Ecological Transformation of Urban Surfaces to Reduce Energy Costs, Peak Load Requirements with Green Jobs

Vegetation-based storm water, combined sewer & grey water treatment: green roofs, walls, & infrastructure
The Simple Story

Plants a half-meter and taller

- Partition sensible and latent heat between upper and lower leaf cover
- Regulate local temperature
Energy Balance Equation

\[ Rn = H + LE + G + R + P \]

- \( Rn \) = Total Radiation
- \( H \) = Sensible Heat
- \( LE \) = Latent Heat, evaporative heat loss
- \( G \) = Heat moved into surrounding materials, -buildings & soil, atmosphere & water
- \( R \) = Respiration (max \( \leq 1\% \))
- \( P \) = Photosynthesis (max \( \leq 1\% \))
**Bowen Ratio** = \( \frac{H}{LE} \)

<table>
<thead>
<tr>
<th>System</th>
<th>Reported Bowen Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert</td>
<td>10</td>
</tr>
<tr>
<td>Urban areas</td>
<td>5</td>
</tr>
<tr>
<td>Mopane woodland (Dry season, S. Africa)</td>
<td>4 - 5</td>
</tr>
<tr>
<td>Irrigated field (Winter)</td>
<td>2.89-3.58</td>
</tr>
<tr>
<td>Pine forest (July)</td>
<td>2</td>
</tr>
<tr>
<td>Forest floor (July)</td>
<td>1.2 - 4.5</td>
</tr>
<tr>
<td>Mopane woodland (Wet season, S. Africa)</td>
<td>1</td>
</tr>
<tr>
<td>Pine forest in Siberia (July)</td>
<td>1</td>
</tr>
<tr>
<td>Douglas fir stand</td>
<td>0.66</td>
</tr>
<tr>
<td>Wheat field (summer)</td>
<td>0.6</td>
</tr>
<tr>
<td>Forest (Indiana) annual average</td>
<td>0.59</td>
</tr>
<tr>
<td>Above forest canopy (summer)</td>
<td>.5 - 3.0</td>
</tr>
<tr>
<td>Soybean field (summer)</td>
<td>0.3</td>
</tr>
<tr>
<td>Irrigated field (April)</td>
<td>.28 -.30</td>
</tr>
<tr>
<td>Irrigated field (August)</td>
<td>.20 -.25</td>
</tr>
<tr>
<td>Rainforest in Amazonia during wet season</td>
<td>0.17</td>
</tr>
<tr>
<td>Huaihe River Basin (ruderal)</td>
<td>0.14</td>
</tr>
<tr>
<td>Tropical ocean</td>
<td>0.1</td>
</tr>
<tr>
<td>Huaihe River Basin (paddy)</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Table 2: Bowen ratios reported for a range of ecosystems and vegetated environments (references 4 – 12). The green vertical arrow indicates the range we estimated for the Penn State green roofs during July 2003.*
93 million miles away, the sun is about \( \frac{1}{2} \) a degree of arc, and casts a shadow about 108 leaf diameters long.

**Figure 4.1.** Shadow of a sunlit leaf.

The scale is obviously distorted, but the triangle including the sun is similar to the triangle containing the leaf. Hence 

\[
\frac{\text{length of umbra}}{\text{distance from tip of umbra to sun}} = \frac{\text{diameter of leaf}}{\text{diameter of sun}}. 
\]

Length of umbra = \( \frac{9.3 \times 10^7}{8.6 \times 10^5} \times \text{diameter of leaf} = 108 \text{ diameter of leaf}.\)
Leaves in layers filter density, lowering light intensity on leaves below

- Shade is eliminated as these layers approach optimal spacings. This partitions radiation, energy and heat loads
- Upper leaves re-radiating more sensible heat
- Lower leaves have higher levels of evaporation, latent heat and water vapor production
The Availability of Water Powers Terrestrial Thermal Regulation
Explosive Water Use Transforms and Regulates Local Climate

18 cubic centimeters of liquid water expands to 22,400 cubic centimeters of water vapor

- 1,000 fold increase
- 5 mm depth equivalent to a 20 foot column of air
Interfacial properties determine energy absorption

Structural complexity modulates radiation intensity, velocity gradients and surface boundary layer of terrestrial vegetation

Complex, three-dimensional arrays are a structural prerequisite for thermal regulation

The geometry of the spatial array of sensible and latent heat loss allows vegetation to effectively regulate heat flux and to locally drop temperature below ambient
Evapotranspiration, Phase Change of Water and Power

- Evapotranspiration -- evaporation from leaves of water that flows through roots and shoots
- 6 mm of water changes phase over 2.5 acres (typical in the temperate zone) removes energy equivalent to 15 tons of dynamite
- 33 gallons of water phase change moves the energy equivalent of a ton of air conditioning
- 25 pounds of evapotranspired water (about 3 gallons) is required to fix or capture 1 pound of carbon
Depiction of various surfaces and PBL processes

Top of the planetary boundary layer
but upwards and into roots and shoots

moves down a concentration gradient

• In the temperate zone roots are not deep and diffuse, but shallow and multiply branched
• 40% to 50% of fine roots occur in the top 10 cm of soil
• 90%+ of water absorption may take place in shallow fine roots

Water in capillary films in soil
Forest floor fine roots ≈ 15 to 20 linear miles per square meter
Soil Systems Connected to Root Structures
Powerful cohesive forces between and amongst water molecules provide it with high tensile strength, allowing it to be hung from great heights in narrow xylem cells.
Water can be put under significant negative pressure between the atmosphere and the root system. When that pressure exceeds the cohesive forces that hold water together, cohesion can fail, and ‘pop’, an air bubble or embolism appears.
Water moves down gradient, but upward from soil through roots to atmosphere through regulatory cells, stomata.

Coverages range from 100 to 1,000 stomata per square millimeter.

Stomata can be from about 15 X 15 to 80 X 40 microns.

Paired stomatal cells can close and open, depending on hydration level and physiological condition of the plant.
Fig. 3. Methodology to analyze the impact of shade trees, cool roofs, and cool pavements on energy use and air quality (smog).
Three-dimensional plant bodies supplied with water integrated radiation and water flow to regulate local temperature

Vegetation systems supplied with water (always) drive local temperature below ambient
What does this mean for Jersey City?

Every inch of runoff from 15 sq. miles discharges 260 million gallons of runoff into the Hudson & Newark Bay.

There are other things to do with water.
Linda Tool Green Roof

- regulates temperature
- reduced air conditioning cost by 33%
Linda Tool Green Roof

Components:

• Native wetland plant communities
• Ultra lightweight green roof medium with high water holding capacity

Roof membrane design to hold water to facilitate capillary uptake and storage
Linda Tool Green Roof

Observations:

- 12,000 sq.ft. roof can evapotranspire ≈ ¼” water per day
- 1” rain captured over 12,000 sf. = 1,000 cu.ft. water
- ¼” evaporation = 250 cu.ft. = 1,875 gal
- 33 gal = 1 ton AC, so 1,875 gal ≈ 57 tons AC -- enough to cool ≈ 23,000 sq.ft. -- almost twice the area of the 12,000 sq.ft. Linda Tool building.
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<tbody>
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<td>12,000</td>
<td>3,000</td>
<td>22,500</td>
<td>$90</td>
<td>$7.50</td>
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<tr>
<td>Area sq.ft.</td>
<td>inches of daily warm season evaporation</td>
<td>cu.ft. of daily warm season evaporation</td>
<td>daily warm season evaporation in gallons</td>
<td>daily evaporation transpiration in tons AC (at 33 gal/ton AC)</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------------------------</td>
<td>----------------------------------------</td>
<td>------------------------------------------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>12,000</td>
<td>0.25</td>
<td>250</td>
<td>1,875</td>
<td>57</td>
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</table>
Eliminated Treatment Cost and Urban Cooling Value

Two Jersey City Row Houses would capture about 250 cu.ft. of water for every 1” storm

Eliminated treatment cost of 250 cu.ft. water at $3/100 cu.ft.

≈ $8

Value added heat removal by 250 cu.ft. evapotranspiration and producing ≈ 60 tons AC per day @ $17.56 per 84kw per 4.4 cu.ft.

≈ $1,000
Linda Tool green roof is worth ≈$8 per day by treating 250 cu.ft. of water

The same Linda Tool green roof is worth ≈ $1,000 a day for reversing urban heat island and lowering local temperature.

While many complexities accompany urban heat transfer, five years of heat flow data and utility bills show a 33% air conditioning cost reduction.
Einstein Medical College Falk Recreation Facility

First green roof built to treat swimming pool filter backwash
Falk Center Green Roof Components

- Roof membrane designed to hold water in swales and facilitate capillary uptake and storage
- Ultra lightweight green roof medium with high water holding capacity (2 X dry weight & ≈ 1/3 volume)
- Saltmarsh and other native wetland and meadow plant communities
Falk Center Green Roof Components

- 16,500 sq.ft. roof can evapotranspire ≈ ¼” water per day
- 1” rain captured over 16,000 sq.ft. = 1,333 cu.ft. water
- ¼” evaporation = 343 cu.ft. = 2,580 gallons
- 33 gal = 1 ton AC, so 2,580 gal ≈ 76 tons AC, or enough to cool ≈ 30,300 sq.ft., cooling almost twice the area of the 16,500 sq.ft. Falk Center recreation building.
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<tr>
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</thead>
<tbody>
<tr>
<td>16,500</td>
<td>11,375</td>
<td>11,000</td>
<td>$44</td>
<td>$10.30</td>
</tr>
<tr>
<td>Area Sf</td>
<td>Daily warm season evaporation</td>
<td>Daily warm season evaporation</td>
<td>Daily warm season evaporation</td>
<td>Daily evapotranspiration (@ 33 gal/ton AC)</td>
</tr>
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<td>--------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>16,500</td>
<td>.25</td>
<td>345</td>
<td>2,580</td>
<td>80</td>
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</tbody>
</table>
Eliminated treatment cost of 250 cu.ft. water @ $3/100 cu.ft.

$10.30

Value added heat removal by 250 cu.ft. evapotranspiration & producing ≈ 60 tons AC per day @ $17.56 per 84kw per 4.4 cu.ft.

$1,370
The Einstein Falk Center green roof is worth $\approx 10$ per day by treating 340 cu.ft. of water.

The same Einstein Falk Center green roof will be worth $\approx 1,370$ a day in lowering local peak load requirement and dropping local temperature.

Under present conditions, 22,000 sq.ft. of black roof releases about 2,000 kW of positive heat load in summer. It will be replaced by a latent heat loss of about 6,000 kW by the green roof, cooling, instead of heating the local environment.
Green Roof at Einstein

Energy partitioning between sensible and latent heat regulates local hydrological mass balance
Energy partitioning between sensible and latent heat regulates local hydrological mass balance
Plant latent heat loss regulates carbon capture
Urban heat island is diminished or eliminated under areas of plant coverage
Plant Leaves are blackbody radiators
Availability of water facilities thermal regulation and the capacity of multilayered plant bodies to drop local temperatures below ambient
Figure 1. Green Roof Storage per Square foot of Planting Bed. This green roof shows a capture zone about equal to the roof area. Green roof media depth is limited by the weight bearing capacity of the structure. This often constrains the plant-growth matrix to half a cubic foot of media per square foot of coverage or less. The maximum water held in ½ cu.ft. would be about 1/6th of a cubic foot of water per cubic foot of soil, or 2” of water per square foot of coverage.¹⁵
Figure 2. Green walls are unique amongst green infrastructure configurations in that catchment capacities are constrained to an area much smaller than their photosynthetic surface, that is, a very limited vertically oriented area around the periphery of the wall. The 60’ wall pictured above would be covered half way up with vines. The catchment is shown as a 2’ wide and 3’ deep planter that runs the 100’ length of each of the walls, and would hold 6” of capillary water per square foot of planter, or 12” water per linear foot. While this is a significant quantity of water, the amount per square foot of ecologically productive surface is a cubic foot per 30 sq.ft. of plant cover, or 0.4” per square foot of evaporative surface, about two days of plant growth (see below). On a volume per area basis, this is approximately 1/5th of the green roof water holding volume.
Figure 3. Street-Side Swale Storage per Square foot of Planting Bed.
Thermal Regulation in Sterile Roofs, Facades, Street Edges and Shorelines

30 sq. miles of roof space, more than 100 square miles of wall area, 6,300 linear miles of roadway, 550 + miles of coastline
NYC grey water, 600 b gallons evapotranspired = 18 m tons of air conditioning. If each ton of AC can cool 400 sq.ft., 18 m tons will cool 260 sq. miles each day.

18 million tons AC is enough energy to cool all of the Bronx, Brooklyn, Queens, & Manhattan, with 40 square miles of cooling capacity left over.
Jersey City grey water, 13 million gallons evapotranspired each day produces 400,000 tons of air conditioning. If each ton of AC can cool 400 sq.ft., 400K tons will cool 6 sq. miles, much of Jersey City.
NYC grey water, 600 b gallons evaporated = 18 m tons of air conditioning. If each ton of AC can cool 400 sq.ft., 18 m tons will cool 260 sq. miles each day. 18 million tons AC is enough energy to cool all of the Bronx, Brooklyn, Queens, & Manhattan, with 40 square miles of cooling capacity left over.
Whats rwong with this Picture?
Value added of 380,000 tons AC = $6,650,000 per day

Avoided cost of removing 1,666,667 cu.ft. from the combined sewer @ $3/100 cu.ft. = $50,000

100,000,000 sq.ft. green wall

100,000,000 sq.ft. green roof
Street Side Park Evaporative Systems

- Decrease local flooding and discharge to catch basins
- Maintain vegetation and cool the urban landscape with no potable water input
- Increase biodiversity
Increasing Tree Pit Scale by a Factor of Five to an Order of Magnitude

• Multiplying tree pit capacity tenfold

• Based on prior work at Sims Recycling and the Command Bus Depot, stormwater capture capacities may reach 5,000 to 10,000 gallons per storm or more. A million tree pits with such capacity could capture billions of gallons of water
Return on a two billion dollar investment in green infrastructure Value added of 380,000 tons AC = $6,650,000 per day

Cooling-value added $2 b/$6,650,000 per day ≈ 300 warm season days
Avoided treatment. $2,000,000,000 / $50,000 ≈ 40,000 days (100 years)

100,000,000 sq.ft. green wall
100,000,000 sq.ft. green roof