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the energy balance approach to green roofs and hydrology

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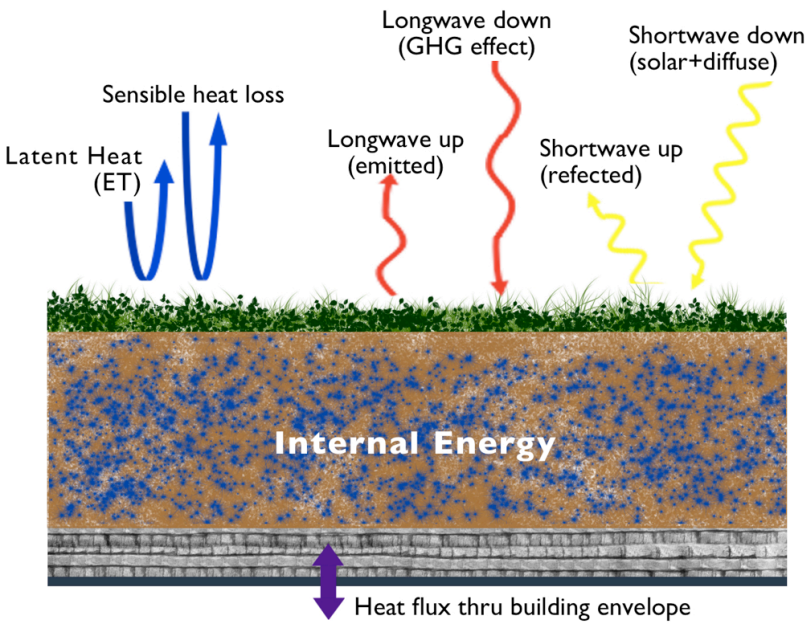
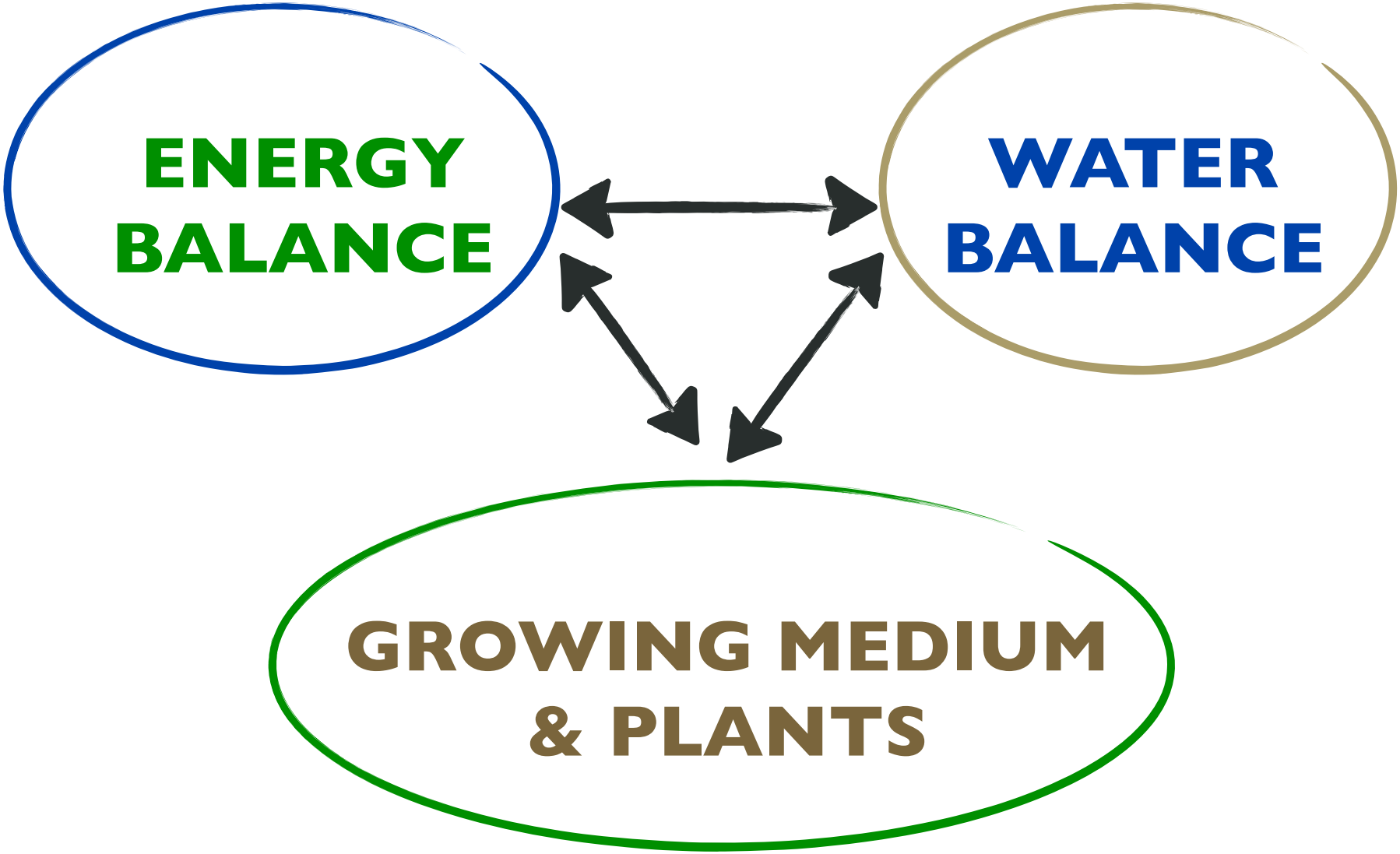
Surface Energy Balance Modeling Is a Powerful Tool



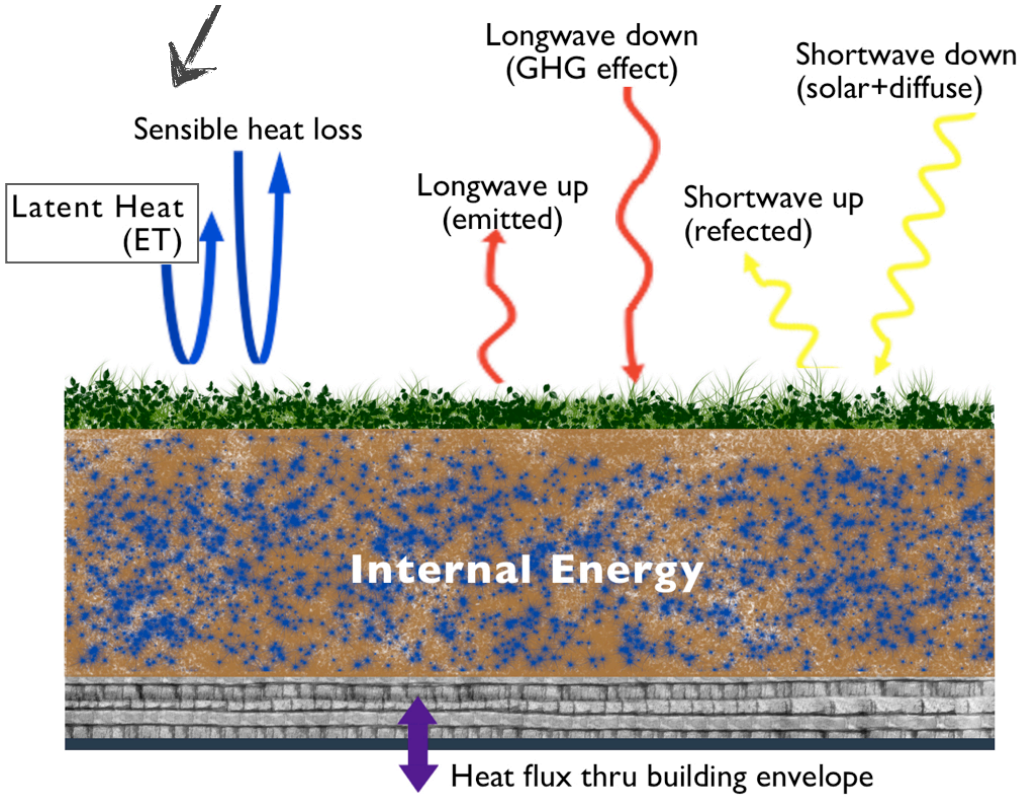
- What albedo is needed on a white roof to match green roof temperatures ?
- How large is ET cooling compared to other heat loss terms ?
- What are the cooling and heating season energy benefits of green roofs ?
- What is the 'equivalent R-value ' of a green roof ?
- **What is the seasonal and annual water retention of a green roof ?**

DIFFERENT DISCIPLINARY POINTS OF VIEW PROVIDE EQUALLY VALID APPROACHES

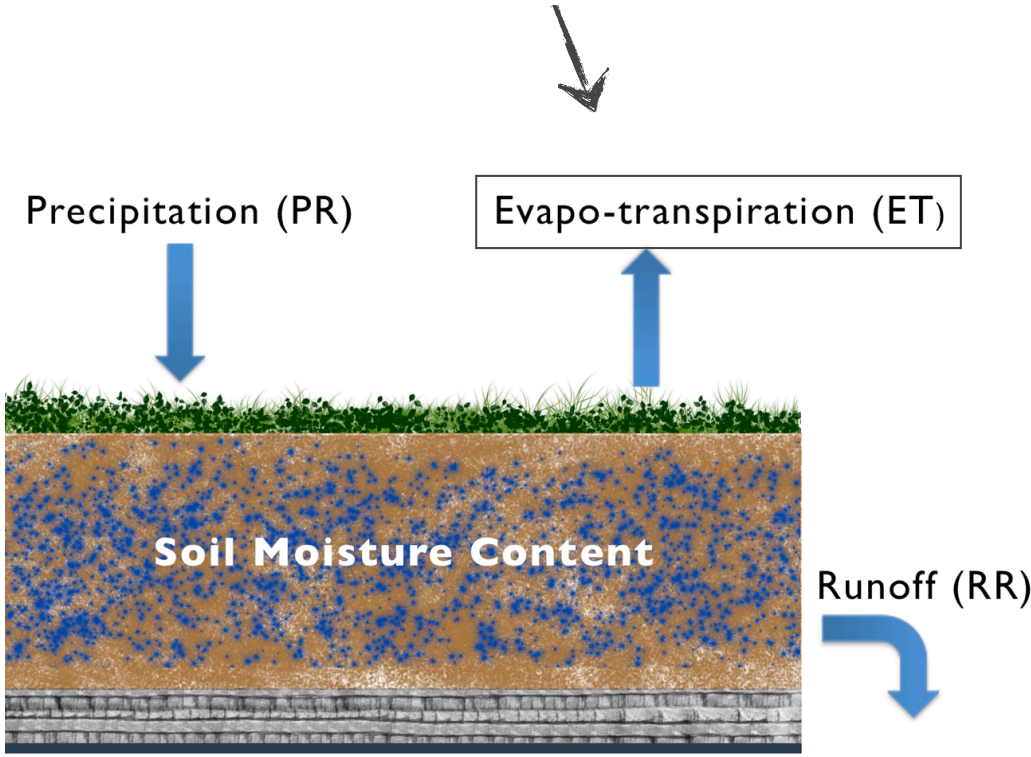


ENERGY AND WATER BALANCE ARE FUNDAMENTALLY CONNECTED BY **ET**

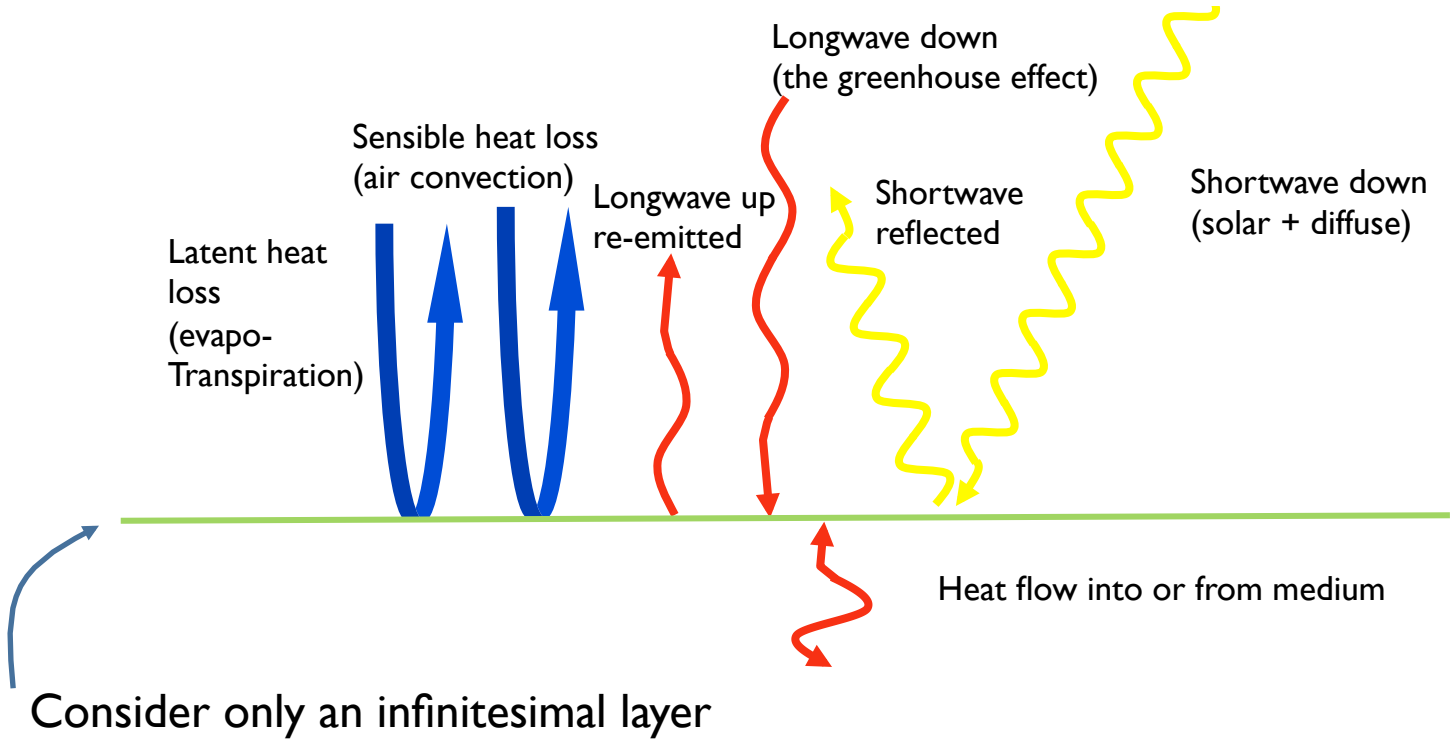
GREEN ROOF ENERGY BUDGET



GREEN ROOF WATER BUDGET



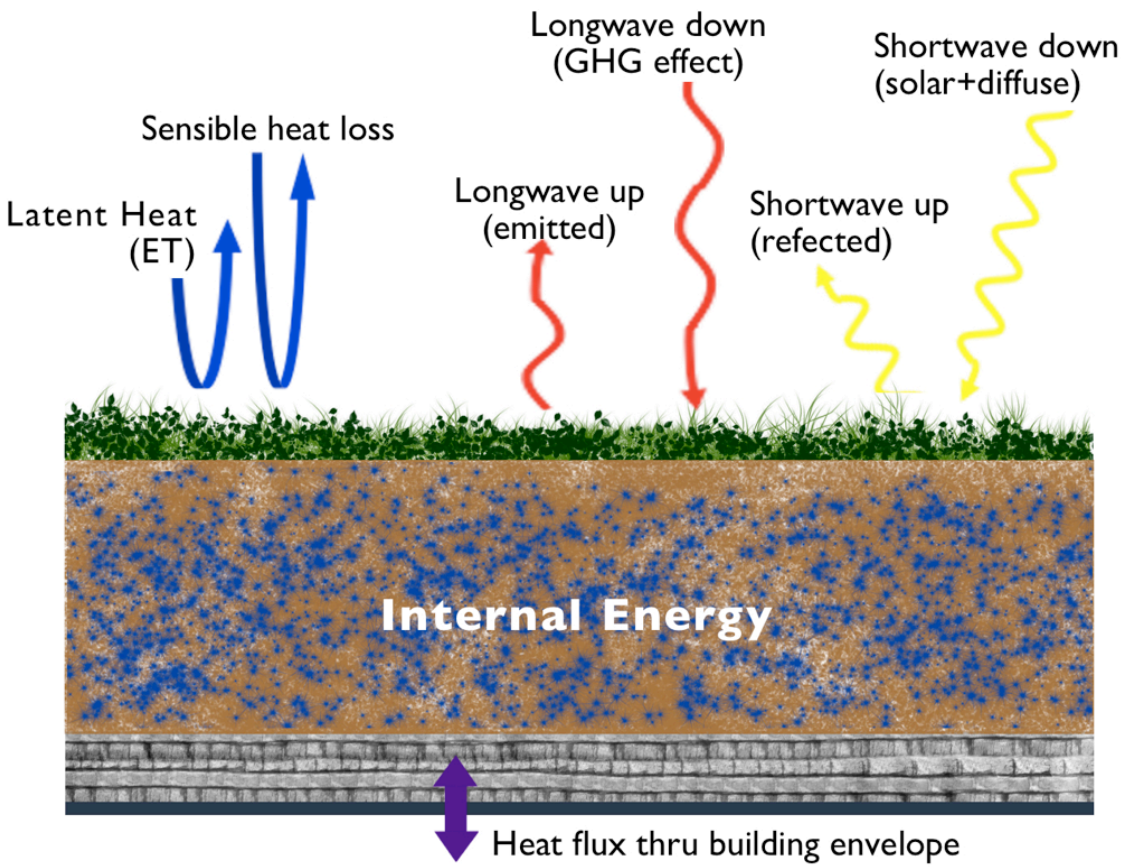
Different Approaches To Surface Energy Balance



<u>PROS</u>: Can ignore 'internal energy' heat flows like the temperature of water entering and leaving, or changes in internal energy due to temperature, etc

<u>CONS</u>: Need to solve the surface heat flow equation for a complex plant-soil system.

Or Consider a Finite Test Volume



PROS: More simply able to measure or monitor heat flow to or from building below.

CONS: May have to track internal energy changes including temperature of water entering and leaving test volume, etc.

We use the time-integrated energy balance equation to solve for latent heat flux:

$$\int (SW\uparrow + SW\downarrow + LW\uparrow + LW\downarrow) = \int SH + \int LH - \int \text{Heat Cond Below}$$

$$+ \cancel{\int \text{Internal Green Roof Energy Change Rate}}$$

small over time

what we're after retention

$$\int (SW\uparrow + SW\downarrow + LW\uparrow + LW\downarrow) \approx \int SH + \int LH - \int \text{Heat Cond Below}$$

Allwave Radiometer data

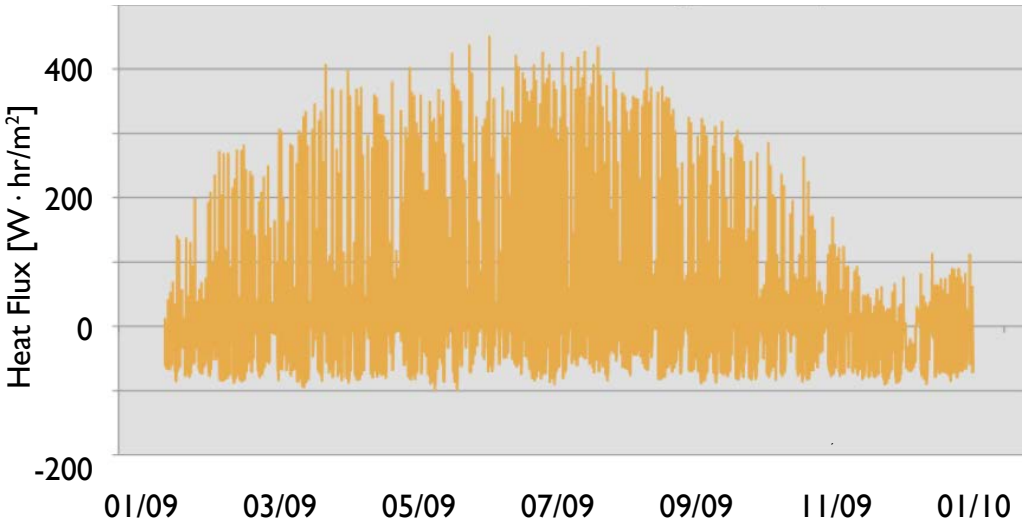
Sensible heat model using weather station data

Heat flux to & from building using R-value & temperature gradient

2009 ENERGY BALANCE FLUXES AT CON EDISON

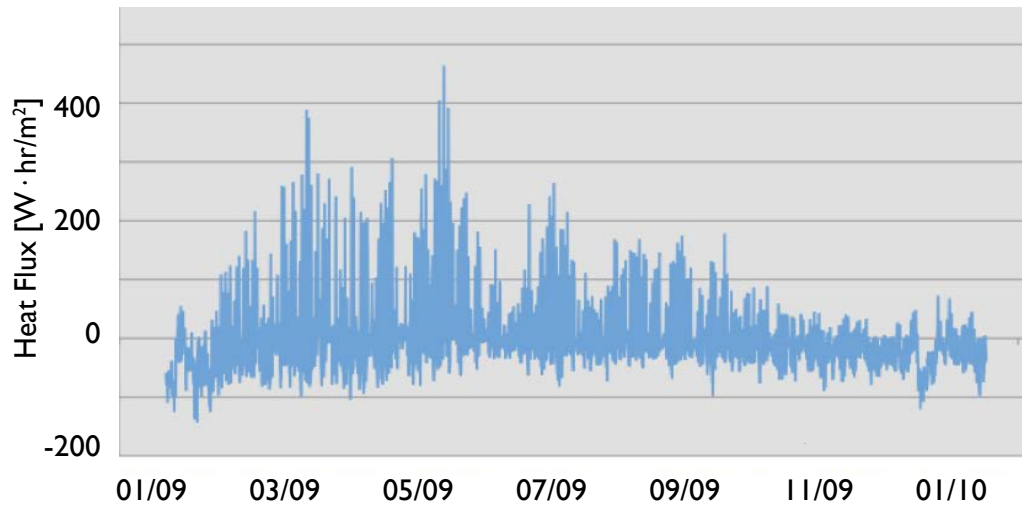
NET ALL-WAVE RADIATION

Cumulative Annual Value = +172,618 W•hr/m²



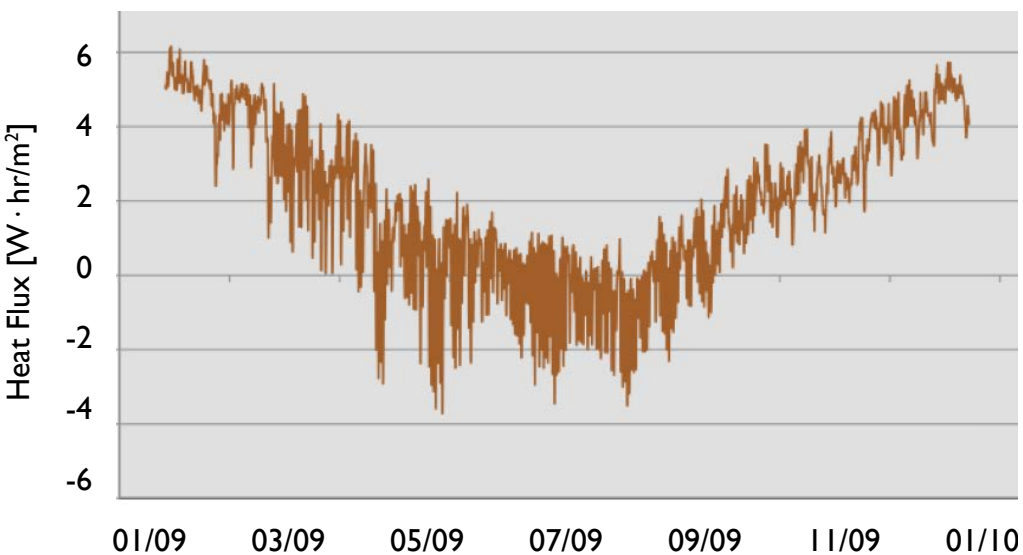
SENSIBLE HEAT FLUX

Cumulative Annual Value = + 39,616 W•hr/m²



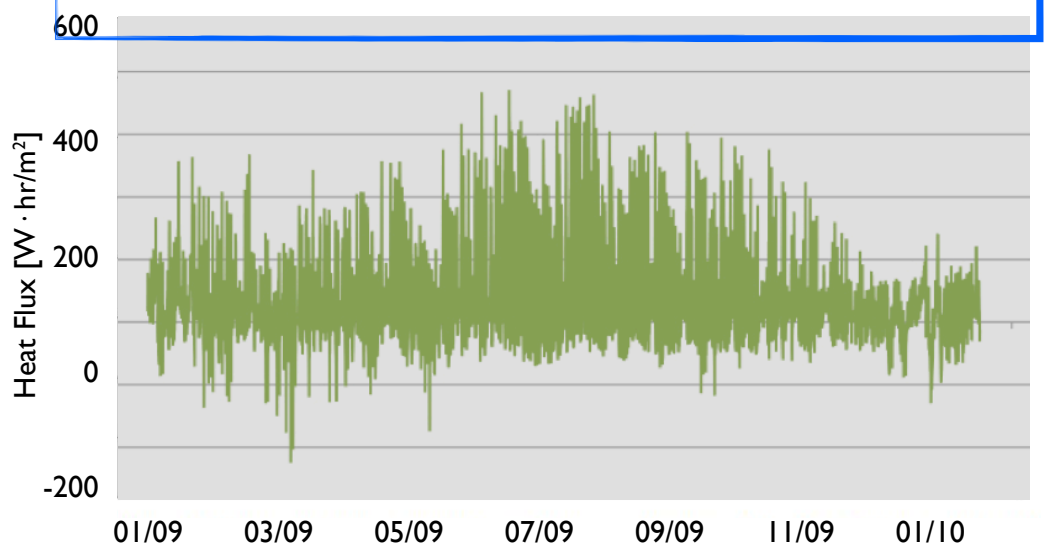
HEAT FLUX FROM BELOW

Cumulative Annual Value = +17,015 W•hr/m²



LATENT HEAT FLUX + INTERNAL ENERGY

Cumulative Annual Value = +229,249 W•hr/m²

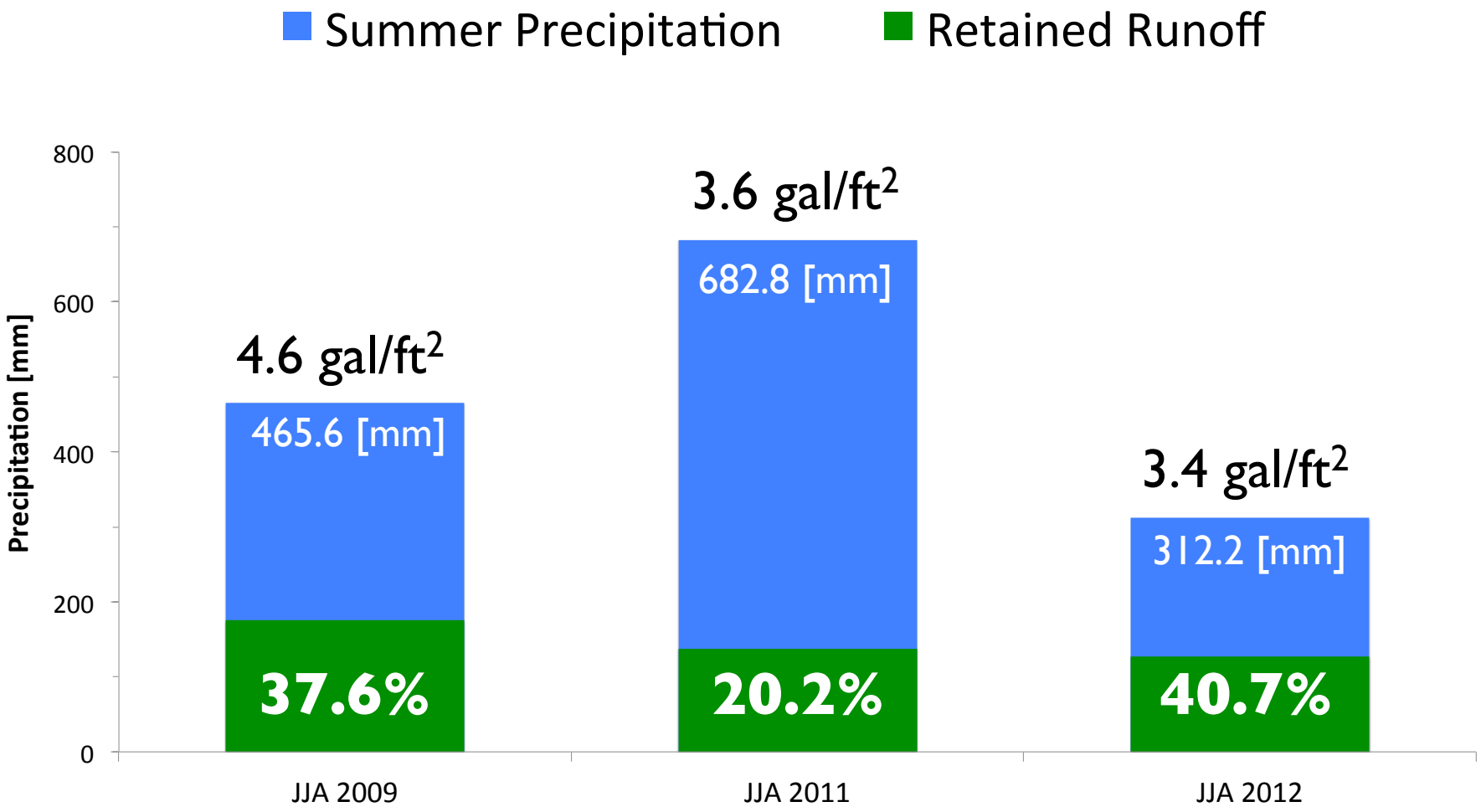


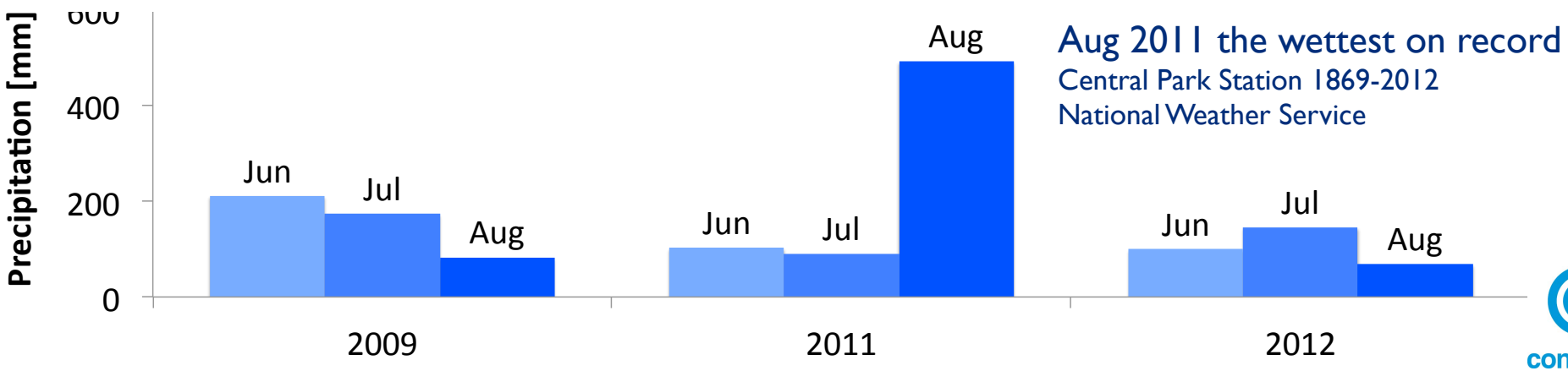
Gaffin *et al.*, 2011

Converting ET to % rainfall (etc.) retained by green roof:

$$\mathrm{ET}\,[\mathrm{W}\cdot\mathrm{hr}] \rightarrow \frac{\mathrm{ET}\,[\mathrm{W}\cdot\mathrm{hr}]}{\ell_{\mathrm{V}}\cdot[\mathrm{Joules}\cdot\mathrm{kg}^{-1}]} \rightarrow \mathrm{H_2O}\ [\mathrm{kg}] \rightarrow \frac{\mathrm{H_2O}\ [\mathrm{kg}]}{\rho_{\mathrm{H_2O}}\left[\mathrm{kg}\cdot\mathrm{m}^{-3}\right]} \rightarrow$$

$$\rightarrow \mathrm{H_2O}\ [\mathrm{m}^3] \rightarrow \frac{\mathrm{H_2O}\ [\mathrm{m}^3]\ \text{of Evapotranspiration}}{\mathrm{H_2O}\ [\mathrm{m}^3]\ \text{of Preciptation}} \mapsto \boxed{\%_{\mathrm{RETAINED}}}$$


Summer Precipitation
Retained Runoff
Precipitation [mm]
800
600
400
200
0
4.6 gal/ft2
465.6 [mm]
37.6%
3.6 gal/ft2
682.8 [mm]
20.2%
3.4 gal/ft2
312.2 [mm]
40.7%
JJA 2009
JJA 2011
JJA 2012


Precipitation [mm]
400
200
0
Jun
Jul
Aug
Jun
Jul
Aug
Jun
Jul
Aug
2009
2011
2012
Aug 2011 the wettest on record
Central Park Station 1869-2012
National Weather Service

conEdison

Comparing different sensor methods

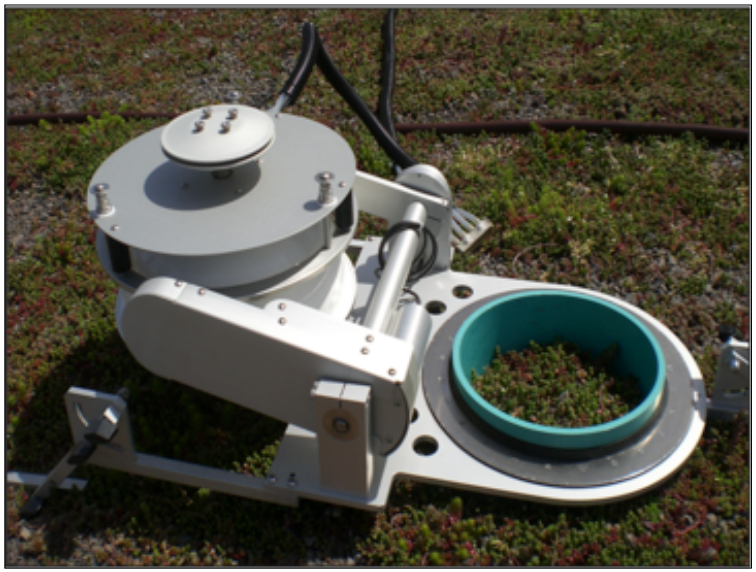
SURFACE ENERGY BALANCE

®CCSR

FLOW METER MEASUREMENT

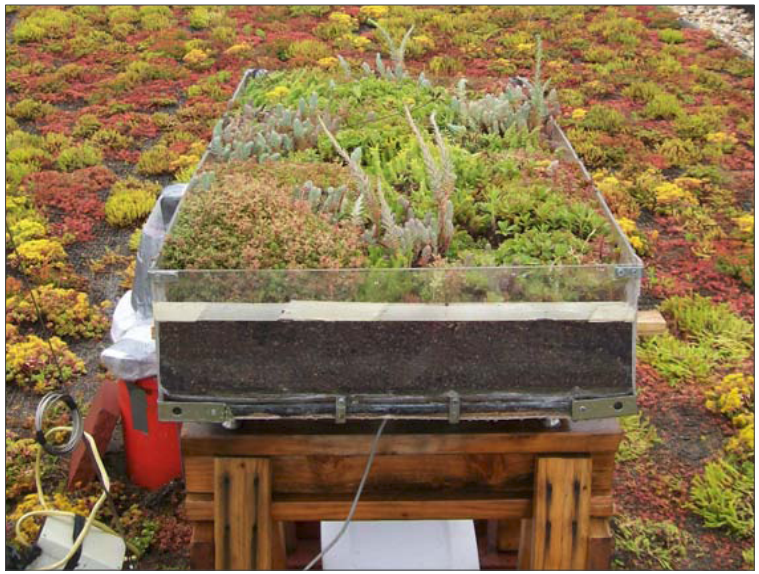
®D Marasco

ENCLOSURE METHOD



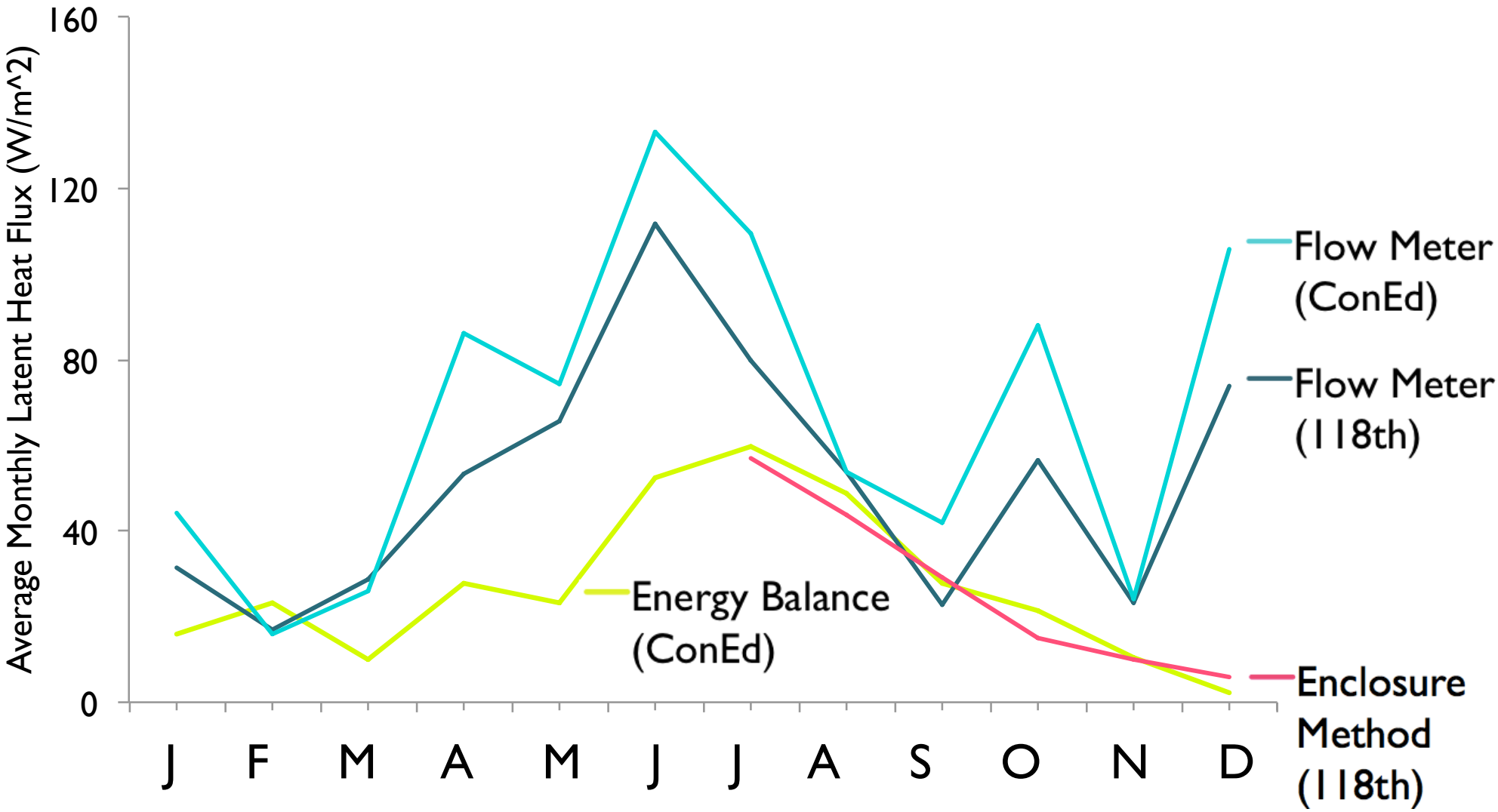
®D. Marasco

WEIGHING LYSIMETER



® K DiGiovanni

MONTHLY LATENT HEAT FLUX VALUES (2009)



Comparing Grass and Sedum ET

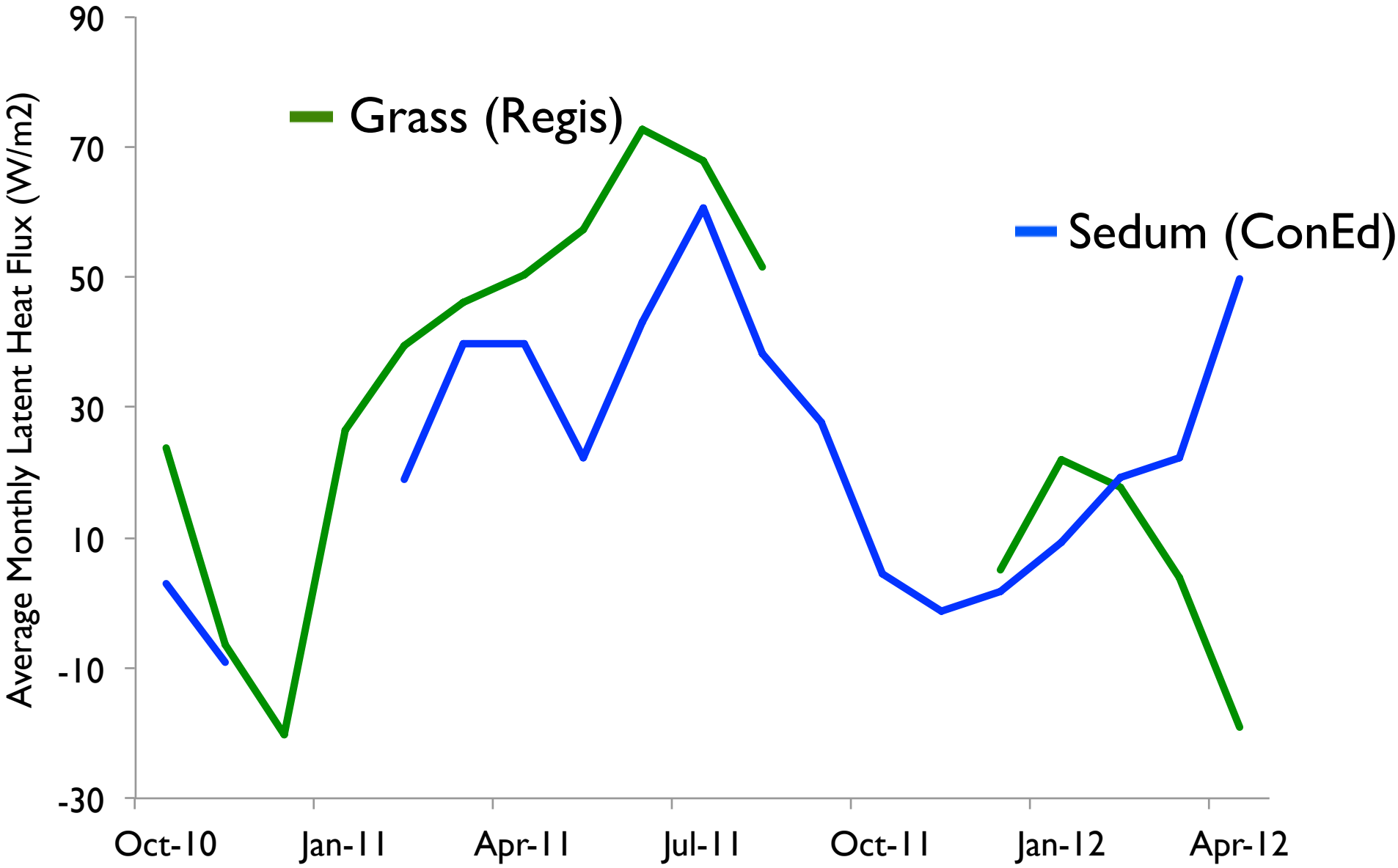
Sesleria Autumnalis, Autumn Moor Grass

Regis High School, Manhattan, NY

Sedums - this roof hosts 15 varieties

Con Edison TLC, Long Island City, NY

MONTHLY AVERAGED LATENT HEAT FLUXES: **SEDUM VS. GRASS**



LH from Sedum was lower by 32%

CONCLUDING REMARKS

I. GR hydrology is intimately coupled to energy, plants, growing medium, etc.

II. Energy balance (EB) is a powerful approach that can answer many questions including hydrology.

III. EB sensors are durable and easy to install and maintain (compared to flow meters perhaps).

IV. One disadvantage is that sensible heat is complex and needs to be modeled.

V. We are just starting to tackle more challenging research questions comparing sensor methods and different plant systems.

MOVING FORWARD

- VALIDATE SENSIBLE HEAT MODELS
- STUDY POSITIVE SYNERGIES BETWEEN GREEN TECHNOLOGIES
  e.e. cool roofs and solar PV efficiency
- ARE URBAN ROOFTOP FARMS TRULY GREEN ROOFS ?