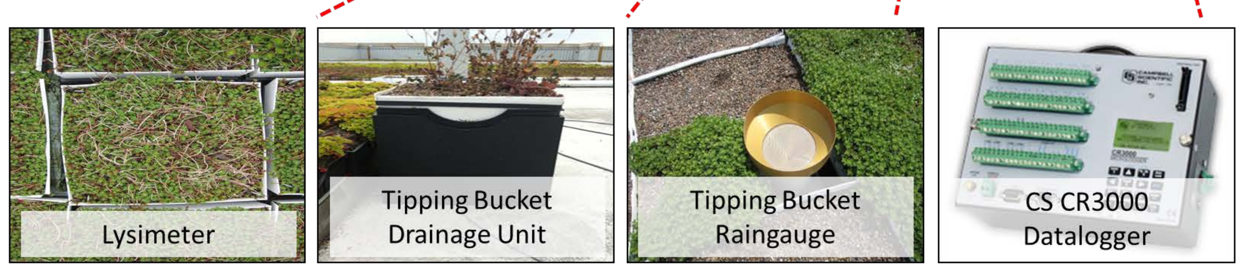
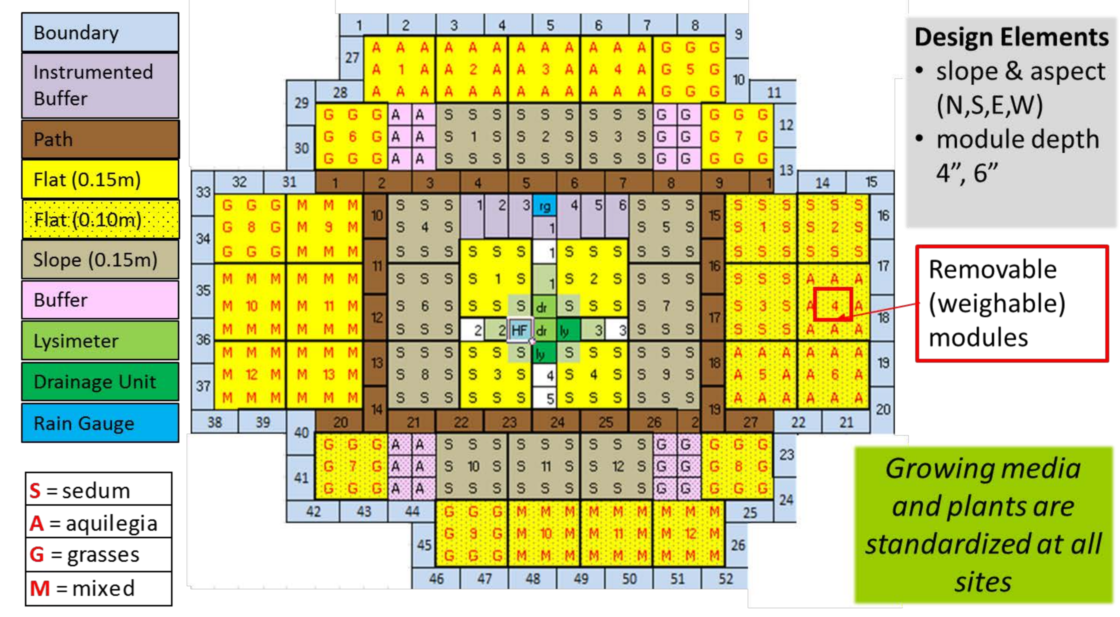
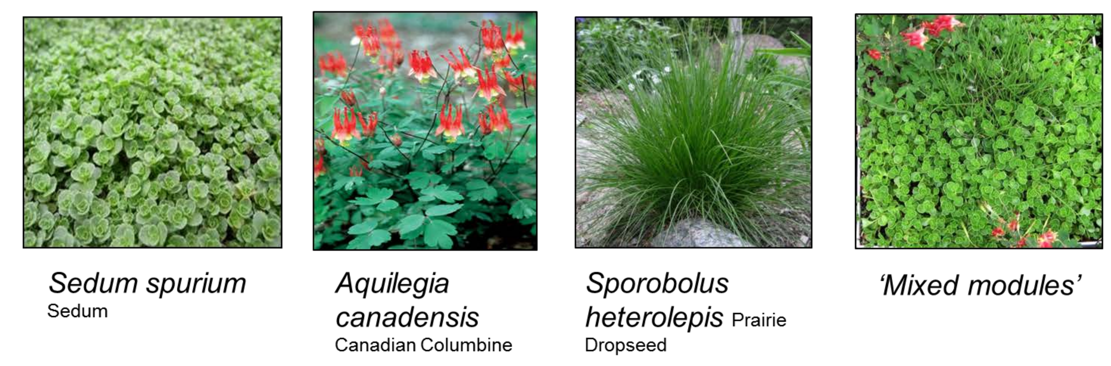
Green roofs are vegetated roof surfaces that alter urban climate by affecting the microclimate and hydrology of urban rooftop surfaces.

The objective of this research is to characterize the energy balance for a green roof under varying climate conditions. Three Canadian cities were chosen for testing the green roof energy balance: London ON, a warm continental climate; Halifax NS, a cool maritime climate; and Calgary AB, a cool arid climate.









$$Q_E = (L_v \Delta W)/(\Delta t\, A)$$

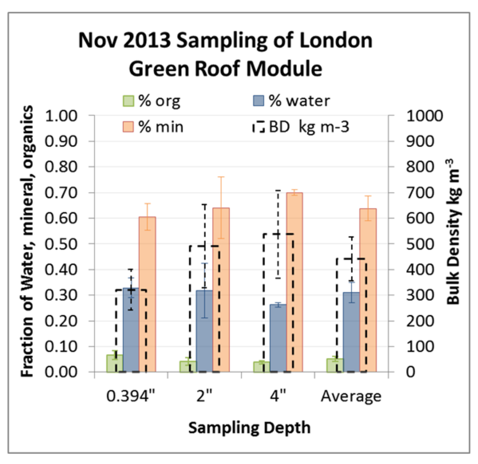
$$Q_G = Q_{Gz} + C(\Delta T/\Delta t)\Delta z$$

$$C = \rho_d\,(c_{min}x_{min} + c_{org}x_{org} + c_w x_w)$$

- *min - mineral, org - organic, w - water*
- *c* – specific heat capacity of component [J kg^{-1}K^{-1}]
- *x* – fraction of components
- ρ_d – is the bulk density [kg m^{-3}]

$$x_w = (M_T - M_D)/MT$$

- M_T – *total mass of module* [kg]
- M_D – *mass of dry module* [kg]



The mass of a dry module was found by destructive sampling of a module. The mass of mineral and organic components in module was found by oven drying, and loss on ignition respectively.

Project Data:

2012 Aug – Oct 2014 April - Nov

2013 May – Nov 2015 May – Sep

London data includes bare module energy balance for 2014 and 2015

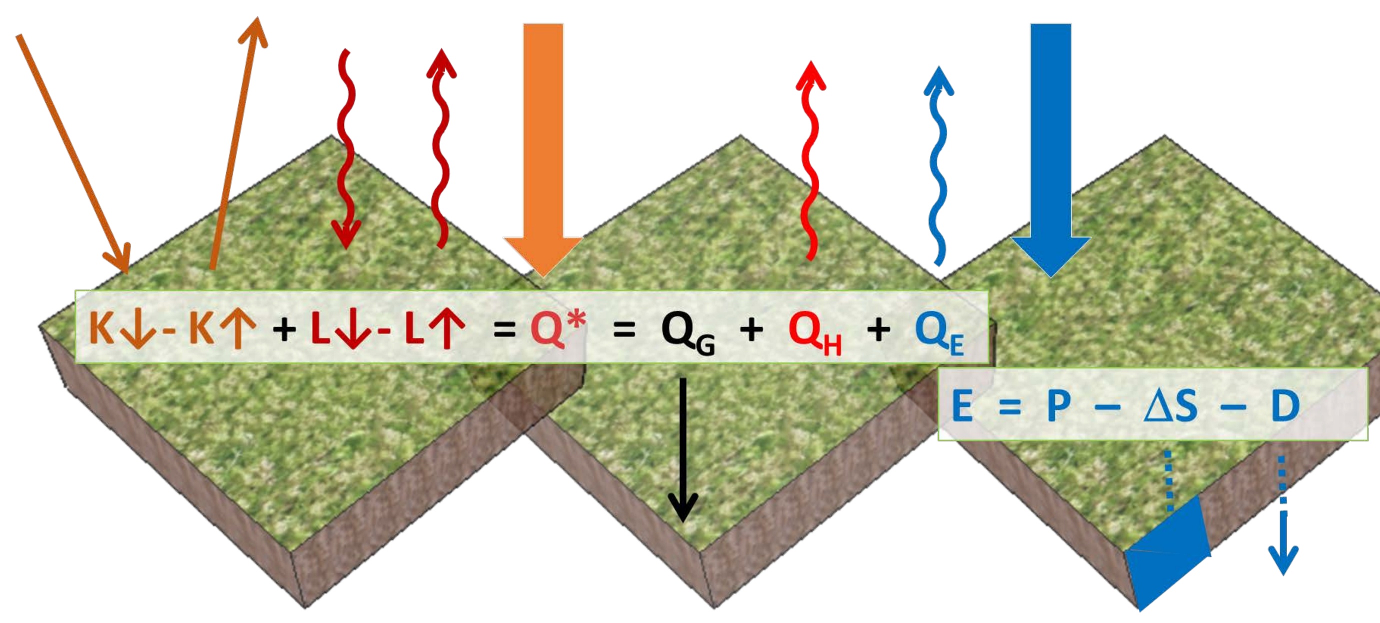


Figure adapted from Oke (1997)

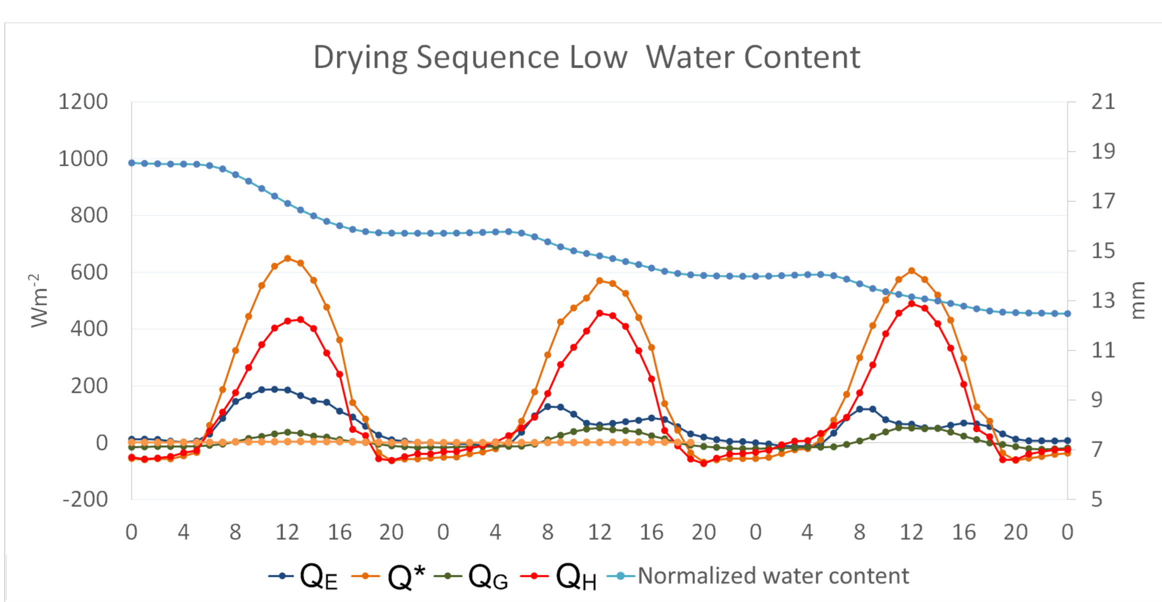
Measurements were taken from three green roof test sites of similar setup in London ON, Halifax NS, and Calgary AB. Each roof is composed of a raised instrumented array of interlocking 30.5 cm x 30.5 cm green roof modules containing sedum plants in growing medium 15cm deep. These were surrounded by sloping and unraised modules. Energy balance measurements were taken using custom built lysimeters for evapotranspiration, heat flux transducers and thermometry for soil heat flux, and radiometers for surface radiative fluxes.

Lysimetry Approach to Energy Balance

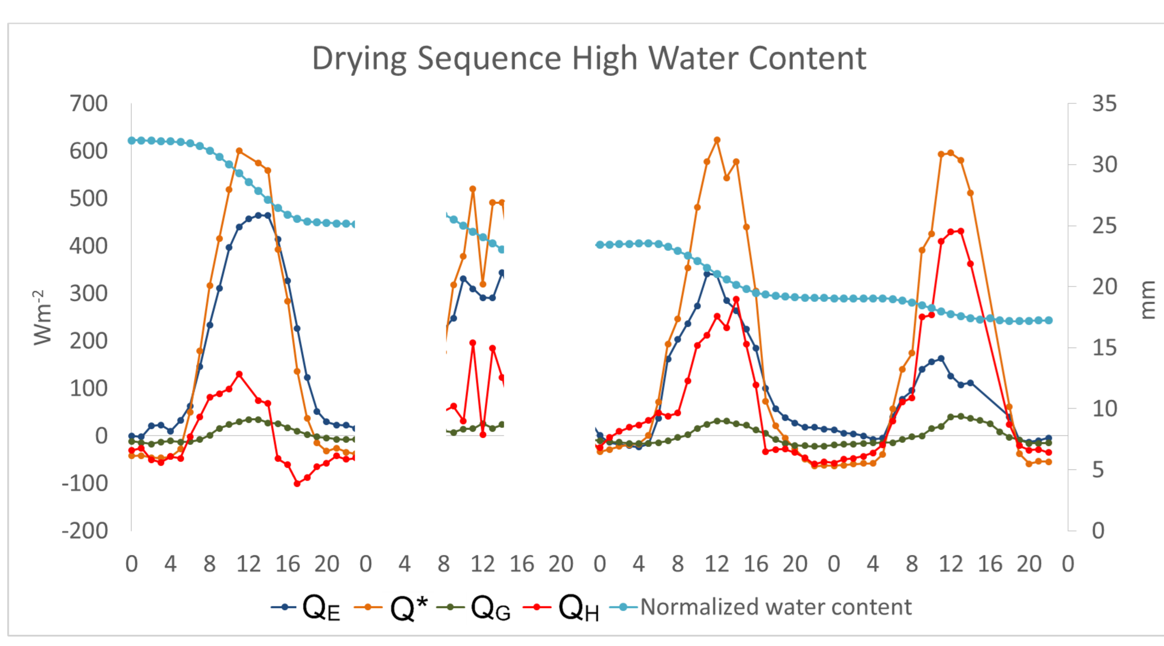
Q* - Net radiation: NR-Lite or Rebs Q7	Q_E - Continuous weighing lysimeters (x2)
Q_G - Soil heat flux plates, T_{soil} and moisture in a single module	Q_H – residual

Radiation Budget and Water Balance

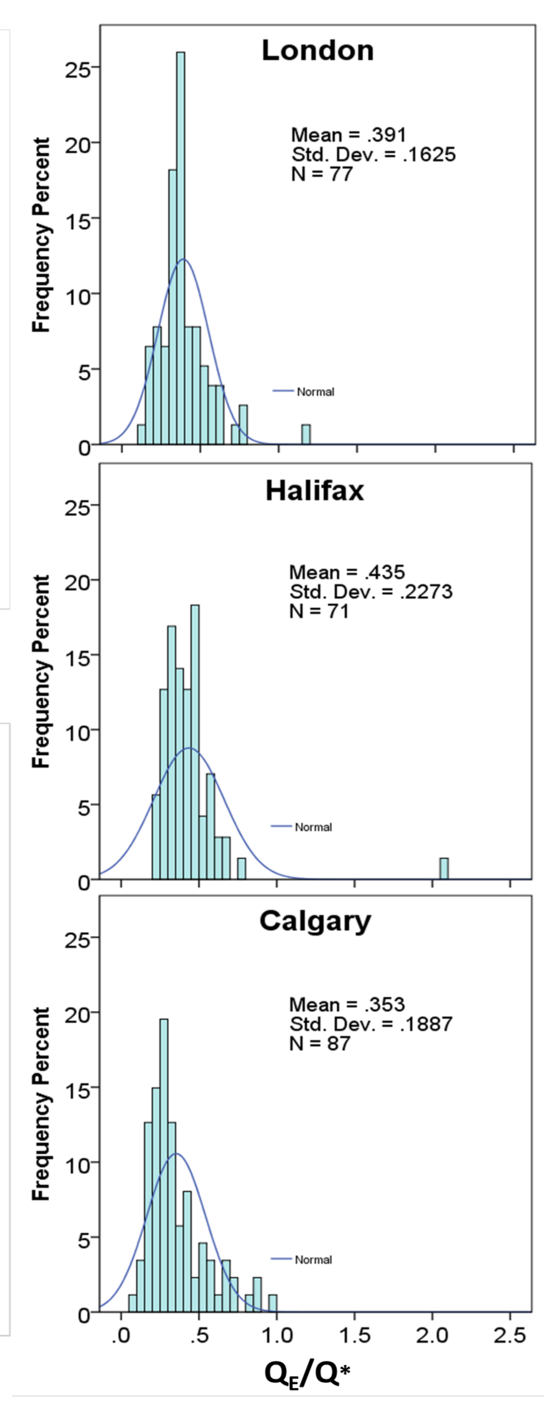
At all sites, basic climate variables, surface temperatures for sedum and bare roof are measured. In London, all components of radiation budget are measured.



London green roof 2014 - 6/5 6/7 6/8



London green roof 2014 - 5/26 5/27 5/28
Normalized water content is mass of lysimeter minus mass at field capacity



London

Month	Daily Flux Ratios Q_E/Q^*	Daily Flux Ratios Q_G/Q^*	Daily Integrated Fluxes K↓	Daily Integrated Fluxes Q^*	Daily Integrated Fluxes Q_E	Daily Integrated Fluxes Q_G	Daily Integrated Fluxes Q_H	Daytime Flux Ratios Q_E/Q^*	Daytime Flux Ratios Q_G/Q^*	Daytime Integrated Fluxes Q_E	Daytime Integrated Fluxes Q_G	Daytime Integrated Fluxes Q^*	Nighttime Flux Ratios Q_E/Q^*	Nighttime Flux Ratios Q_G/Q^*	Nighttime Integrated Fluxes Q_E	Nighttime Integrated Fluxes Q_G	Nighttime Integrated Fluxes Q^*	Total Rainfall
Apr	0.45	0.05	24.22	10.12	4.53	0.49	5.11	0.30	0.10	3.92	1.36	13.03	-0.28	0.42	0.34	-0.64	-1.57	80.96
May	0.61	0.01	26.84	11.92	7.02	0.29	4.61	0.49	0.05	6.68	0.70	13.61	-0.29	0.31	0.25	-0.41	-1.49	77.86
Jun	0.41	0.02	29.95	13.86	5.23	0.38	8.25	0.34	0.06	4.84	0.85	15.06	-0.18	0.34	0.18	-0.41	-1.25	75.95
Jul	0.38	0.02	29.99	13.45	5.10	0.23	8.12	0.34	0.04	4.86	0.60	14.57	-0.07	0.29	0.09	-0.32	-1.18	112.93
Aug	0.38	0.02	31.03	12.29	4.55	0.20	7.54	0.34	0.05	4.49	0.67	13.34	0.05	0.39	-0.06	-0.39	-1.03	67.23
Sep	0.31	0.02	28.94	10.57	3.32	0.18	7.07	0.31	0.06	3.45	0.72	10.89	0.37	0.48	-0.41	-0.55	-1.16	186.87
Oct	0.32	-0.01	25.52	5.75	1.59	-0.05	4.21	0.21	0.06	1.40	0.42	6.95	-0.03	0.36	0.03	-0.48	-1.42	70.24

Halifax

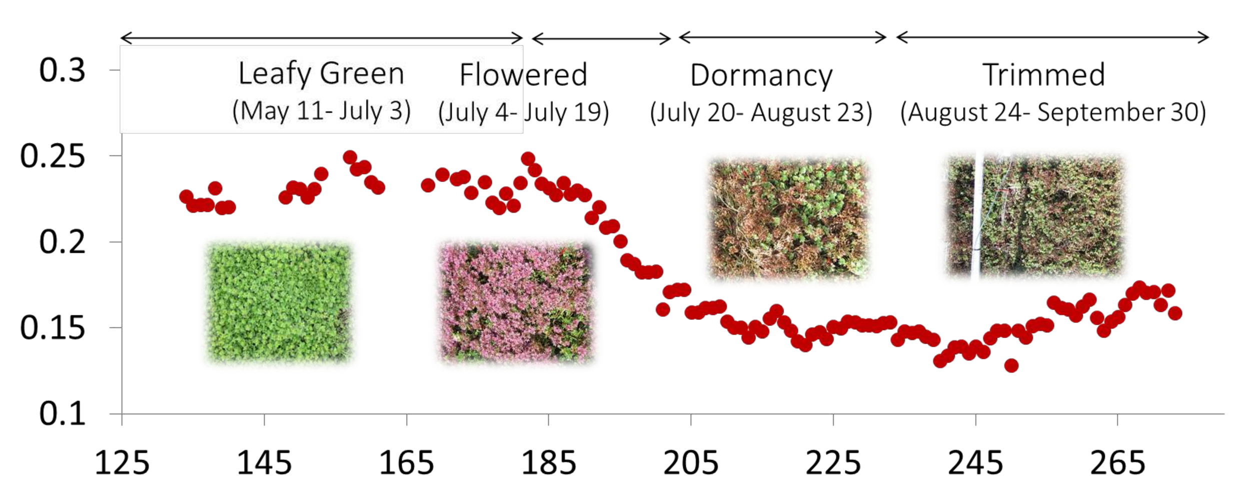
Month	Daily Flux Ratios Q_E/Q^*	Daily Flux Ratios Q_G/Q^*	Daily Integrated Fluxes K↓	Daily Integrated Fluxes Q^*	Daily Integrated Fluxes Q_E	Daily Integrated Fluxes Q_G	Daily Integrated Fluxes Q_H	Daytime Flux Ratios Q_E/Q^*	Daytime Flux Ratios Q_G/Q^*	Daytime Integrated Fluxes Q_E	Daytime Integrated Fluxes Q_G	Daytime Integrated Fluxes Q^*	Nighttime Flux Ratios Q_E/Q^*	Nighttime Flux Ratios Q_G/Q^*	Nighttime Integrated Fluxes Q_E	Nighttime Integrated Fluxes Q_G	Nighttime Integrated Fluxes Q^*	Total Rainfall
May	0.50	0.01	16.85	8.41	4.22	0.18	4.00	0.37	0.11	3.48	1.02	9.28	-0.20	0.42	0.32	-0.68	-1.11	18.80
Jun	0.54	0.04	24.82	12.34	6.64	0.47	5.22	0.42	0.09	6.05	1.29	14.14	-0.13	0.17	0.48	-0.60	-1.40	127.81
Jul	0.36	0.03	23.66	12.29	4.26	0.35	7.67	0.24	0.08	3.25	1.11	13.57	-0.10	0.23	0.53	-0.52	-1.22	29.60
Aug	0.35	0.04	19.80	10.02	3.41	0.38	6.23	0.23	0.10	2.63	1.17	11.59	-0.15	0.19	0.46	-0.59	-1.53	52.63
Sep	0.39	0.05	18.22	7.44	2.86	0.37	4.21	0.21	0.14	2.10	1.36	9.92	-0.12	0.19	0.56	-0.85	-2.47	124.15
Oct	0.58	0.19	9.71	3.35	1.56	0.41	1.37	0.22	0.20	1.04	0.89	5.00	-0.25	0.10	0.30	-0.51	-1.67	98.21

Calgary

Month	Daily Flux Ratios Q_E/Q^*	Daily Flux Ratios Q_G/Q^*	Daily Integrated Fluxes K↓	Daily Integrated Fluxes Q^*	Daily Integrated Fluxes Q_E	Daily Integrated Fluxes Q_G	Daily Integrated Fluxes Q_H	Daytime Flux Ratios Q_E/Q^*	Daytime Flux Ratios Q_G/Q^*	Daytime Integrated Fluxes Q_E	Daytime Integrated Fluxes Q_G	Daytime Integrated Fluxes Q^*	Nighttime Flux Ratios Q_E/Q^*	Nighttime Flux Ratios Q_G/Q^*	Nighttime Integrated Fluxes Q_E	Nighttime Integrated Fluxes Q_G	Nighttime Integrated Fluxes Q^*	Total Rainfall
May	0.54	0.12	20.81	11.63	6.14	1.51	3.97	0.35	0.16	4.88	2.23	13.99	-0.47	0.52	0.63	-0.71	-1.41	69.66
Jun	0.59	0.05	23.42	13.04	7.66	0.81	4.58	0.32	0.08	4.69	1.19	14.54	-0.36	0.35	0.41	-0.39	-1.18	89.28
Jul	0.27	0.06	23.85	12.30	2.51	0.96	8.82	0.14	0.11	1.98	1.52	13.85	-0.21	0.34	0.27	-0.47	-1.42	18.69
Aug	0.29	0.09	17.33	9.71	2.79	0.91	6.01	0.20	0.16	2.18	1.72	10.97	-0.18	0.56	0.29	-0.94	-1.67	43.90
Sep	0.39	-0.35	13.28	7.14	2.15	0.30	4.68	0.17	0.19	1.47	1.91	9.07	-0.28	0.85	0.43	-1.01	-1.57	57.57
Oct	0.42	-0.31	9.38	3.36	1.06	-0.50	2.80	0.12	0.14	0.69	0.88	6.03	-0.16	0.51	0.35	-1.11	-2.23	7.25

2014 data. Only days with no rain or no missing data included, therefore this data is biased toward clear sky days. All data are calculated from hourly data integrated over a day, daytime, or nighttime. Flux ratios are performed on a per day basis. All per day data are averaged over a month. Daily flux ratios are skewed by low Q* days which disproportionately bias averages late in season.

Q_E changes rapidly through time, especially following rain events. Distribution of daily Q_E/Q^* is asymmetric.



Daily albedo through time (in year days), calculated from fixed instruments by integrating K↓ and K↑ for Z < 85° for London. The albedo of the green roof changes throughout the summer as the plants go through their phenological stages.

A comparison of the 3 sites indicates:

- *Q_E/Q^* lower in Calgary*
- *Q_E high in spring relative to other months for all sites*
- *High rainfall does not necessarily coincide with high Q_E/Q^**
- *Q_G more important in Calgary than other sites*

References:

Oke, T. R. 1997. "Surface Climate Processes." The Surface Climates of Canada. Montreal: McGill-Queen's UP, 1997. 21-43.

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