Thermal Remote Sensing and the Thermodynamics of Ecosystem Development

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In Memory of James J. Kay 1954-2004
Energy $\textbf{IN} = \text{Energy } \textbf{OUT}$

Exergy $\textbf{IN} \gg\gg \text{Exergy } \textbf{OUT}$

High quality energy input (electricity)

Task done

Light

Image

Sound

Heat

Degraded energy
Bénard Cells

The System

- Cold Sink
- Working Fluid
- Hot Source

Conduction

- Cold Sink
- Hot Source

Convection

- Cold Sink
- Boundary Layer
- Hot Source

Temperature

height

Q
"Tornado in the Bottle"

**Gradient Dissipation Rate (cm/sec)**

- Y-axis: Gradient Dissipation Rate (cm/sec)
- X-axis: Initial Gradient (height, cm.)

**Time to Drain (secs)**

- Y-axis: Time to Drain (secs)
- X-axis: Initial Gradient (height, cm.)
Dissipation rate for a chicken embryo

(Data from Briedis and Seagrave, 1984)
Second law and ecosystems

What is the thermodynamic game?

- Store energy
- Increase Biomass

Make use of as much of the exergy as possible to perform tasks. Make the most effective use of the energy. **Win!** 😊

(H.T. Odum was right! If maximum work principle means extract the most available work from the energy source.)
In thermodynamics, the exergy of a system is the maximum work available through any process that brings the system into equilibrium with a heat reservoir (environment). Exergy is the energy available for use.
Which degrades more energy?

3° K → 5600° K

Forest → Desert

Temperature differences and energy degradation are illustrated with arrows pointing from one area to another.
The distribution of solar energy during the growing season in the Hubbard Brook Forested Ecosystem
(From Bormann and Likens, 1978)

- Photosynthesis (2%)
- Reflected (15%)
- Evapotranspiration (42%)
- Heat (41%)
HYPOTHESES

- For more developed ecosystems:
  - The ratio $\frac{R_n}{K^*}$ will be larger.
  - Lower surface temperature.
  - Smaller temperature change in response to a given amount of energy input (net radiation).
  - Spatial variation of surface temperature will be less.
Thermal Response Number

\[ TRN = \frac{Q^*}{\Delta T} \]

where:
\[ Q^* = \text{net radiation} \]
\[ \Delta T = \text{change in temperature} \]

- Uses the change in surface temperature between 2 measurement times
- Uses surface net radiation as amount of energy available the surface for partitioning
- Produces a quantifiable value \((\text{kJ m}^{-2} \text{oC}^{-1})\)
- Allows the classification of land use in terms of energy partitioning
<table>
<thead>
<tr>
<th></th>
<th>Quarry</th>
<th>Clearcut</th>
<th>Douglas Fir Plantation</th>
<th>Natural Forest</th>
<th>400 year old Douglas Fir Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>50.7</td>
<td>51.8</td>
<td>29.9</td>
<td>29.4</td>
<td>24.7</td>
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<tr>
<td>$R_n/K^*$ (%)</td>
<td>62</td>
<td>65</td>
<td>85</td>
<td>86</td>
<td>90</td>
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<tr>
<td>Beta Index</td>
<td>12.9</td>
<td>6.3</td>
<td>34.4</td>
<td>17.2</td>
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<tr>
<td>TRN</td>
<td>168</td>
<td>406</td>
<td>1631</td>
<td>788</td>
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</table>

**Beta Index:** Spatial variability in the surface temperature

**Thermal Response Number (TRN):** For a given input of energy over a given time, the change in surface temperature. Temporal variability.

Both are measures of inertia, so bigger means less variability.
1997 Corn Yield vs Remote Sensing

Harvested September, 1998       June 26, 1998
Thermal Band correlation $> 0.86$

D. Rickman, et al., 1999
Nonequilibrium thermodynamic hypotheses concerning ecosystem development

• Exergy utilization will increase
  – $\frac{Rn}{K^*}$ will increase
  – Surface temperature will decrease

• Internal equilibrium will increase
  – Spatial variation in surface temperature will decrease (Beta index increases)
  – Temporal variation in surface temperature will decrease (TRN increases)
Conclusions

- Ecosystems develop structure and function that degrades the quality of the incoming energy more effectively.

- The ecosystem T and Rn/K * and TRN are excellent candidates for indicators of ecological integrity.

- The potential for these methods to be used for remote sensed ecosystem classification and ecosystem health/integrity evaluation is apparent.


