Representation of Ecoroofs in Building Energy Simulations

EPA Heat Island Reduction Initiative (HIRI)
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- Project Goals
  - To develop and implement a physically-based model of ecoroofs in a building energy simulation program
  - To develop a simplified web tool to assist in ecoroof design decisions

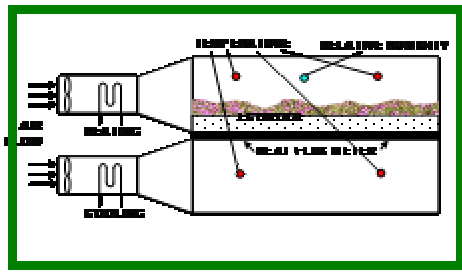
- Team
  - Dave Sailor, Graig Spolek, and Dave Ervin: PSU
  - Students: PSU
  - Allen Lee, Tony Larson, Rick Ogle, and Heather Williams: Quantec LLC

The Need

- Growing interest in ecoroof technologies
- Limited data related to building energy savings
- Design decisions are poorly informed
  - Soil type & depth
  - Construction details
  - Vegetation selection
  - Irrigation options
- Better quantification of energy impacts will facilitate the market penetration of ecoroof technologies.

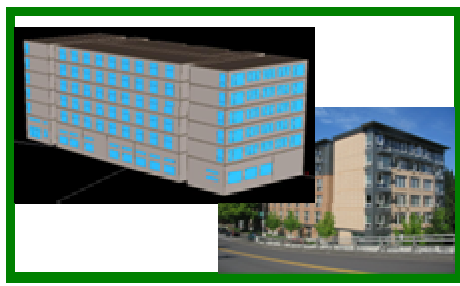
Ongoing Research Thrusts

1. **Laboratory measurements to determine thermal properties of ecoroof soils**



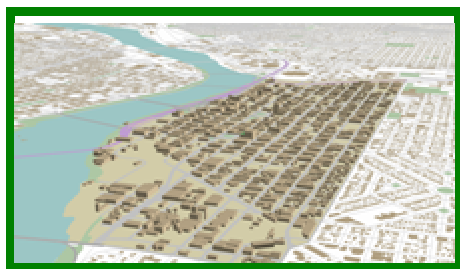
2. Laboratory and field measurements of heat fluxes through ecoroof constructions to gather validation data

3. **Ecoroof module for building energy simulation**



4. **Web tool development**

5. Large-scale modeling of the impacts of ecoroofs on city-scale climate.



Ecoroof Soil Testing

Sample #	Pumice	Expanded Shale	Compost	Sand
DH01	50%	0%	10%	40%
DH02	50%	0%	0%	50%
DH03	75%	0%	0%	25%
DH04	75%	0%	10%	15%
DH05	0%	50%	10%	40%
DH06	0%	50%	0%	50%
DH07	0%	75%	0%	25%
DH08	0%	75%	10%	15%

** Compositions are measured by volume.*

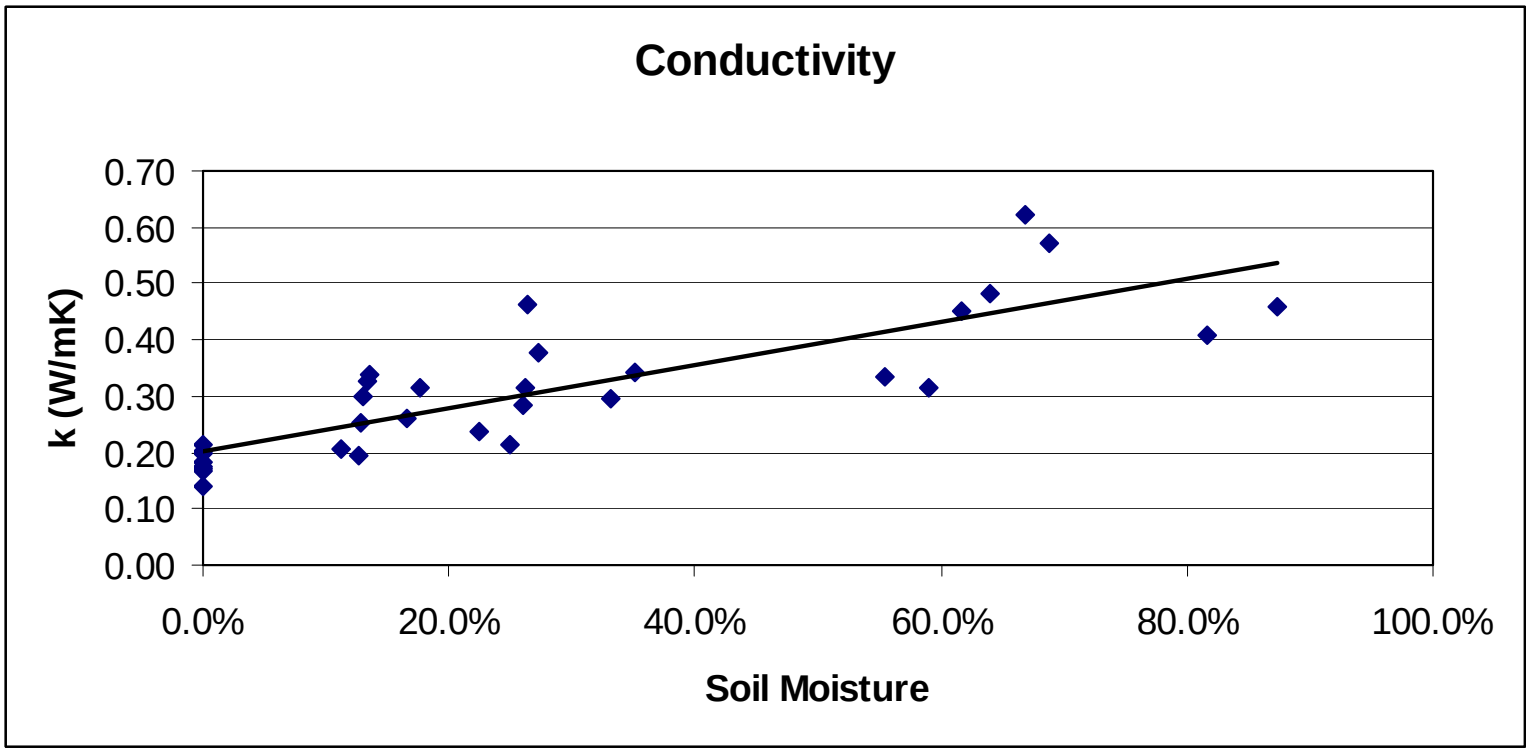
Also testing AXIS (a porous silica based aggregate from AMS Inc.).
Plans to look at other aggregates and other organic matter choices.

Thermal Property Measurements

- **Conductivity** and **specific heat capacity** measured using line heat source method with needle probes
  - IEEE 442-1981 and ASTM D 5334-00
  - 3 replicates each
  - 4 moisture levels

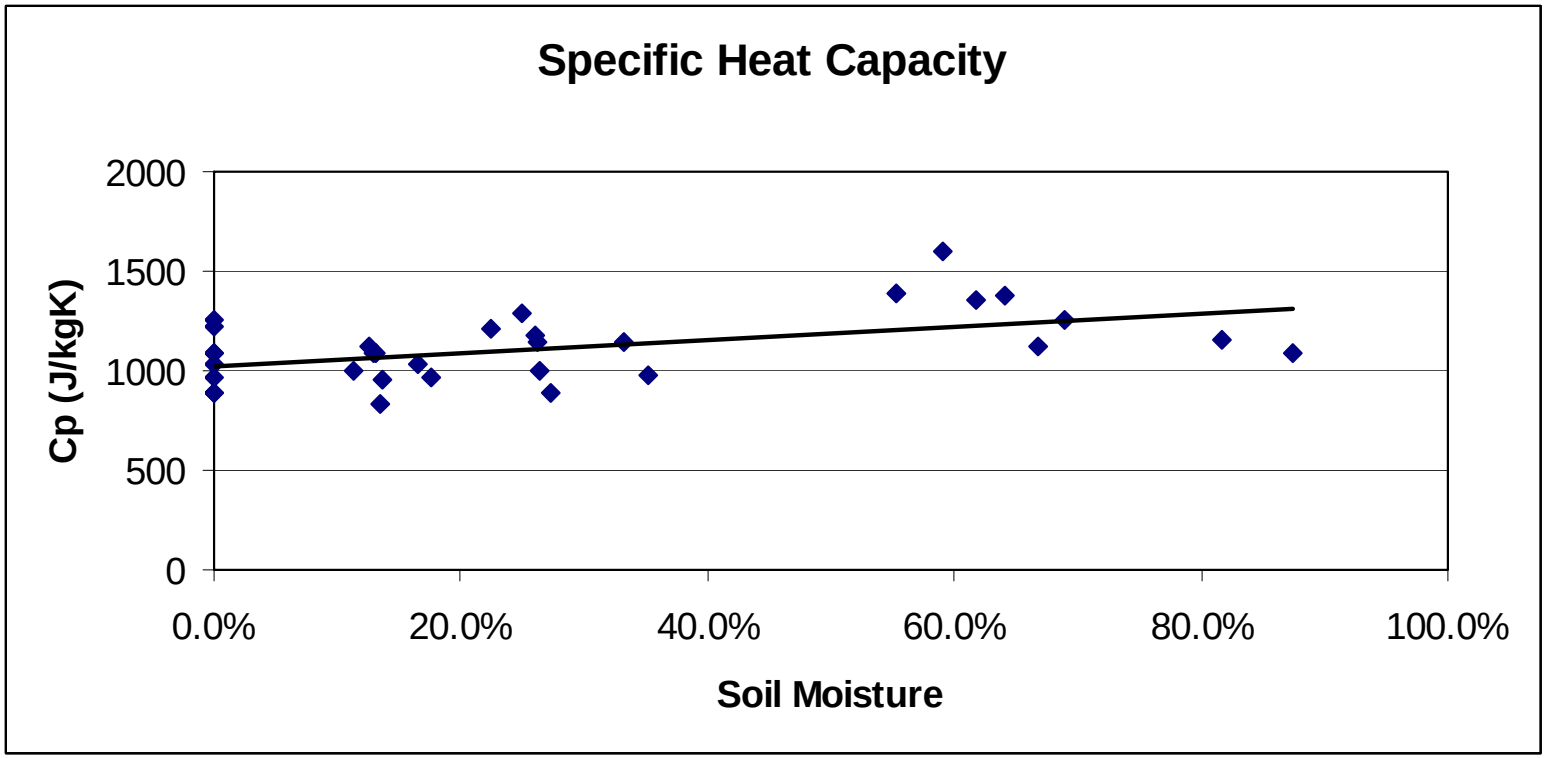
- **Albedo** tested using established method (Sailor et al., 2006)

- **Emissivity**
  - ASTM E1933-99a



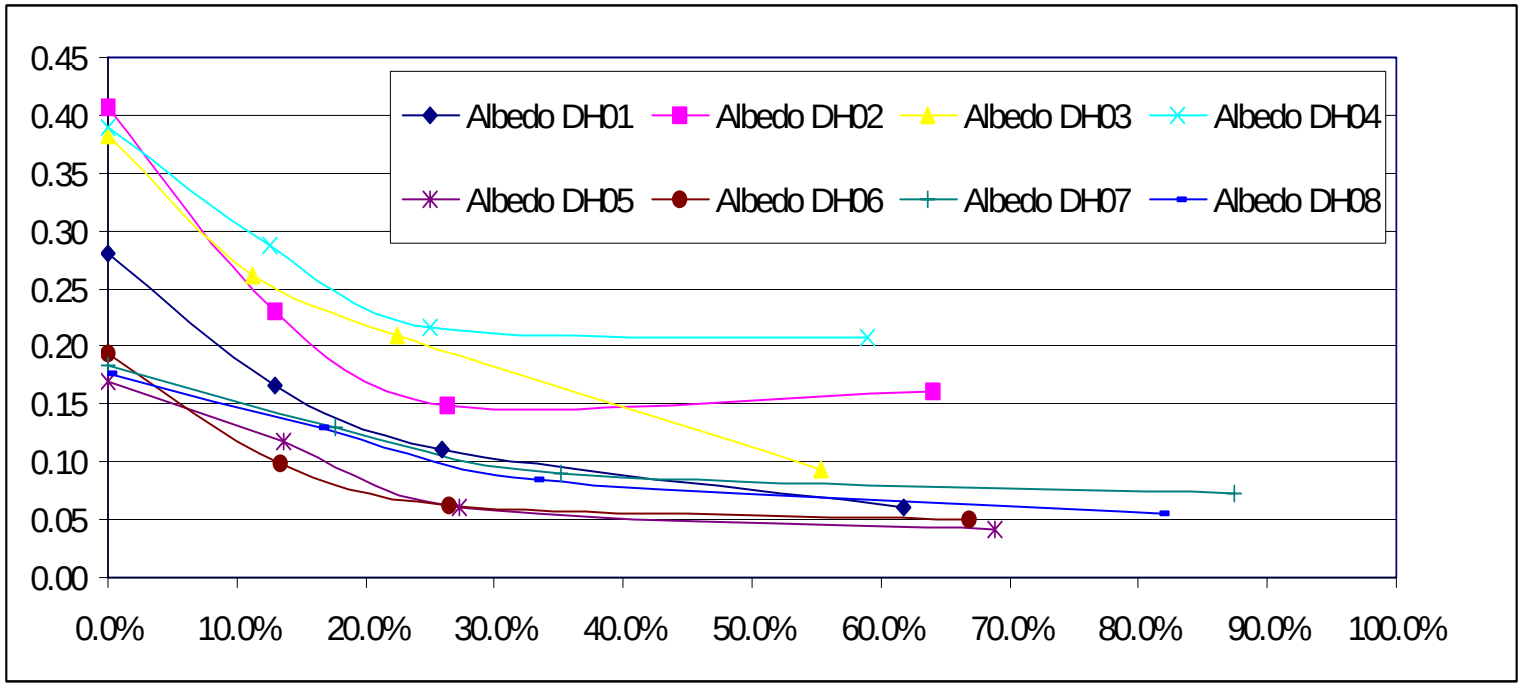
** All 8 samples shown on single figure.*

Conductivity of “soil” from literature varies widely:
1.0 to 2.0 W/mK for dry and wet soil (Cengel, 2003)



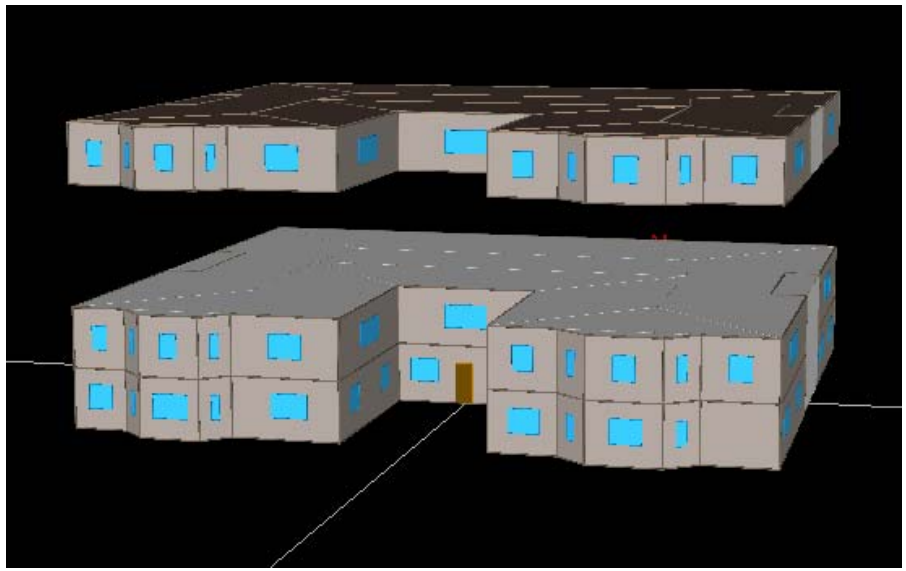
** All 8 samples shown on single figure.*

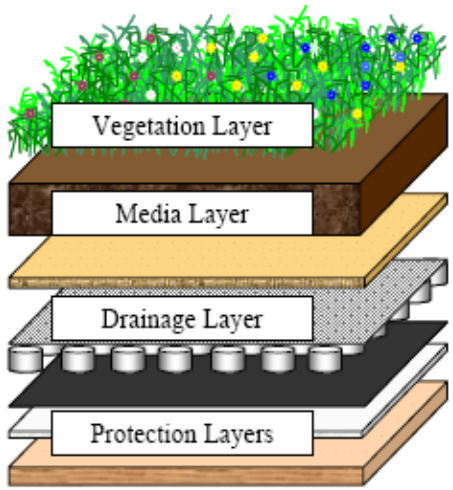
Specific Heat of “soil” from literature varies widely:
1900-2200 J/kgK for dry and wet soil (Cengel, 2003)



Albedo of “soil” from literature varies widely:
0.40 to 0.05 for dry and wet soil (Oke, 1986)

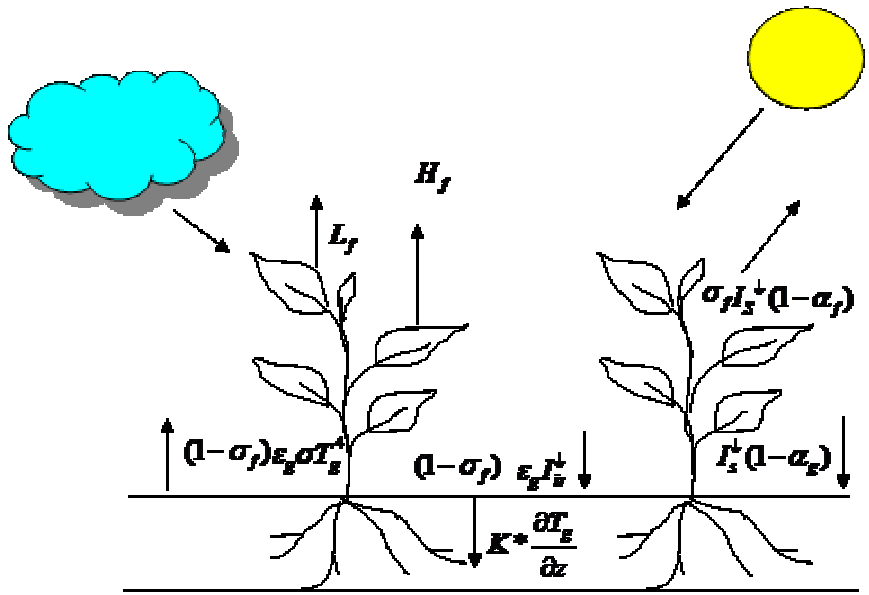
Ecoroof Energy Model





Ecoroof Energy Model

- Variation of the FASST vegetation models from US Army Corps of Engrs (2004)
- Draws heavily from BATS (Dickenson et al., 1993) and SiB (Sellers et al., 1996)
- Updated parameterizations
- Moisture transport under development



Ecoroof Energy Model

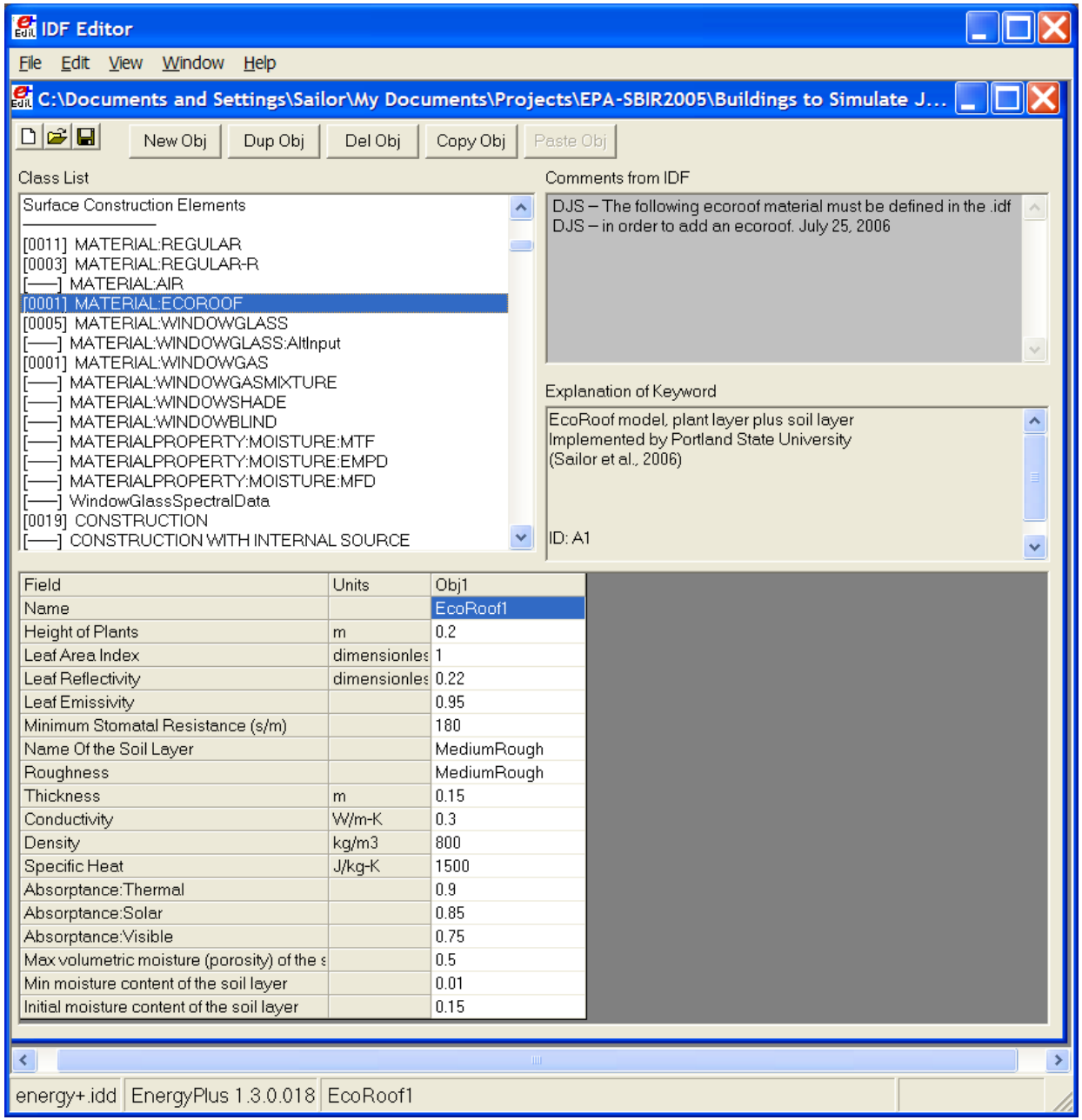
- Write two energy budget equations for foliage (f) and ground (g)
- Evaluate/parameterize individual heat flux terms
- Solve simultaneously

$$F_f = \sigma_f \left[I_S^{\downarrow}(1-\alpha_f) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^{\,4} \right] + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(T_g^{\,4} - T_f^{\,4} \right) + H_f + L_f$$

$$F_g = (1-\sigma_f)\left[I_s^{\downarrow}(1-\alpha_g) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g T_g^4 \right] - \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(T_g^4 - T_f^4 \right) + H_g + L_g + K * \frac{\partial T_g}{\partial z}$$

Implement Solution in a Building Energy Simulation Code

- EnergyPlus v1.3 (soon v1.4) – new generation of building energy simulation program from DoE
- Subroutines (Fortran95) modified to allow definition of a new material type (ecoroof)
- Addition of a new subroutine to handle the ecoroof energy and moisture budget as a special case


IDF Editor
File Edit View Window Help
C:\Documents and Settings\Sailor\My Documents\Projects\EPA-SBIR2005\Buildings to Simulate J...
New Obj
Dup Obj
Del Obj
Copy Obj
Paste Obj
Class List
Surface Construction Elements
[0011] MATERIAL:REGULAR
[0003] MATERIAL:REGULAR-R
[——] MATERIAL:AIR
[0001] MATERIAL:ECOROOF
[0005] MATERIAL:WINDOWGLASS
[——] MATERIAL:WINDOWGLASS:AltInput
[0001] MATERIAL:WINDOWGAS
[——] MATERIAL:WINDOWGASMIXTURE
[——] MATERIAL:WINDOWSHADE
[——] MATERIAL:WINDOWBLIND
[——] MATERIALPROPERTY:MOISTURE:MTF
[——] MATERIALPROPERTY:MOISTURE:EMPD
[——] MATERIALPROPERTY:MOISTURE:MFD
[——] WindowGlassSpectralData
[0019] CONSTRUCTION
[——] CONSTRUCTION WITH INTERNAL SOURCE
Comments from IDF
DJS – The following ecoroof material must be defined in the .idf
DJS – in order to add an ecoroof. July 25, 2006
Explanation of Keyword
EcoRoof model, plant layer plus soil layer
Implemented by Portland State University
(Sailor et al., 2006)
ID: A1
Field | Units | Obj1
Name | | EcoRoof1
Height of Plants | m | 0.2
Leaf Area Index | dimensionles | 1
Leaf Reflectivity | dimensionles | 0.22
Leaf Emissivity | | 0.95
Minimum Stomatal Resistance (s/m) | | 180
Name Of the Soil Layer | | MediumRough
Roughness | | MediumRough
Thickness | m | 0.15
Conductivity | W/m-K | 0.3
Density | kg/m3 | 800
Specific Heat | J/kg-K | 1500
Absorptance:Thermal | | 0.9
Absorptance:Solar | | 0.85
Absorptance:Visible | | 0.75
Max volumetric moisture (porosity) of the s | | 0.5
Min moisture content of the soil layer | | 0.01
Initial moisture content of the soil layer | | 0.15
energy+.idd
EnergyPlus 1.3.0.018
EcoRoof1

Ecoroof Sensitivity Tests

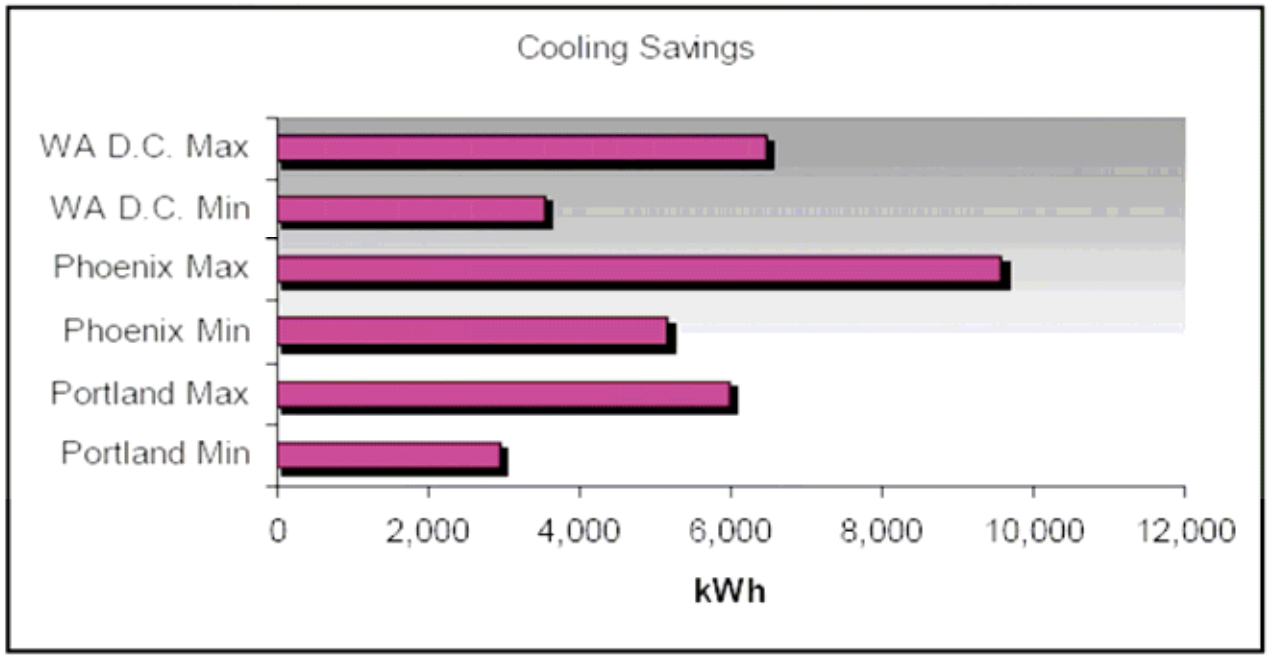
Apply model to 1-story office bldg. in 3 cities

Variable		Value	Units	Variable		Value	Units
Plant Height	Min.	0.147	m	Conductivity	Min.	0.05	W/(m*K)
	Max.	1.5	m		Max.	1	W/(m*K)
Leaf Area Index	Min.	0.5		Soil Density	Min.	100	kg/m^3
	Max.	7			Max.	2000	kg/m^3
Leaf Reflectivity	Min.	0.05		Specific Heat	Min.	800	J/(kg*K)
	Max.	0.5			Max.	5000	J/(kg*K)
Leaf Emissivity	Min.	0.7	%	Thermal Absorption	Min.	0.9	
	Max.	1	%		Max.	1.0	
Min Storage Resistance	Min.	10	s/m	Solar Absorption	Min.	0.5	
	Max.	1000	s/m		Max.	1.0	
Roughness	Min.	Smooth		Visible Absorption	Min.	0.7	
	Max.	Rough			Max.	1.0	
Thickness	Min.	0.0762	m	Max Vol Moisture	Min.	0.2	
	Max.	0.4572	m		Max.	_	

Cooling Savings:

One-story 10,000 sq. ft. bldg with and without an ecoroof

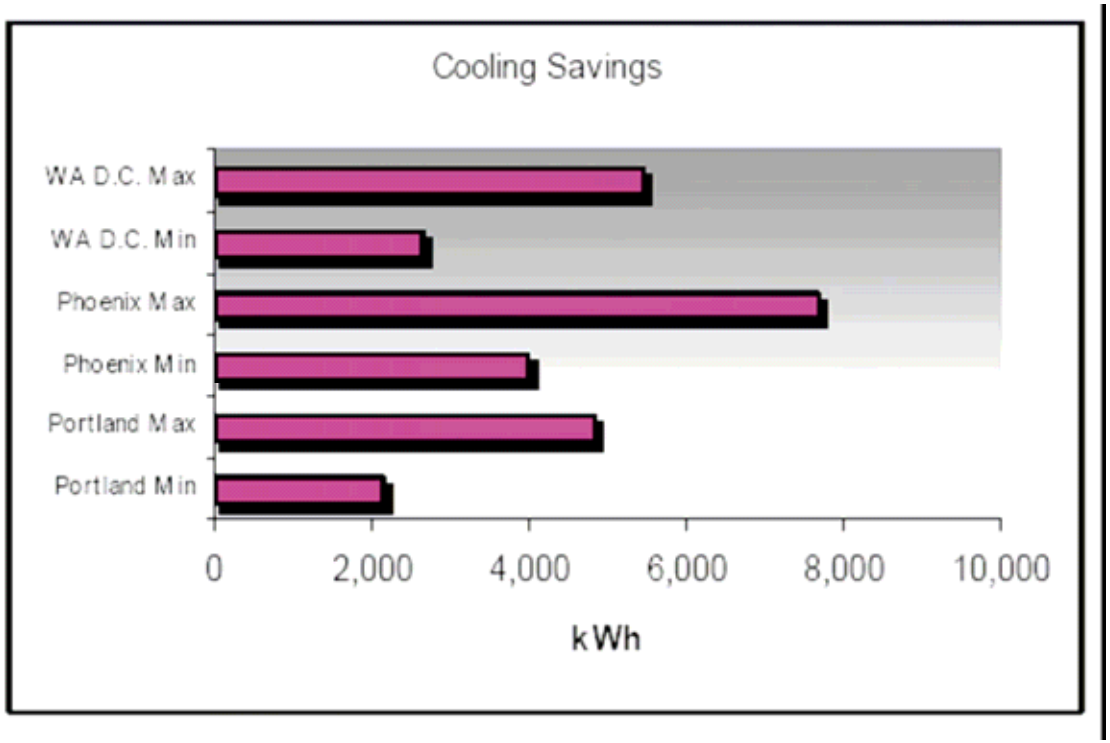
Varying LAI from Min of 0.5 to Max of 7.0



Cooling Savings:

One-story 10,000 sq. ft. bldg with and without an ecoroof

Varying Soil Thickness from Min of 0.08 to Max of 0.46 m



Ecoroof Web Tool Development

- Use 1000's of parametric runs of the Ecoroof version of EnergyPlus
  - Vary location, building type, building height, soil thickness, vegetation type…
- Develop interpolation model and implement it in a user-friendly web-tool.
- A draft interface has been created, but the bulk of the work is yet to begin…

greenroof
How does your roof grow?

Input | Comparison

Powered by quantec

Input

1. Fill out inputs on form to create a new scenario -- OR -- select an existing scenario from the pull-down menu
2. Click on Calculate button to view results based on new or revised inputs
3. Adjust inputs further and Calculate again -- OR -- save input/output scenario
4. Print input/output scenario
5. Start over (saving as many inputs as wanted)

Comparison

1. Select which scenarios to compare
2. Click on View Comparison button to generate comparison
3. View comparison
4. Select another combination of scenarios to compare
5. Click on View Comarison button to regenerate comparison
6. View comparison

Draft

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How does your roof grow?

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Input | Comparison

1 Fill out inputs 2 Calculate results 3 Save Scenario 4 Print Scenaro

-- Select scenario -- New scenario

Inputs:

Building Type
- ○ Residential
- ○ Institutional
- ○ Retail
- ○ School
- ○ Office

No. of Floors
- ○ Low rise (1 - 3 story)
- ○ Mid rise (4 - 6 story)
- ○ High rise (>6 story)

Roof/Ceiling Insulation enter R-value

Plant Choices

Ground Cover	%	of plant choices	sq. ft.
Shrubs (Deciduous)	%	of plant choices	sq. ft.
Shrubs (Evergreen)	%	of plant choices	sq. ft.
Trees (Deciduous)	%	of plant choices	sq. ft.
Trees (Evergreen)	%	of plant choices	sq. ft.
Total	100%		X, XXX sq. ft.

Irrigation
- ○ As needed based on conditions
- ○ None
- ○ Fixed schedule by season

Heating Fuel Type ○ Electricity ○ Gas

Air Conditioned ○ Yes ○ No

Roof Structure
- ○ Lightweight (wood frame)
- ○ Steel
- ○ Heavy (concrete)

Roof Shading % of annual average shading

Location/Climate -- Select --

Results: Calculate Save Print

Energy Savings X value kWh per year

X value Therm per year

$X

Incremental Cost $X

Payback X years

Other Benefits

Benefit A | Benefit C

Benefit B | Benefit D

Soil Attributes

Air space	%	
Field moisture capacity	g/mL	
Total saturation capacity	g/mL	
Dry weight per cubic foot	kg	
Solar reflectivity		(0.0 to 1.0)
Depth	enter inches	
Emittance factor		(0.0 to 1.0)

Energy Costs $ per kWh

$ per Therm

Draft

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How does your roof grow?

Powered by quantec
Raising the bar in analytics

Input | Comparison

Select scenarios to compare: ☒ Scenario 1 ☐ Scenario 2 ☒ Scenario 3 ☒ Scenario 4 ☐ Scenario 5 ☒ Scenario 6 ☐ Scenario 7

View Comparison

Scenario Comparison Results:

	Scenario 1	Scenario 3	Scenario 4	Scenario 6
Results				
Energy Savings				
kWh per Year	$X	$X	$X	$X
Therm per Year	$X	$X	$X	$X
Incremental Cost	$X	$X	$X	$X
Payback	X years	X years	X years	X years
Other Benefits	Benefit A	Benefit B	Benefit C	Benefit B
Inputs				
Building Type	Residential	Residential	Residential	Residential
No. Floors	Low rise (1 – 3 story)	Low rise (1 – 3 story)	Low rise (1 – 3 story)	Low rise (1 – 3 story)
Roof/Ceiling Insulation	X R-Value	X R-Value	X R-Value	X R-Value
Plant Choices:				
Ground Cover	X%, X sq ft.		X%, X sq ft.	X%, X sq ft.
Shrubs (Deciduous)		X%, X sq ft.	X%, X sq ft.	X%, X sq ft.
Shrubs (Evergreen)	X%, X sq ft.			
Trees (Deciduous)		X%, X sq ft.	X%, X sq ft.	X%, X sq ft.
Trees (Evergreen)	X%, X sq ft.			
Irrigation	None	Fixed schedule	As needed	As needed
Heating Fuel Type	Electricity	Electricity	Electricity	Electricity
Air Conditioned	No	No	No	No
Roof Structure	Heavy	Heavy	Heavy	Heavy
Roof Shading	X%	X%	X%	X%
Location/Climate	*text text text*	*text text text*	*text text text*	*text text text*
Soil Attributes:				
Air Space	X%	X%	X%	X%
Field Moisture Capacity	X g/ML	X g/ML	X g/ML	X g/ML
Total Saturation Capacity	X g/ML	X g/ML	X g/ML	X g/ML
Dry Weight/Cubic Foot	X g/ML	X g/ML	X g/ML	X g/ML
Solar Reflectivity	X	X	X	X
Depth	X inches	X inches	X inches	X inches
Emittance Factor	*text text text*	*text text text*	*text text text*	*text text text*
Energy Costs				
Per kWh	$X	$X	$X	$X
Per Therm	$X	$X	$X	$X

Draft

Conclusions…

- Ecoroof soils differ substantially from “typical” soils
- For soil moisture ranging from 0 to 60% thermal properties of ecoroof soils vary substantially:
  - K doubles
  - C_p increases by ~25%
  - Albedo decreases by a factor of 2 to 4
- Building energy simulations show significant sensitivity to soil properties, depth, and vegetation characteristics
  - Cooling and heating savings of 10-25% for 1 story bldg.
  - Qualitatively the results make sense, but further validation is needed.

…and ongoing work

- Incorporate moisture transport model
  - Migration of moisture within soil
  - Evaporation from soil surface
  - Plant extraction from root zone
  - Precipitation
  - Irrigation

- Validate
  - Energy flux data from existing ecoroofs
  - Replicate laboratory measurements under controlled conditions

- Web tool
  - Conduct model training simulations