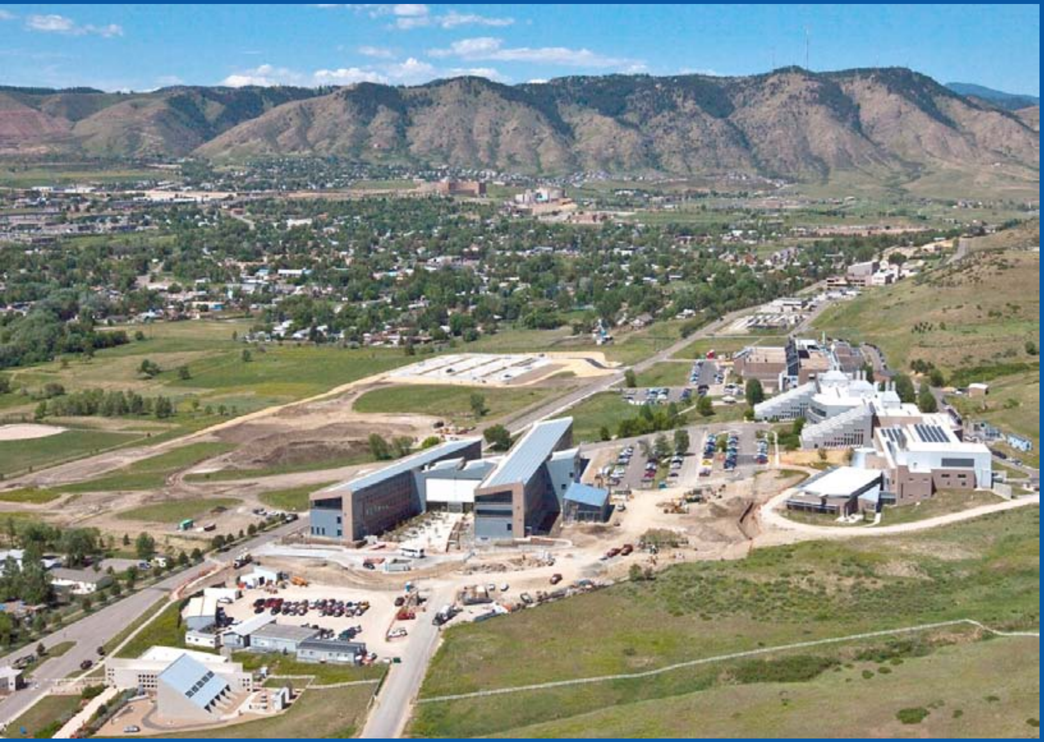
Estimating Heat and Mass Transfer Processes in Green Roof Systems: Current Modeling Capabilities and Limitations



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Work done at:

Building Science Group

Architectural Engineering Dept.

Pennsylvania State University

Outline

1. Introduction
2. Heat and Mass Transfer
3. Current Capabilities and Limitations
4. Inputs
5. Conclusions

Roofs

Roofs receive an important amount of solar radiation during summer

- 50% more in summer months than south walls at 40^{o}N latitude (Duffie and Beckman 1991)

Green roofs are becoming a popular sustainable technology

- Growth of 30%–50% during the last 5 years
- 703 green roofs nationwide
- ~102 acres (greenroofsplants.com)

Green Roofs

Green roofs are "specialized roofing systems that support vegetation growth on rooftops"

Consist of several layers:

1. Vegetation
2. Substrate (porous media)
3. Drainage/filter membrane

Green Roof Classification

Extensive

- Substrate thickness < 6’’
- Lower costs and loading capacity
- Limited selection of hardy plants, and
  - *Sedums, Delosperma*...
- Two thirds of total green roof area installed in North America

Intensive

- Substrate thickness >6’’
- Higher cost and maintenance
- Irrigation (usually)
- Wider variety of plants

Green Roof Benefits

1. Reduce energy demand on space conditioning
2. Extend life of roofing membrane
3. Reduce the urban heat island effect in cities
4. Reduce storm water runoff
5. Improve air quality
6. Improve roof aesthetics

Green Roof Drawbacks

1. Cost ($10-24 ft^2)
2. Hard for retrofit
3. More complicated design
4. Water leaks?
5. Structural load

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Thermal Benefits of Green Roofs

Not a conventional insulation material

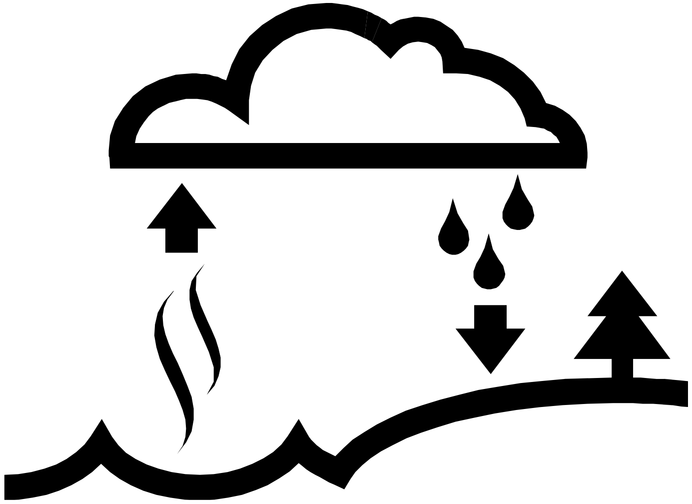
Modulate heat flux through the roof by:

- Shading
- Insulation
- Thermal mass
- Evapotranspiration (ET, Q_{ET})

Combined effect:

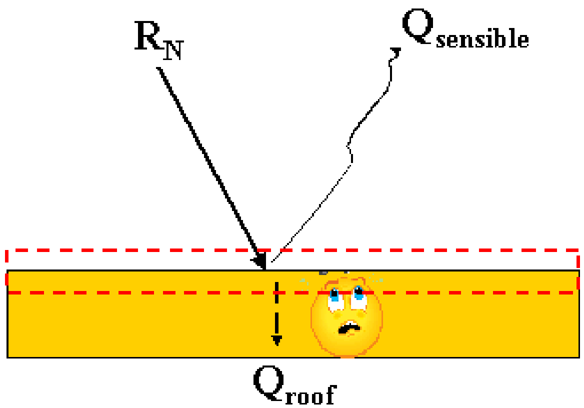
- Plants and substrate

Require energy and mass balance



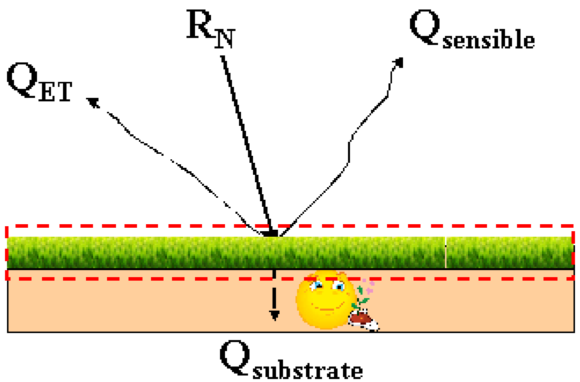
Energy Balance

Traditional Roof



$$R_N - Q_{sensible} - Q_{roof} = 0$$

Green Roof



$$R_N - Q_{sensible} - Q_{ET} - Q_{substrate} = 0$$

Where,

R_N = net radiation

$Q_{sensible}$ = sensible heat flux due to convection

Q_{ET} = latent heat flux due to convection

$Q_{substrate/roof}$ = conductive heat flux through roof

Energy Balance

$$R_N = Q_{ET} + Q_{sensible} + Q_{roof,GR}$$

Substrate wetness	$\frac{Q_{ET}}{R_N}$	$\frac{Q_{sensible}}{R_N}$	$\frac{Q_{roof,GR}}{R_N}$
"Wet"	0.68	0.23	0.09
"Dry"	0.29	0.57	0.14

Tabares –Velasco & Srebric. 2011

Accurate energy balance required mass balance and vice versa

Net Radiation

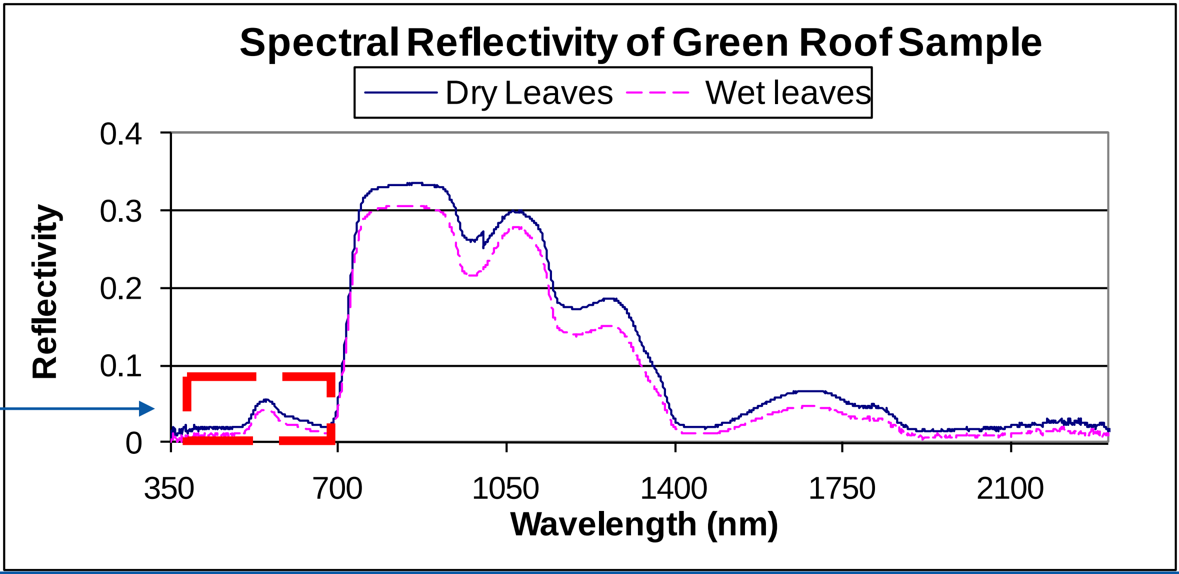
$R_N = Q_{ET} + Q_{sensible} + Q_{substrate}$

- Absorbed short-wave irradiance
- Thermal radiative heat transfer between:
  - Plants and sky
  - Plants and top substrate

$$R_n = Q_{solar}\left(I_{solar}, \rho_{soil}, \rho_{leaf}, \tau_{solar}, LAI\right) + Q_{IR}\left(T_{sky}, T_{soil}, T_{leaf}, \varepsilon_{soil}, \varepsilon_{leaf}, \tau_{IR}, LAI\right)$$

PAR

Visible



Evapotranspiration

$$R_N = Q_{ET} + Q_{sensible} + Q_{substrate}$$

- Constant

$$solar\ reflectance = solar\ reflectance \times Q_{ET_{factor}}$$

- Bowen Ratio

$$Q_{ET} = \frac{Q_{sensible}}{\beta} = \frac{h_{convection}(\Delta T)}{\beta}$$

- Vapor Pressure Differential
  - Plant’s stomata resistance, r_s
  - Soil/Substrate resistance , r_s

$$Q_{ET} = \frac{\rho C_p}{\gamma(r_s + r_a)}(e_{so} - e_{air})$$

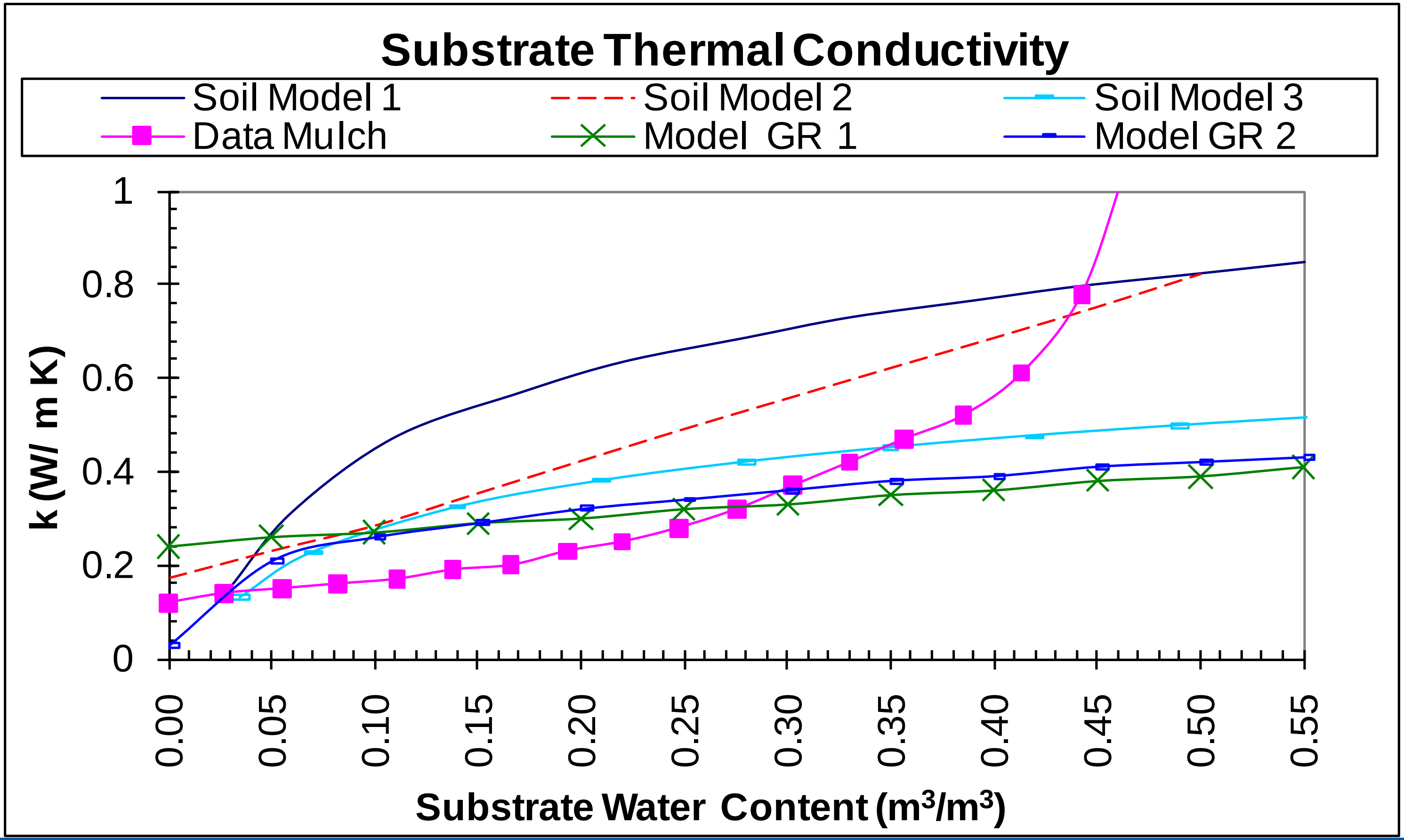
$$r_s = \frac{r_l}{LAI} f(solar) f(water) f(VPD) f(temp)$$

Plants transpiration is controlled by stomatal resistance: adjustable pores in the leaf that allow the gas transport into leaf/enviroment

Conduction

$$R_N = Q_{ET} + Q_{sensible} + Q_{substrate}$$

- Thermal conductivity depends on substrate type and water content
- Previous soil models overestimate thermal conductivity of green roof substrate



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Studies

Field Experimentation:

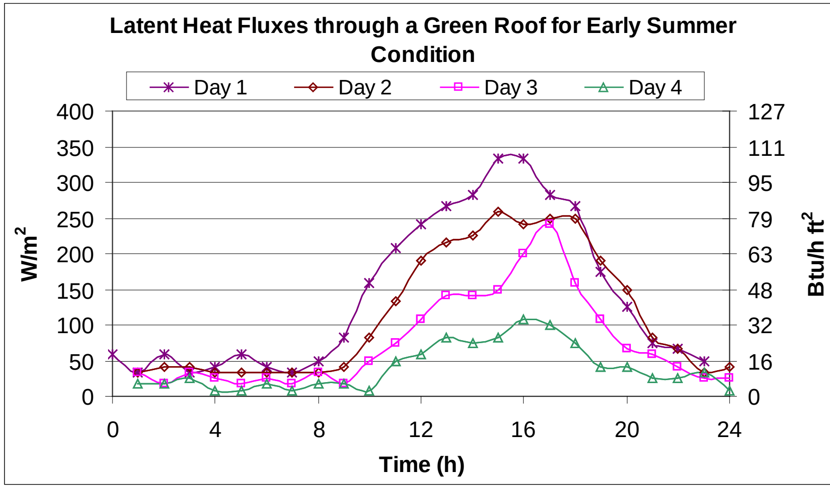
- Temperature Reduction (Hoeschele and Schmidth 1977)
- Heat Flux Reduction (Liu and Baskaran 2003)
- R-value (Minke et al. 1982, Wong et al. 2003)
- Evapotranspiration (Schmidt 2003, Berghage et al. 2007)

Wind Tunnel/Lab:

- R-value (Bell and Spolek 2009, Tabares-Velasco and Srebric 2009)
- Cooling effect (Onmura et al. 2001)
- Soil evaporation (Yamanaka et al. 1997)
- Soil properties (Sailor et al 2008)

Full Laboratory Experimentation

- (Tabares-Velasco 2009, Tabares-Velasco and Srebric 2011)



Berghage et al. 2007

Software and Models

Theoretical Models:

- Early model (Saiz Alcazar 2005, Hilten 2005, Wong et al 2003)
- Latest models (Gaffin et al. 2005, Sailor 2008, Tabares-Velasco and Srebric 2009)

Software:

- Using early models: DOE 2
- Using latest models : ESP-r, EnergyPlus, MIT Design Advisor
- Web-based: Green Roof Energy Calculator

Gaps and Limitations: Previous Studies

1. Experimental data for validation
2. Complete model validation
3. Constant properties for roof substrate
4. Mass balance
5. Drainage layer performance data
6. Experimental data for winter conditions
    1. Snow melting
    2. Plant dormancy
7. Inter-comparison model performance for winter and summer

Gaps and Limitations Addressed at PennState

1. Experimental data for validation
2. Complete model validation
3. Constant properties for roof substrate
4. ~Mass balance

Penn State Center for Green Roof Research

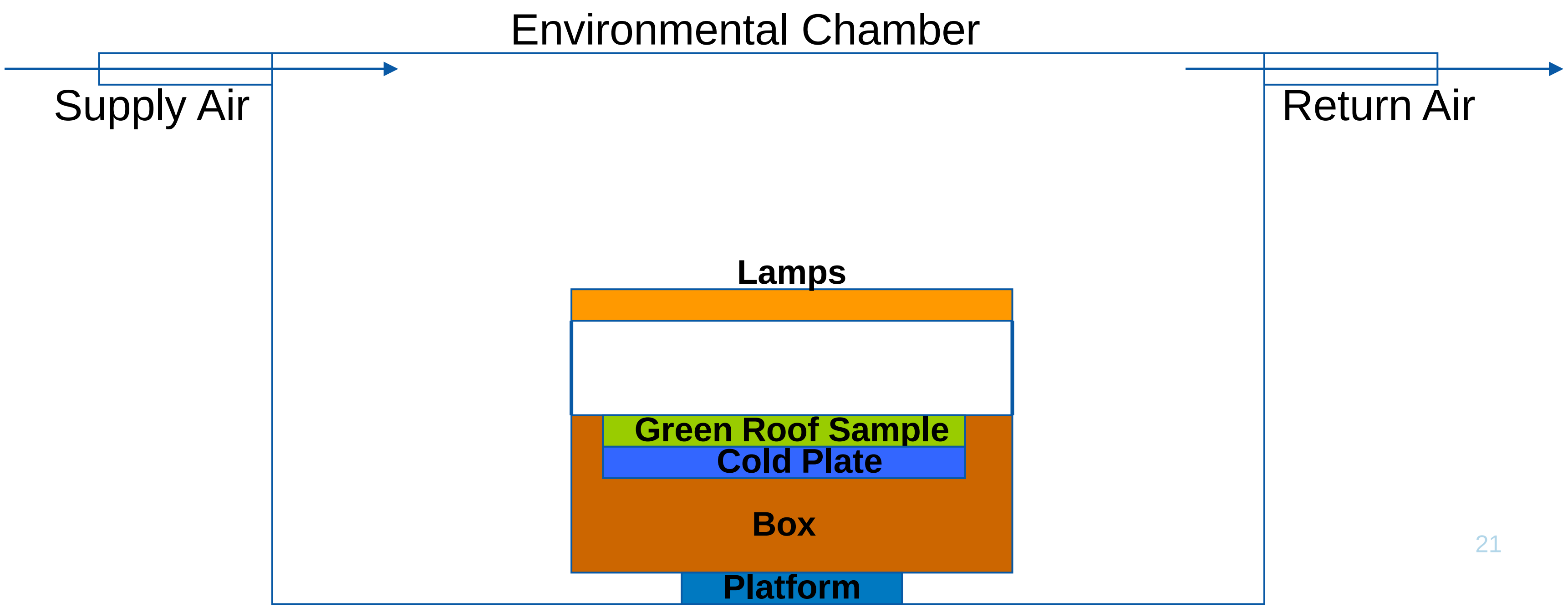
Previous Work at PennState

Developed and validated a heat and mass transfer green roof model

- Designed and built a new apparatus “cold plate”
- Obtained dynamic and quasi-steady state data
- Verified and validated green roof model
    - Detailed laboratory experiments
        - Surface temperature
        - Evapotranspiration
        - Conduction
        - Net radiation…
    - Outdoor validation

"Cold Plate" Apparatus

- Inspired by ASTM C177 "hot plate" and C1363 "hot box"
- Requires an environmental chamber
- Measures simultaneously heat and mass transfer phenomena



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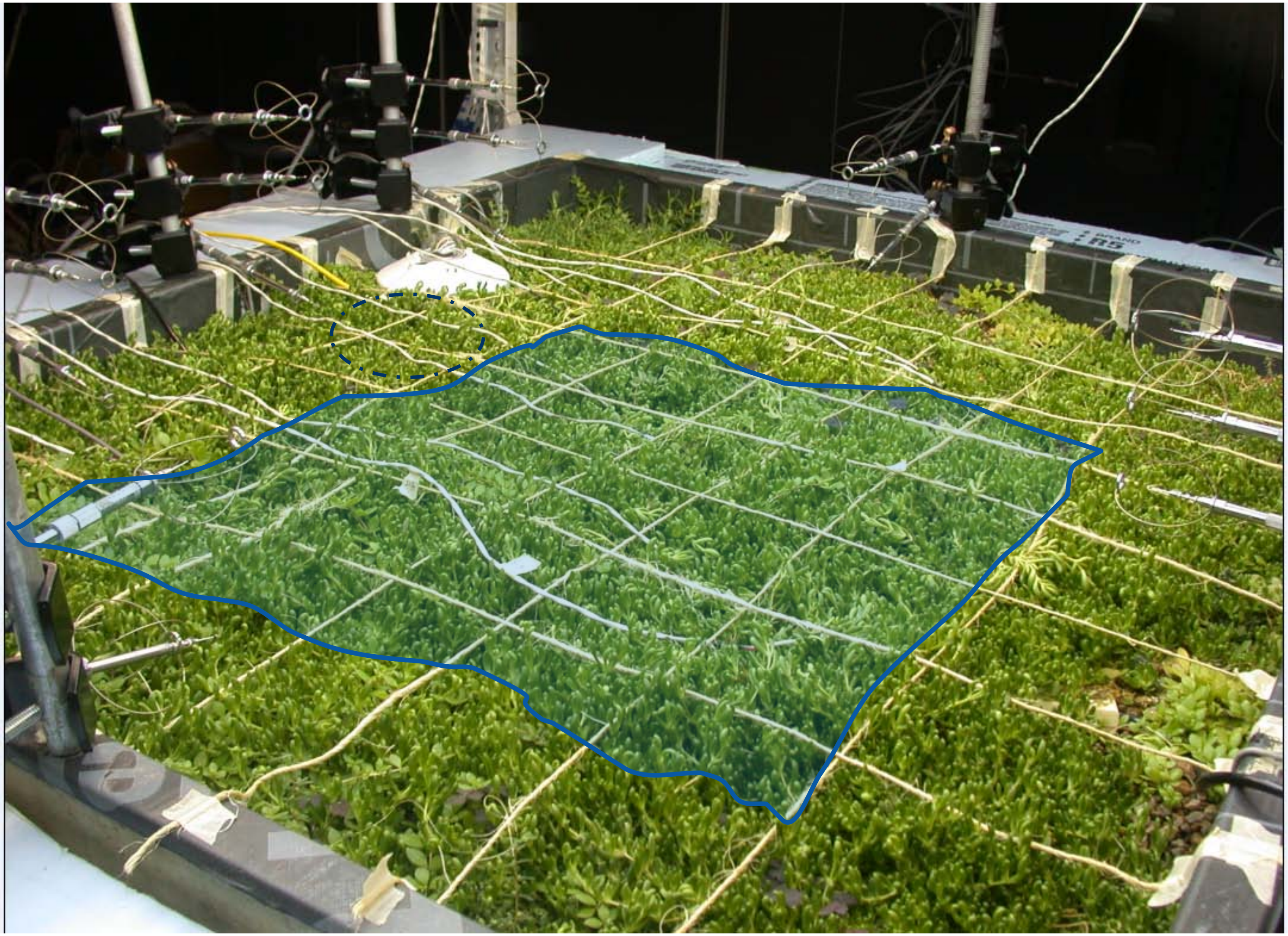
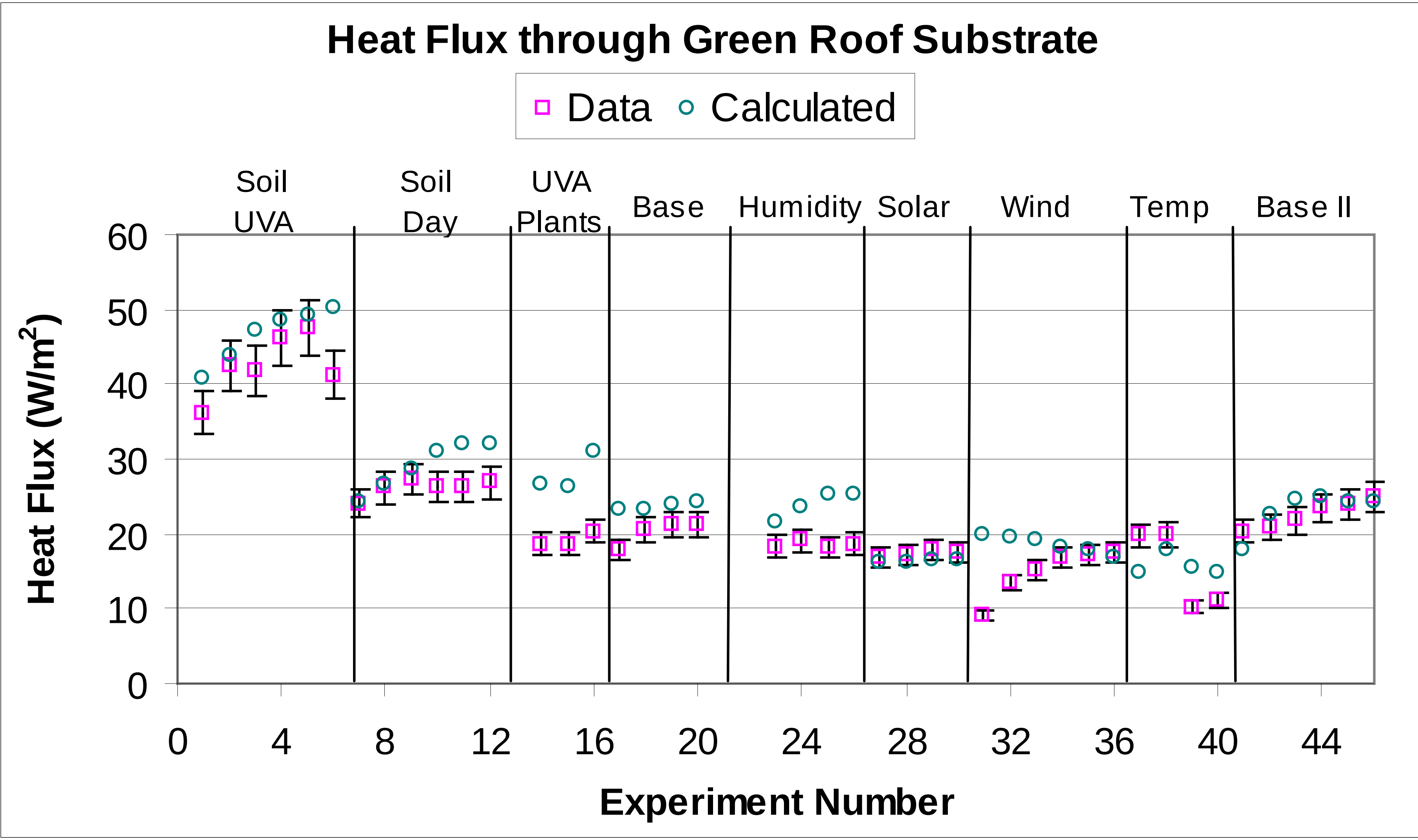
“Cold Plate” Apparatus



Model Validation: Conduction



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Model Inputs

- LAI: 0-5 (typically 1–3)
- Stomatal resistance:
  - Succulent plants: 450–1000 s/m
  - Desert plants: 225–1125 s/m (Jones 1992)
  - Lab experiments for Sedums/Delosperma 500–700 s/m (Tabares-Velasco and Srebric 2011)
  - EnergyPlus limit is 300 s/m!!!
- Plant coverage 0%–100% (upper limit about 80%)
- Irrigation: extensive roofs typically not irrigated

Model Inputs (continued)

- Substrate thermal conductivity
  - ~0.2 W/mK (dry)
  - ~ 0.4-0.6 W/mK (wet)
- Bowen ratio: ~0.2
- Green roof R-value (under laboratory conditions): 4.3–4.8 ft^2hF/Btu (but don't use it!)

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Conclusions

- Current green roof models are more sophisticated and complete than 10 years ago
- Accurate green roof modeling requires energy and mass balance
- All models should to be (fully) validated before implementation in building energy simulations software
- DON’T try this at HOME!
- Validated green roof model is coming soon!

Thank you!

Acknowledgments

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