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THE EPiCC VANCOUVER EXPERIMENT : HOW DO URBAN VEGETATION CHARACTERISTICS AND GARDEN IRRIGATION CONTROL THE LOCAL-SCALE ENERGY BALANCE?

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1 INTRODUCTION

The Environmental Prediction in Canadian Cities (EPiCC) network is seeking to improve Canada's weather forecasting system for urban areas. Further the EPiCC network will contribute to models that will support a better system for conservation of water resources and support sustainable design in cities (Voogt et al., same conference). Whilst the performance of current urban canopy parameterizations such as the Town Energy Balance (TEB) Scheme (Masson, 2000) has been excellent at several relatively dry sites in densely built areas (Masson 2002, Lemonsu et al., 2004) - it has been less tested and less successful at more vegetated suburban environments with extensive irrigation. The role of anthropogenic water release associated with irrigation / sprinkling of urban green-space can be large in suburban residential areas, rivaling precipitation as the main source of external water availability. The wet-dry contrasts of adjacent urban surfaces that result from irrigation and paving are further known to boost evaporation in a non-linear fashion.

We discuss results in the framework of the neighborhood-scale urban energy balance following Oke (1998):

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S \qquad (1)$$

Q^* is net all-wave radiation, Q_H and Q_E are the latent and sensible heat flux densities. ΔQ_S is the storage heat flux density in the three-dimensional urban interface, and Q_F is the anthropogenic heat flux density. In analogy, the urban water balance can be written as:

$$p + F + I = E + \Delta r + \Delta S \qquad (2)$$

where p is precipitation, F water released due to combustion, I is irrigated water, E is evapotranspiration, Δr is run-off and drainage and ΔS is water storage change in urban soils and fabrics.

2 METHODS

In this contribution, data from two contrasting neighborhoods in Vancouver, BC, Canada are used in combination with a rural reference site to explore the effect of urban vegetation and garden irrigation on the urban energy and water balance.

The two suburban neighborhoods that are part of this study are composed of single-family residences. The neighborhoods are 4 km apart from each other and we assume they have the same atmospheric forcing, however the urban structure is significantly different: 'Vancouver-Sunset' is subdivided into smaller lots and has a low fraction of lawns, and a high degree of impervious ground cover (roads, sidewalks, concrete etc). In the 'Vancouver-Sunset' neighborhood irrigation is mainly done manually. 'Vancouver-Oakridge' on the other hand has substantially less buildings per area, but with a larger volume / plan area, and a high fraction of vegetated surfaces. In 'Vancouver-Oakridge', 61% of all lawns have automatic sprinkling systems installed (Tab. 1, Fig. 1). A rural reference site 'Westham Island' is located on flat, unmanaged and non-irrigated grassland, 16 km to the south of the two urban neighborhoods in an area that is dominated by intensive farming.

Each of the three sites was equipped with measurement systems that provide continuous data of Q^*, Q_H and Q_E (Q_H and Q_E by means of eddy covariance, Tab. 2). Advection of energy on the neighborhood-scale was neglected, and ΔQ_S and Q_F together form

Table 1: Land cover and site characteristics in the footprint of the two suburban energy balance sites. Data is from LIDAR, satellite and aerial photo analysis.

Site	*Vancouver-Sunset*	*Vancouver-Oakridge*
Land-use	Residential suburban	Residential suburban
Homes / ha	19	9
Plan area fraction of buildings λ_P	21%	23%
Plan area fraction of roads and concrete λ_R	35%	21%
Plan area fraction of vegetation λ_V	44%	56%
Average building height z_h	6.6 m	
Average plan area of buildings	110 m^2	255 m^2
Homes with automatic lawn sprinkling systems	61%	1%
Homes with regular or irregular manual lawn irrigation	34%	79%
Homes with no lawn irrigation	5%	20%

Fig 1: Two typical lots: (left) in the 'Vancouver-Sunset' neighborhood with manual or no lawn irrigation and (right) in the 'Vancouver-Oakridge' neighborhood with predominantly automatic lawn sprinkling systems.

the residual term in this study. Details of the instrumentation are summarized in Tab. 2. Flux densities were calculated for 30-minute block averages following standard protocols.

In the immediate neighborhood of the two urban towers, eight homes have been intensively monitored for water use, soil physics, and soil hydrology. The lots have been chosen to represent a variety of irrigation regimes and different building volumes, materials and ages. Those eight sites feature each a continuously operated TDR system to estimate ΔS, soil temperature, soil-heat flux, and surface wetness sensors in a representative location. Further water meters were installed to measure daily water use (Fig. 2). In 2008, water conservation regulations in the city of Vancouver restricted automatic lawn irrigation from June 1 to September 30. Lawn sprinkling was allowed only from 4 to 9 am and 7 to 10 pm on Wednesday and Saturday (odd numbered addresses) and on Thursday and Sunday (even numbered addresses) at the same times of day. On Monday, Tuesday and Friday, no lawn sprinkling was permitted. On one lawn area per neighborhood, precipitation p was monitored using a rain gauge.

Table 2: Instrumentation of the energy balance towers and the homes monitored.

Site	*Vancouver-Sunset*	*Vancouver-Oakridge*	*Westham Island*
Height of EC and radiation measurements	28 m 4.2 z_h	29 m 4.1 z_h	1.5 - 2 m
Q^*	Kipp & Zonen CNR1	Kipp & Zonen NR Lite	Kipp & Zonen CNR1
Q_H	CSI CAT-3	CSI CAT-3	CSI CAT-3
Q_E	CSI CAT-3 / Licor 7500	CSI CAT-3 / Licor 7500	CSI CAT-3 / Licor 7500
ΔQ_S	Residual and 4 x Middleton HFP	Residual and 4 x Middleton HFP	3 x Middleton HFP
Soil Volumetric Water Content	4 x CSI CS 616	4 x CSI CS 616	2 x CSI CS 616
Precipitation	RM Young 52203	Environ. Canada	RM Young 52203

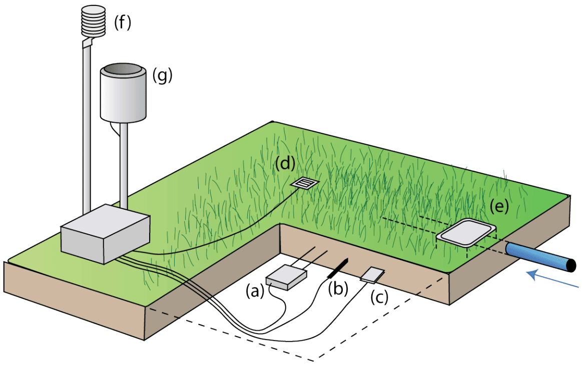

Fig 2: Instrumentation of the eight soil hydrology sites: (a) Time domain reflectometry (TDR, CS616 at 5cm depth), (b) Soil temperature sensor (thermocouple at 5 cm depth), (c) Soil heat flux plate (Middleton, at 5cm depth), (d) Surface wetness sensors, (e) water meter that measures the individual water use of each building. On one lawn per neighborhood there was also (f) screen level temperature / humidity sensor and (g) rain gauge installed.

3 RESULTS AND DISCUSSION

Figure 3 shows the daily totals of Q_E / Q^*, precipitation p and average soil volumetric water content over three consecutive summertime months at the two urban EC sites (for Oakridge, data is only available from July 9 to August 27, 2008). The figure illustrates the evident relationship between water availability (primarily due to input by precipitation and storage in the soil shown as the changing soil volumetric water content) - and Q_E / Q^*. Generally, Vancouver-Oakridge is characterized by slightly but consistently higher Q_E / Q^* values than Vancouver Sunset due to its high fraction of intensively irrigated lawns and a higher vegetation plan area fraction.

The highlighted week (August 11 – August 17, 2008) is a mostly clear-sky period with no precipitation. Figure 4 shows the ensemble diurnal course of all energy balance components for this week at all three sites. Table 3 summarizes the daily totals and the relative daytime ratios of the turbulent energy flux densities in relation to Q^*, and the daytime Bowen ratio $\beta = Q_H / Q_E$.

Table 3: Energy balance flux densities and ratios for the week August 11 to August 17, 2008. Daytime values are average values from 10:00 to 16:00 LST.

	Vancouver-Sunset	Vancouver-Oakridge	Westham Island
Total daily Q^* ($MJ\ m^{-2}\ d^{-1}$)	11.34	10.32	13.01
Total daily $Q_{H\,*}$ ($MJ\ m^{-2}\ d^{-1}$)	8.2	5.6	5.0
Total daily $Q_{E\,*}$ ($MJ\ m^{-2}\ d^{-1}$)	2.9	3.8	4.9
Daytime Q_H^*/Q_H	0.59	0.45	0.38
Daytime Q_E^*/Q_H	0.17	0.25	0.33
Daytime $\beta=Q_H/Q_E$	3.43	1.86	1.13

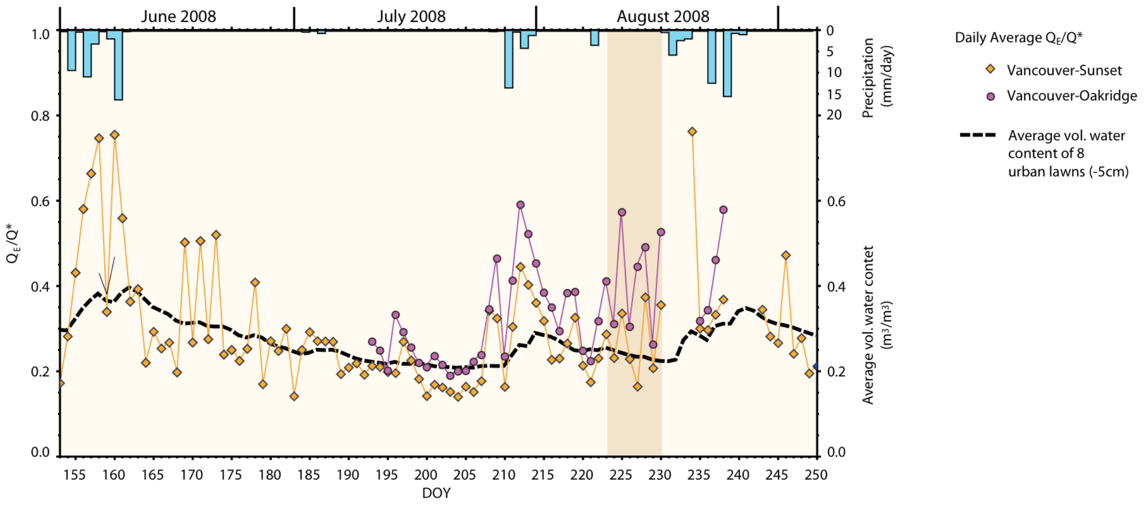

Fig 3: The ratio of the daily totals of Q_E and Q at Vancouver sunset (orange) and Vancouver Oakridge (purple) over the period June 1 to September 9, 2008. Also indicated is daily total precipitation (top) and the average volumetric water content measured at the 8 lawns. Note, 'Vancouver-Oakridge' was operated from July 9 to August 27 only.*

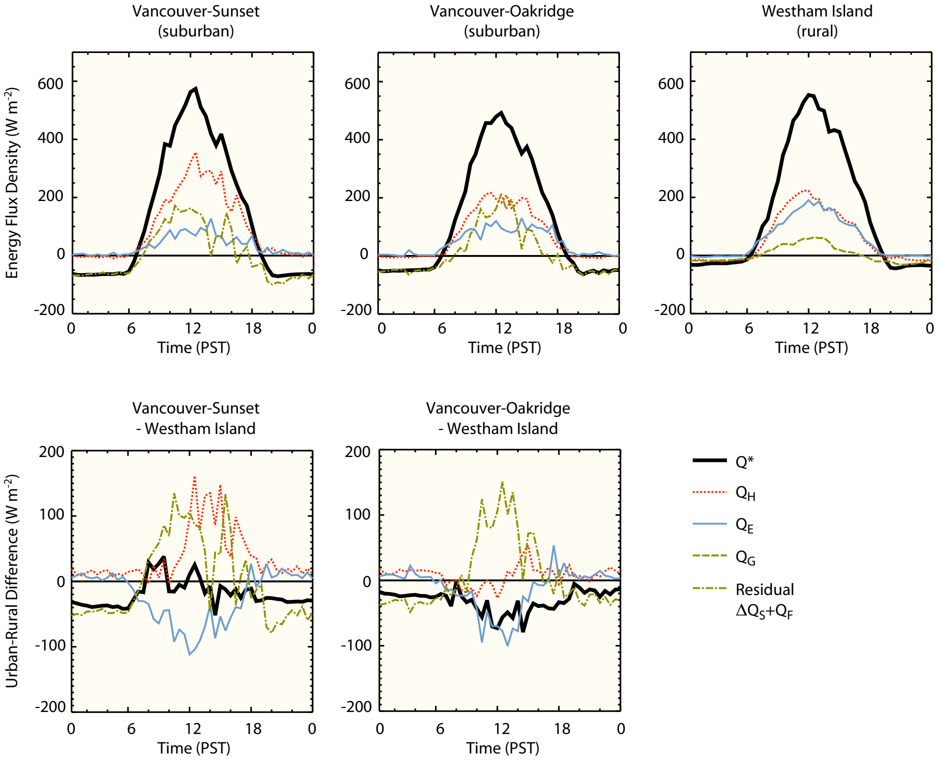

Fig 4: Ensemble energy balance for the week August 11 to August 17, 2008. The top row shows the measured and residual components of the energy balance, the bottom row are urban-rural differences.

Net all-wave radiation Q* is reduced compared to the rural value at both urban sites because of a lower albedo (Vancouver Sunset: 10.9% vs. Westham Island: 14.7%), and increased long-wave emittance $L_{\uparrow}$ (Vancouver Sunset: 38.7 MJ m^{-2} d^{-1} vs. Westham Island: 35.7 MJ m^{-2} d^{-1}).

As expected, the daytime β increases with decreasing vegetation fraction from 1.1 (Westham Island, λ_V = 100%) to 1.9 (Vancouver Oakridge, λ_V = 56%) to 3.4 (Vancouver Sunset, λ_V = 44%). In absence of irrigation, urban ecosystem Q_E – as measured by eddy covariance – is often modeled as a linear addition of

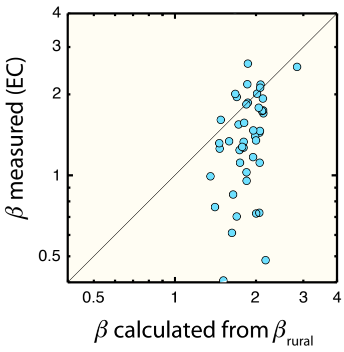

Fig. 5: Predicted urban Bowen ratio β based on urban vegetation fraction λ_V and the rural measured β_{rural} vs. directly measured urban β from the eddy covariance site. Data is from the four days with irrigation in the week Aug 11 to Aug 17, 2008. The systematic overestimation by the linear addition approach suggests that lawn irrigation is an important water source.

Q_{Ev} from the vegetated urban fraction (e.g. using a regular SVAT scheme) and Q_{Ei} from the impervious fraction (using a 'bare' urban surface parameterization):

$$Q_E = \lambda_v Q_{Ev} + (1 - \lambda_V) Q_{Ei} \tag{3}$$

For the discussed week with no precipitation it is justified to assume that Q_{Ei} from impervious surfaces is negligible small, so $\beta_i \rightarrow \infty$. Then, β of the urban ecosystem can be calculated in a simplified form of the relationship based on (3) as described in Christen and Vogt (2004):

$$\beta = \frac{1}{\lambda_V} + \beta_v - 1 \tag{4}$$

Further, in absence of irrigation and assuming that the rural site responds similarly to a vegetated urban surface, we can set $\beta_v = \beta_{rural}$ to evaluate if the above relation holds. Figure 5 shows the calculated β based on Eq. (4) and using the rural value $\beta_{rural} = \beta v$ vs. the measured β at Vancouver Oakridge. The measured urban β is significantly lower (i.e. the urban Q_E is relatively higher) than predicted by Eq. 4 taking the vegetation fraction into account.

There are two explanations for this failure: (i) As mentioned in the introduction, this approach neglects the fact that wet-dry contrasts of adjacent urban patches can boost evaporation in a non-linear fashion and (ii) it completely ignores anthropogenic water input - primarily lawn irrigation.

To estimate the magnitude of lawn irrigation, continuous readings from the water meters installed at the eight properties / buildings were stratified by day of the week. Weekdays when irrigation was permitted (Wed, Thu, Sat, Sun) show significantly elevated water consumption (Fig 6).

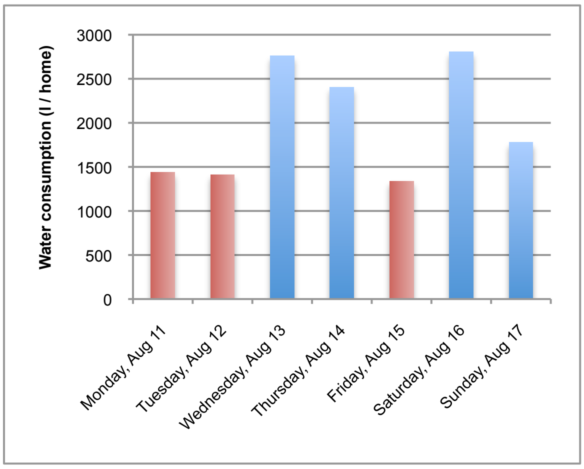

Fig. 6: Measured water consumption per building (average of Vancouver-Sunset and Vancouver-Oakridge). In blue are days with lawn sprinkling permitted for either odd or even numbered addresses, red indicates day when lawn sprinkling was not permitted at all.

In the Oakridge neighborhood, the base-line water consumption for in-home use was estimated 1264 l per building and day from the days when automatic irrigation was not permitted. On weekdays with irrigation permitted, an additional 2262 l was consumed per building and day (Note that Fig. 6 shows the average of Vancouver Sunset and Vancouver Oakridge, and not only Oakridge). This difference was then multiplied by 4/7 to upscale to the whole week and via building density (9 homes / ha) converted to mm d^{-1} for the whole urban surface.

Table 4 shows the average daily water balance in mm d^{-1}. Lawn irrigation is the largest water input (1.16 mm d^{-1}), followed by change in soil water content (0.52 mm d^{-1}). The two together come close to the measured loss through evapotranspiration (1.57 mm d^{-1}).

Tab. 4: Average measured and estimated water balance components in the Vancouver Oakridge neighborhood during the period August 11 to August 17, 2008.

Precipitation *p* (directly measured)	0.00	mm d^{-1}
Lawn irrigation *I* (measured and up-scaled, see text)	1.16	mm d^{-1}
Water release by combustion *F* (upper estimate via CO_2 flux density)	< 0.01	mm d^{-1}
Evapotranspiration *E* (directly measured by EC)	1.57	mm d^{-1}
Soil moisture change ΔS (measured by TDR)	-0.52	mm d^{-1}
Run-off / drainage (residual term)	0.12	mm d^{-1}

4 CONCLUSIONS

Vegetation fraction and lawn irrigation significantly affect the partitioning of turbulent fluxes in the energy balance of a North American suburb. In the study area, lawn irrigation was the most important water input during the analyzed summertime week. Lawn irrigation increases urban Q_E significantly compared to a non-urban Q_E weighted by the corresponding urban vegetation fraction. Therefore, an appropriate modeling of the urban energy balance in Vancouver must - in addition to inclusion of the anthropogenic heat flux Q_F - also take anthropogenic water input through lawn irrigation into account.

Note, from the current analysis it is not clear what the effect of a potential enhancement of Q_E by micro-scale advection as a consequence of wet-dry patches is. In any case, inhabitants will likely adjust their rate of irrigation to compensate for the latter effect.

ACKNOWLEDGEMENTS

The Environmental Prediction in Canadian Cities (EPiCC) Network is funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). Selected research infrastructure was supported by NSERC RTI (Christen, #344541-0) and NSERC Discovery Grants (Christen, Oke). We acknowledge support by BC hydro, the City of Vancouver, all home owners who allowed us to install meters and sensors on their lawns, and the technical contributions by Jonathan Bau, Kate Liss, Rick Ketler, Zoran Nesic and Chad Siemens.

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