A Thermodynamic Basis for Thermal Remote Sensing: The Theory and Application to Natural and Managed Ecosystems Productivity

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In Memory of James J. Kay 1954-2004
https://en.wikipedia.org/wiki/James_J._Kay

θΔics

LIFE AS A MANIFESTATION OF THE SECOND LAW OF THERMODYNAMICS

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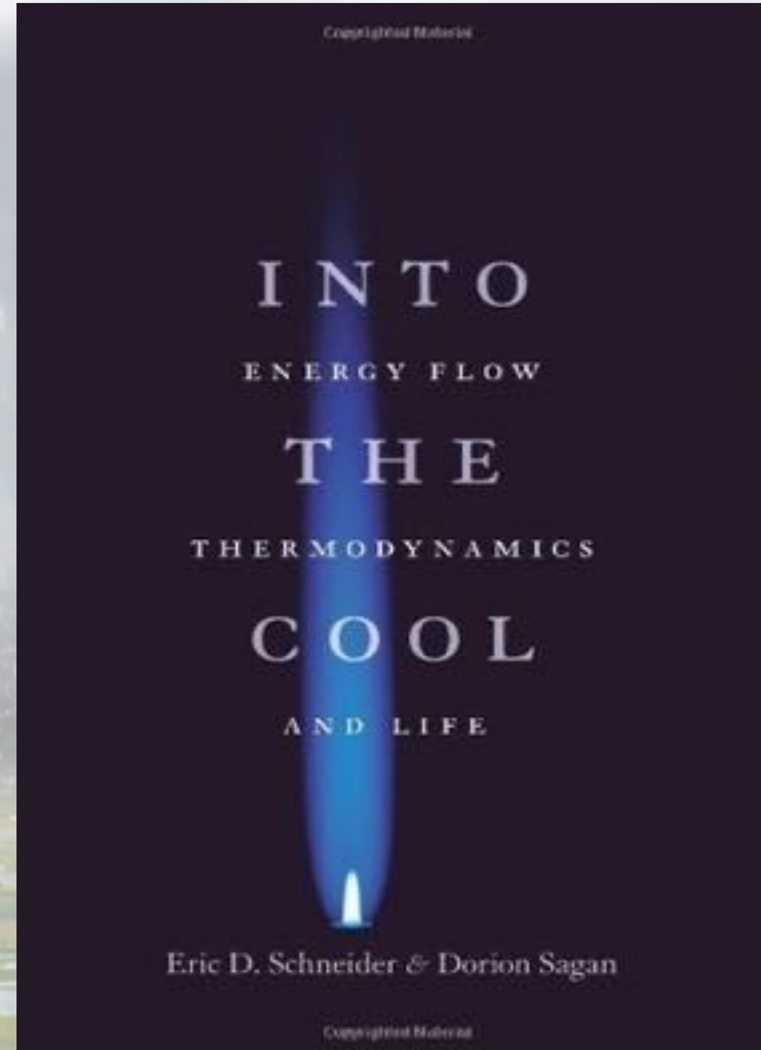


Nonequilibrium Thermodynamic Hypotheses Concerning Ecosystem Development

- *Exergy*- A measure of available work content of energy. It reflects the quality of the energy. Irreversible processes destroy exergy

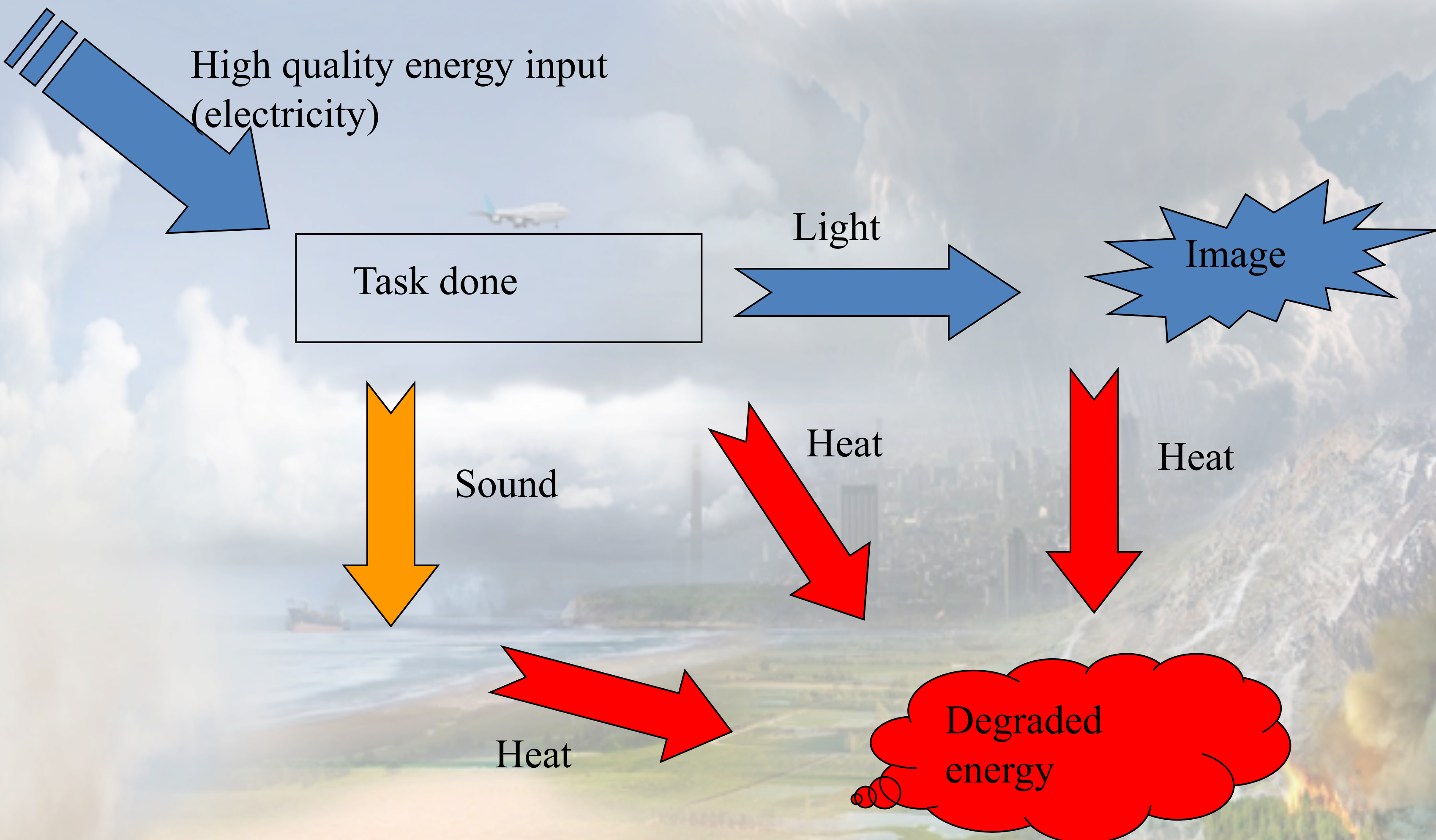
- *Forests – health, recovery, management*

- *Agriculture- yield & optium nitrogen ferterilizer levels*

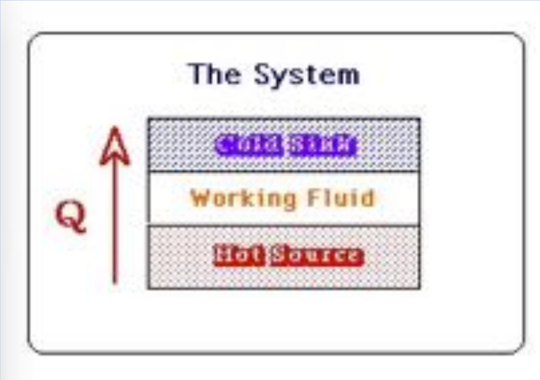
- *Urban areas - urban climatology & public health*

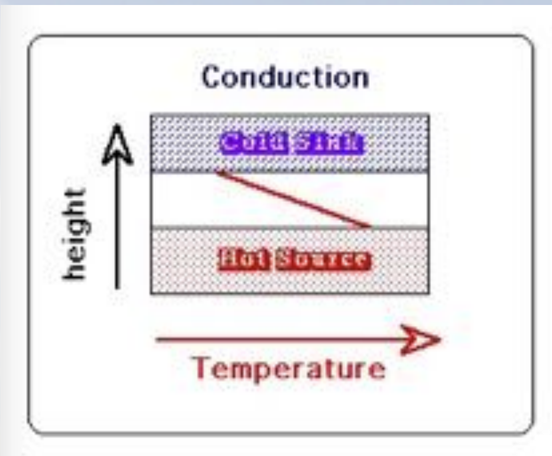
Energy IN = Energy **OUT**

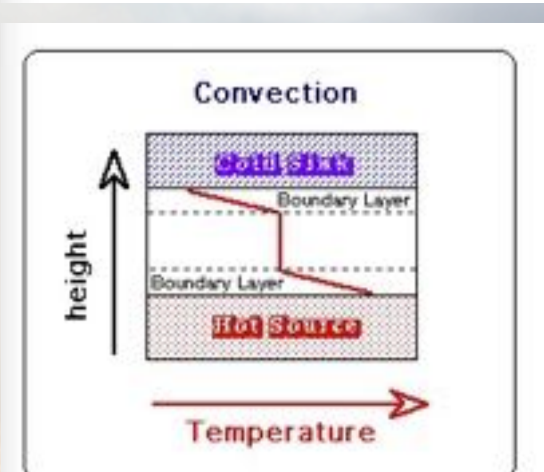
Exergy IN »»» Exergy **OUT**



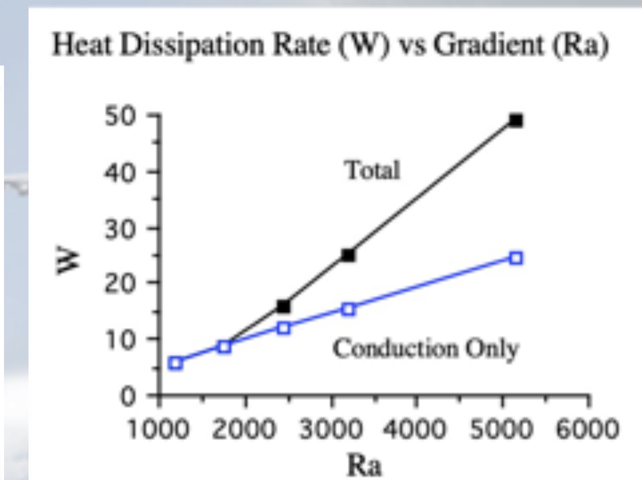
Bénard Cells

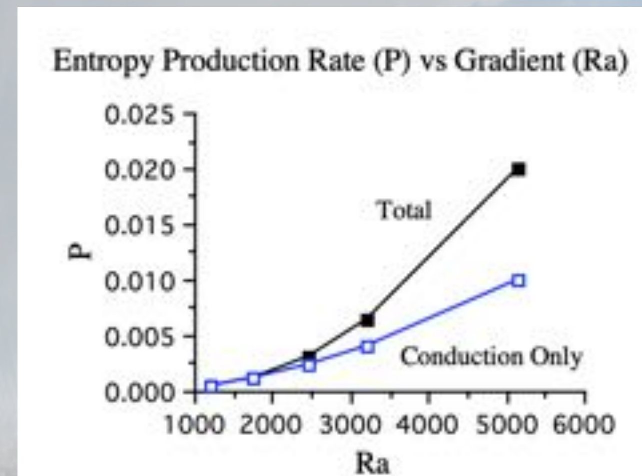


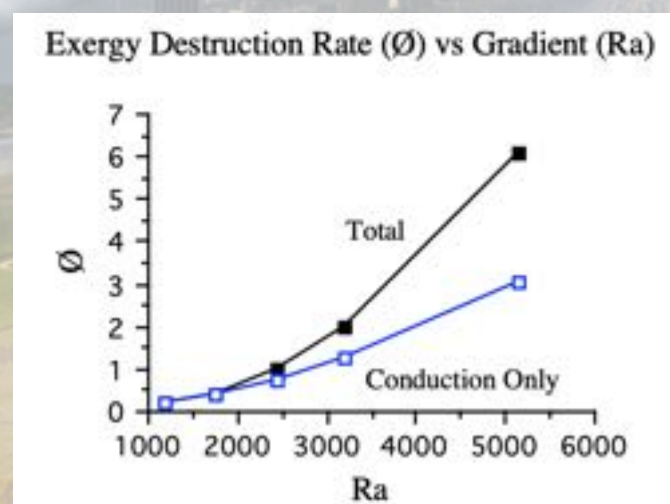




"We believe that these analyses are significant, in that we have calculated for the first time the entropy production, exergy drop and available work destruction, resulting from these organizing events[1]. "

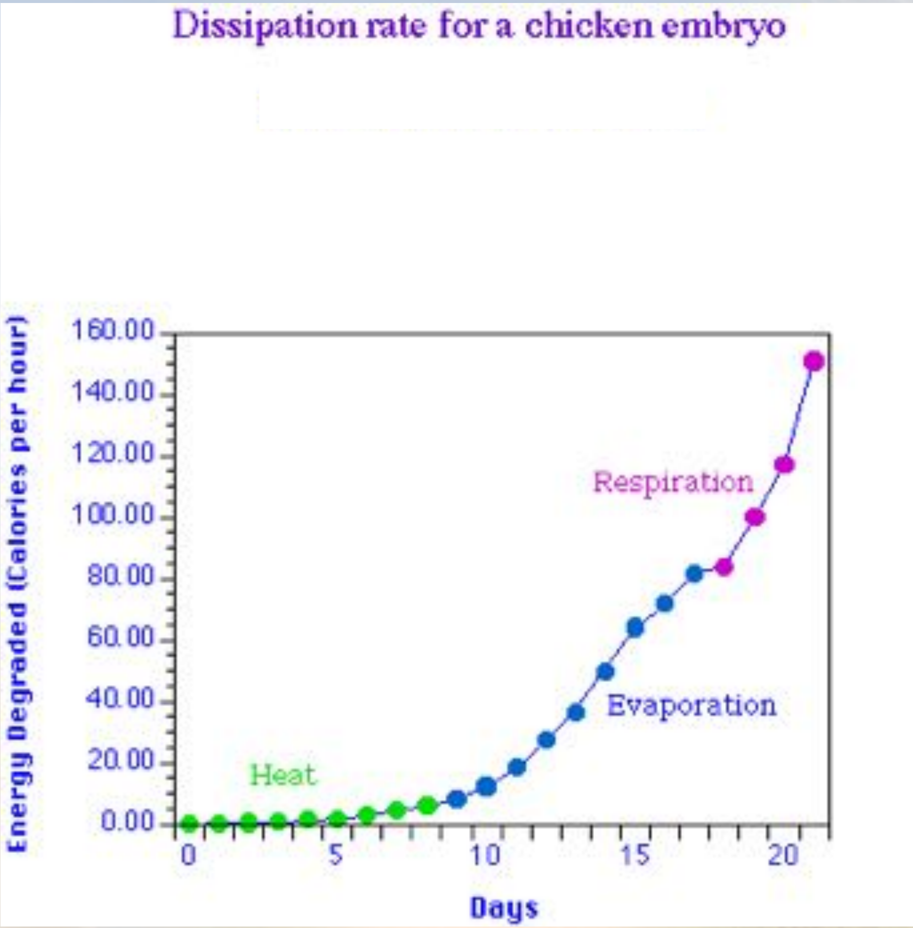


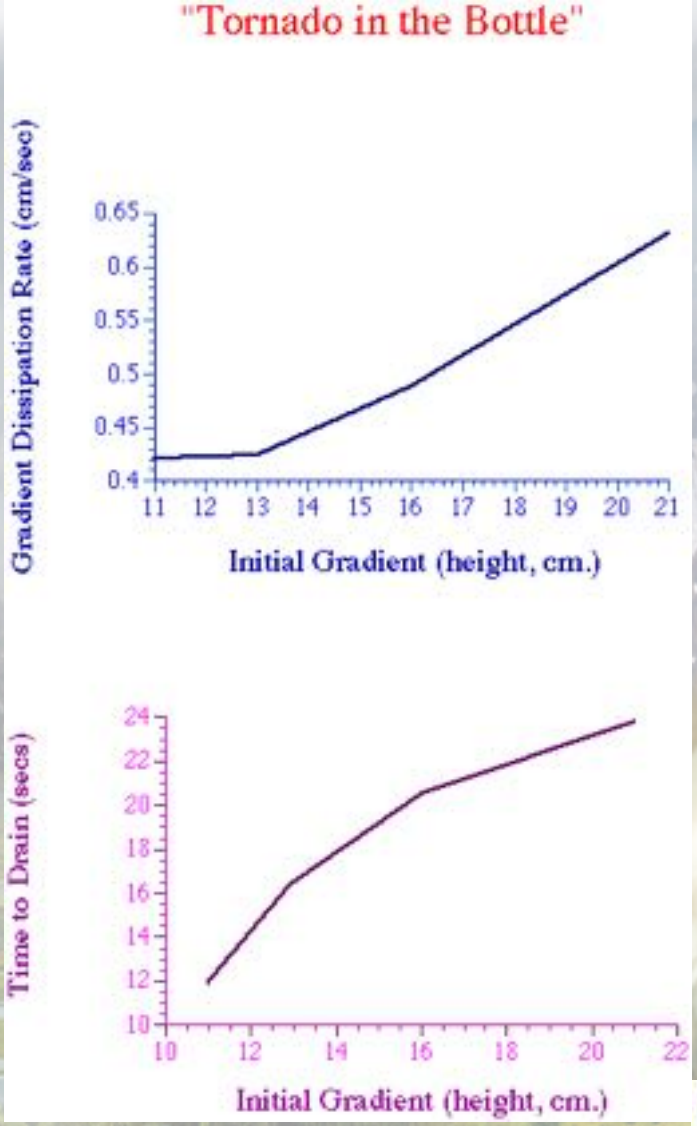




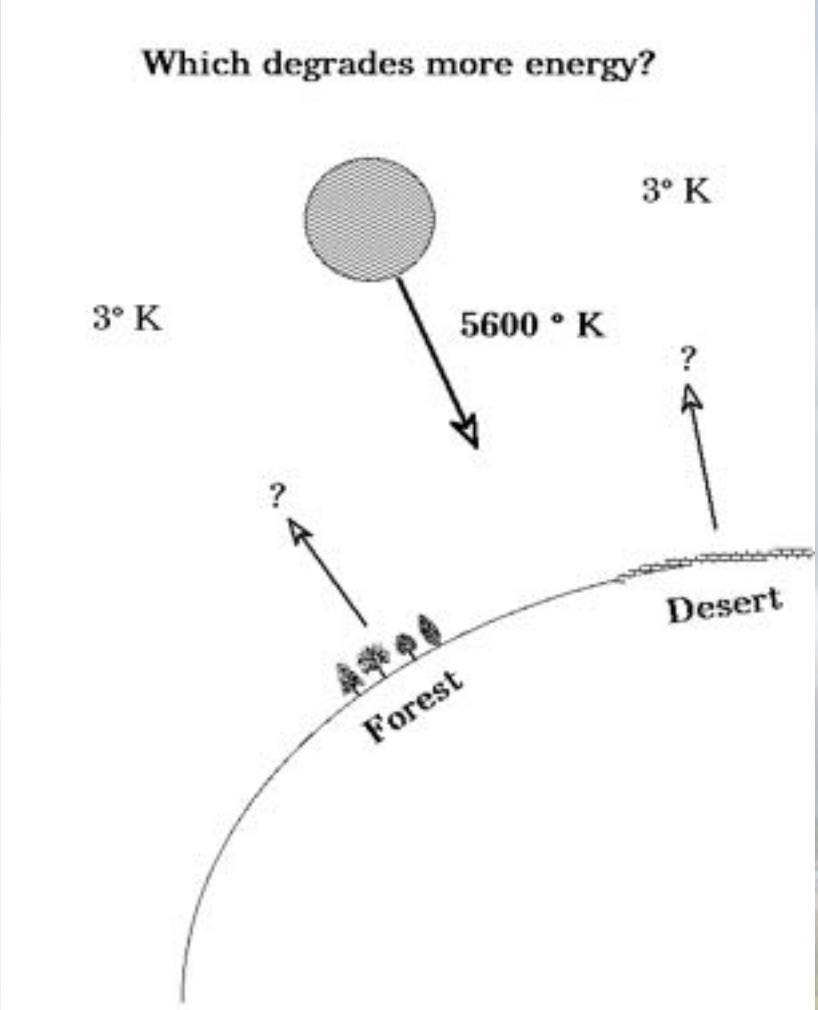
[1]Schneider & Kay 1994

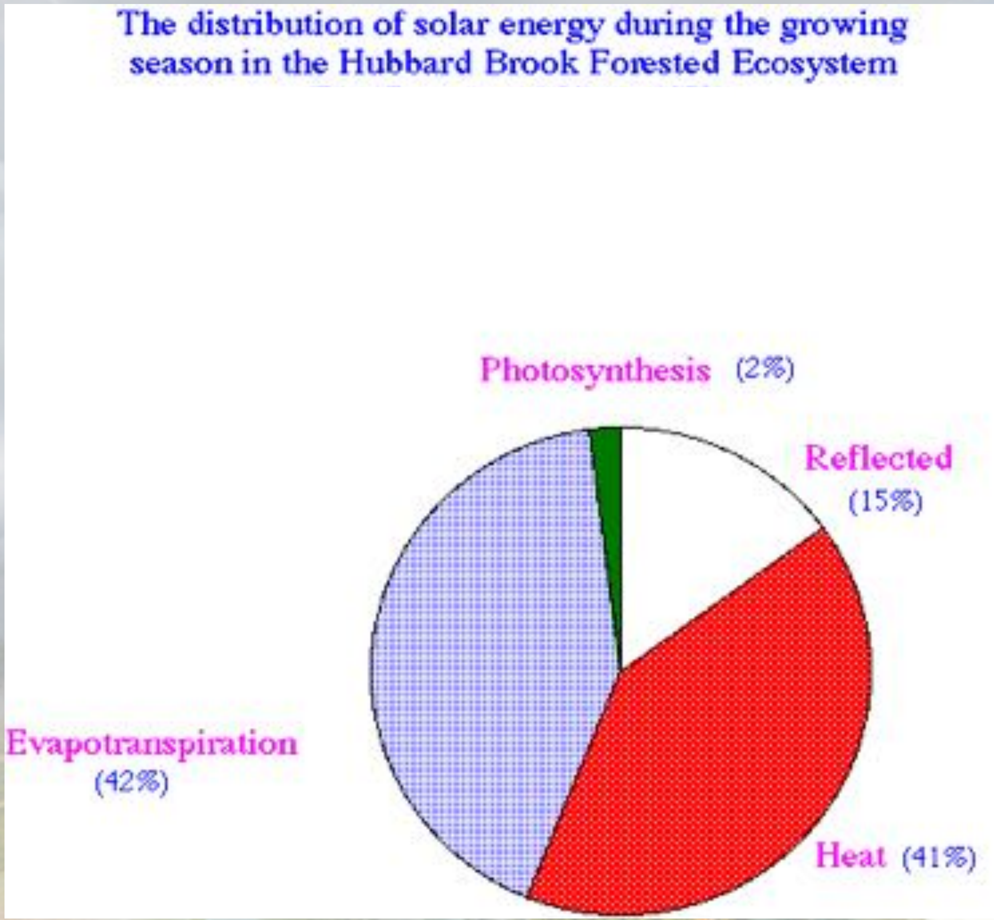
Dissipative Structures Produced by Self Organizing Systems
Leads to More Effective Dissipation of the Larger Driving Gradient





Schneider & Kay 1994





Schneider & Kay 1994

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.)

Nonequilibrium Thermodynamic Hypotheses Concerning Ecosystem Development

*Ecosystems, which also include crop plant systems, develop so as to degrade **exergy** more effectively, as revealed by surface temperature measurements, according to the exergy destruction principle*[1]

1. The ratio (Rn/K*) of net all-wave radiation to net short-wave radiation (K*) received at the surface will be larger for more developed ecosystems and these systems will have a ***lower surface temperature- Exergy utilization will increase***

   *For agriculture crops **lower surface temperatures** are related to yield and optium levels of nitrogen fertilize*r (Akbari 1995, Lawrence 2016, Alzaben 2020).

2. ***Spatial variation of surface temperature (T) will be less for more developed*** ecosystems. The spatial variation can be indexed using the beta index (Holbo and Luvall 1989). The more developed ecosystems will have a larger beta index. The departure from uniformity is a measure of constraints on the system and the nature of the departure is indicative of the nature of the constraint(s). This is a thermodynamic statement about the system at a point in time- ***Internal equilibrium will increase***

3. More developed ecosystems will exhibit a ***smaller temperature change in response to a given amount of energy input (net radiation)***. This is a thermodynamic statement about the system as a derivative of time. This can be measured using **Thermal Response Number** (TRN) (Luvall and Holbo 1989). The more developed ecosystems should have a larger TRN - ***Internal equilibrium will increase***

[1]Prigogine 1977;Kay 1991; Schneider & Kay 1994;Kay et al., 2001;Fraser & Kay 2004;Schneider & Sagan 2006

Surface Radiation and Energy Budgets

$$Q^* = (K\downarrow + K\uparrow) + (L\downarrow + L\uparrow)$$

$K\downarrow$ = Incoming Solar

$K\uparrow$ = Reflected Solar

$L\downarrow$ = Incoming Longwave

$L\uparrow$ = Emitted Outgoing Longwave

$$Q^* = H + LE \pm G$$

H = Sensible Heat Flux

LE = Latent Heat Flux

G = Storage Flux

The ratio of net radiation to change in temperature can be used to define a surface property referred to as the **Thermal Response Number (TRN)**.[1]

$$TRN = \sum_{t1}^{t2} Q_* \Delta t \,/\, \Delta T$$

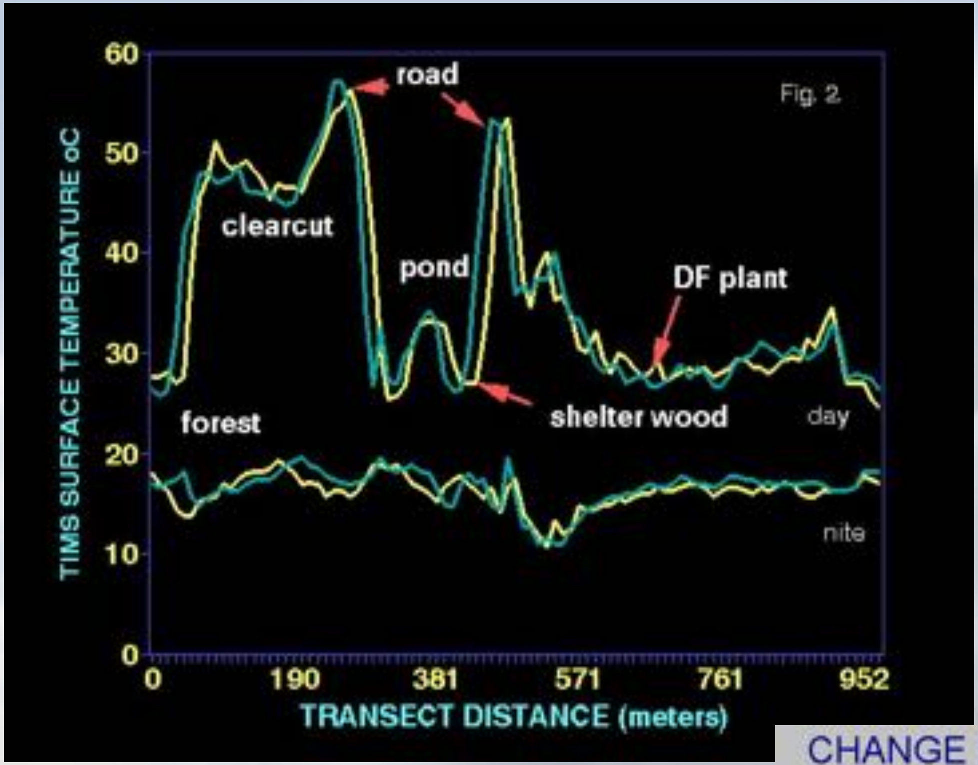
where $\sum_{t1}^{t2} Q_* \Delta t$

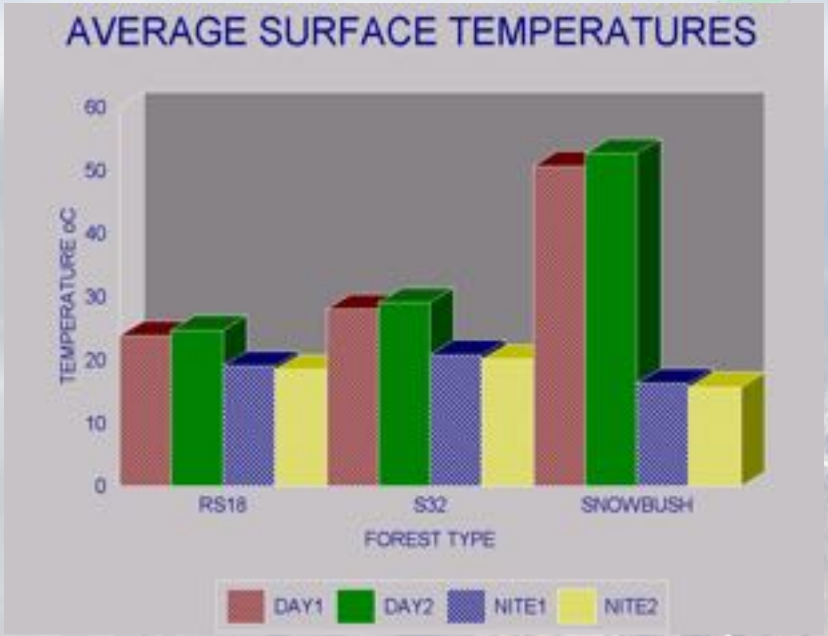
represents the total amount of net radiation (Q*)for that surface over the time period between flights($\Delta t = t2 - t1$) and ΔT is the change in mean temperature of that surface.

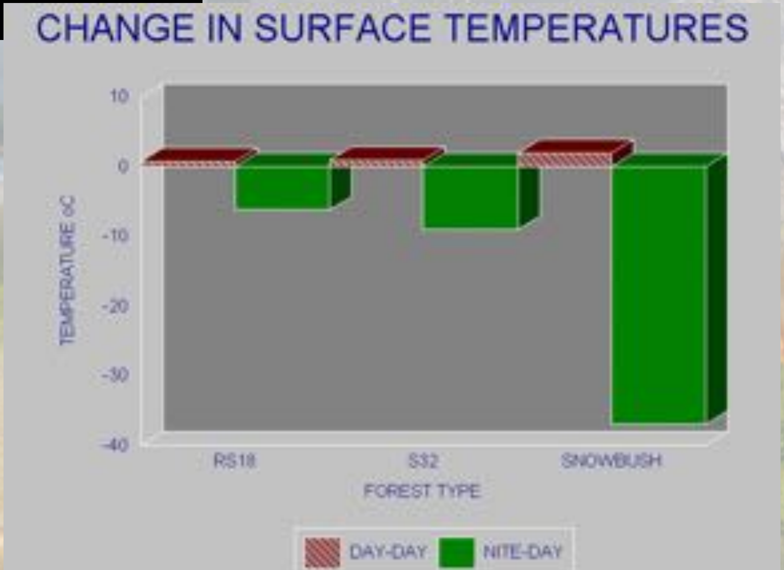
Typically a polygon of composed many pixels is extracted from the surface of interest allowing the assessment of T variability for the ***Beta Index***

[1]Luvall and Holbo 1989

Thermal Infrared Multispectral Scanner (TIMS) 10m August 1985
US Forest Service - HJ Andrews Experimental Forest, Oregon, USA







Luvall & Holbo 1989

Thermal Infrared Multispectral Scanner (TIMS) 10m August 1985
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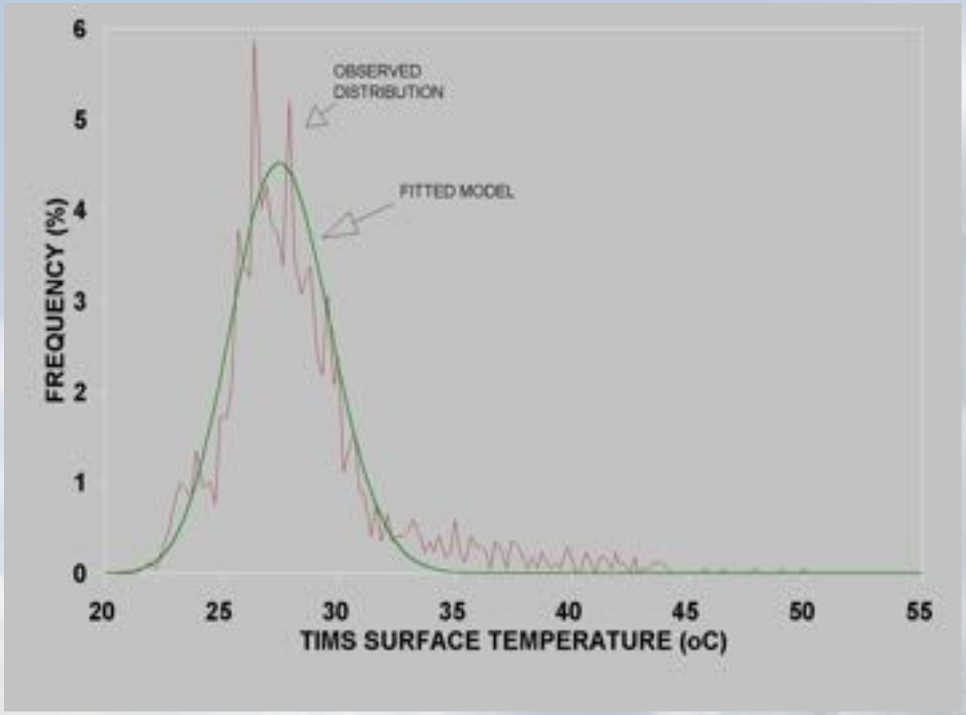
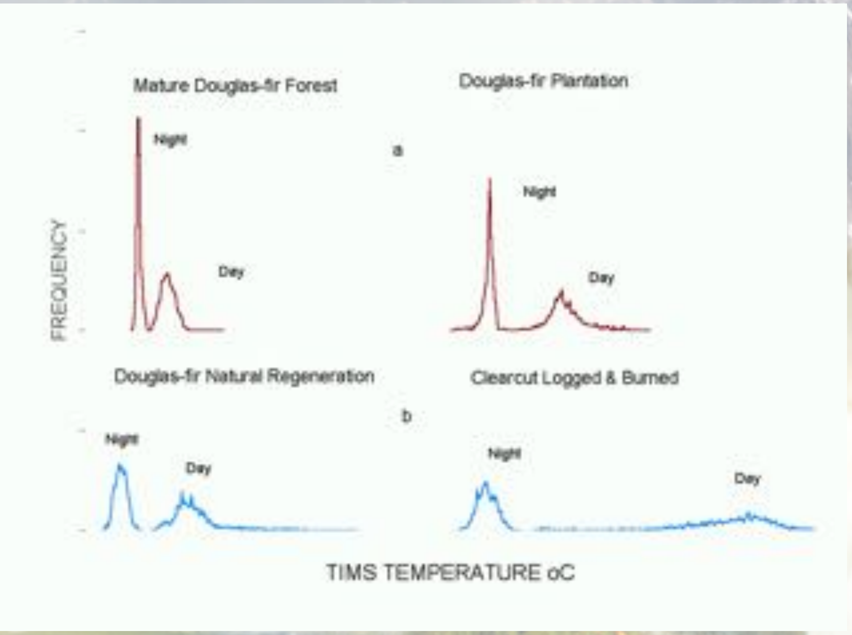


Beta Index



Holbo & Luvall 1989

US Forest Service - HJ Andrews Experimental Forest, Oregon, USA

	Quarry	Clearcut	Douglas Fir Plantation	Natural Forest	400 year old Douglas Fir Forest
T (^{o}C)	50.7	51.8	29.9	29.4	24.7
R_n/K^* (%)	62	65	85	86	90
Beta Index	12.9	6.3	34.4	17.2	130.7
TRN	168	406	1631	788	1549

[1]**Beta Index:** Spatial variability in the surface temperature

[2]**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 larger values means less variability.

[1]Holbo & Luvall 1989; [2]Luvall & Holbo 1989

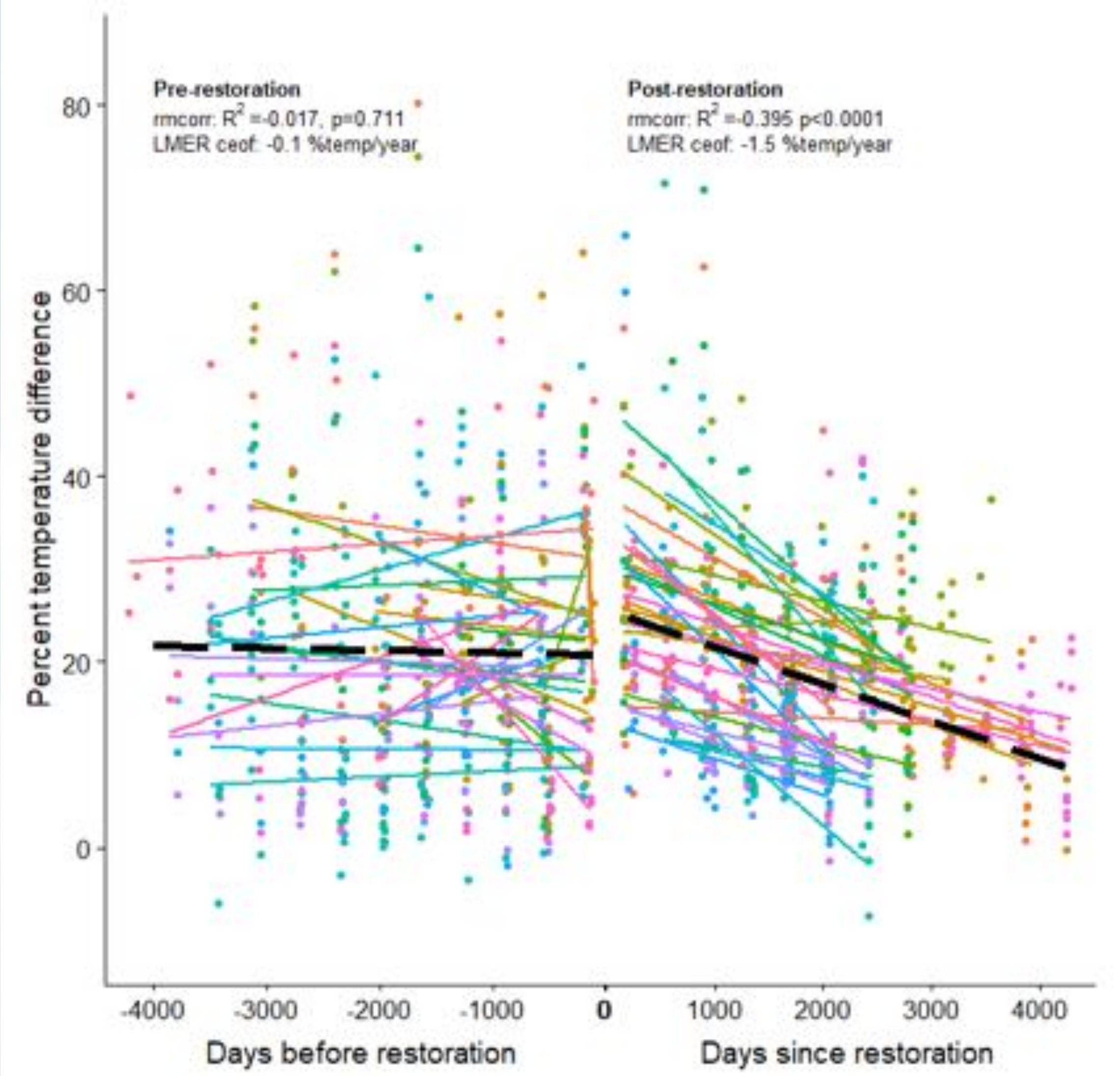
Comparing ECOSTRESS[1] Surface Temperature to Biodiversity and Biomass

59 2x2m plots
In three fields surveyed for all plants by professionals 2007-2017

Three areas (yellow) were unseeded controls

3 paired areas were compared

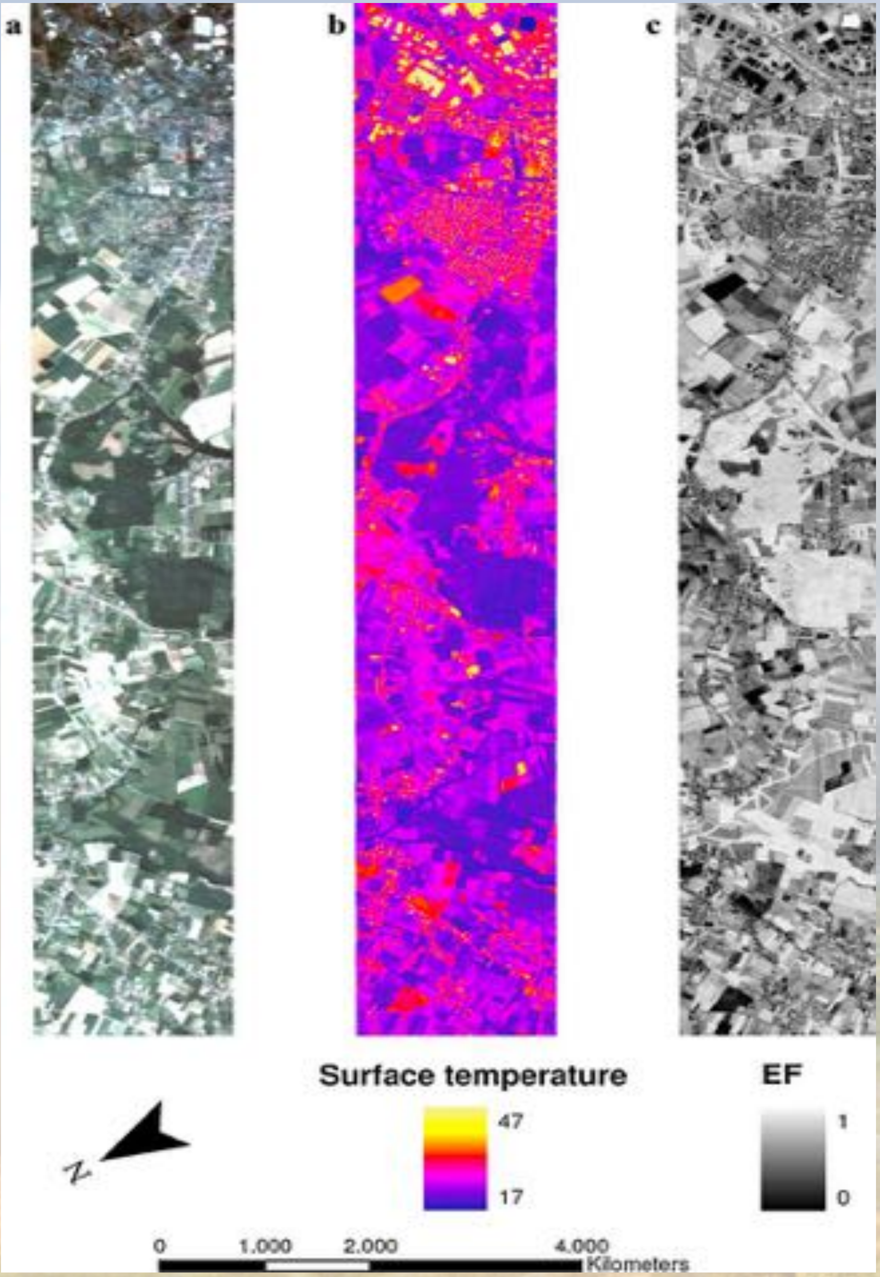
[1]ECOSTRESS early adopter-Hamberg et al., 2020



Mean temperature decrease -1.5 % pts. per year.
Equals approximately -4.5 ° C in 12 years on a summer day

Hamberg et al., 2020

DAIS Thermal Imagery, Obtained During the Summers of 1998 and 2001 in the Sandy and Sandy Loam Regions of Flanders (Belgium)[1]

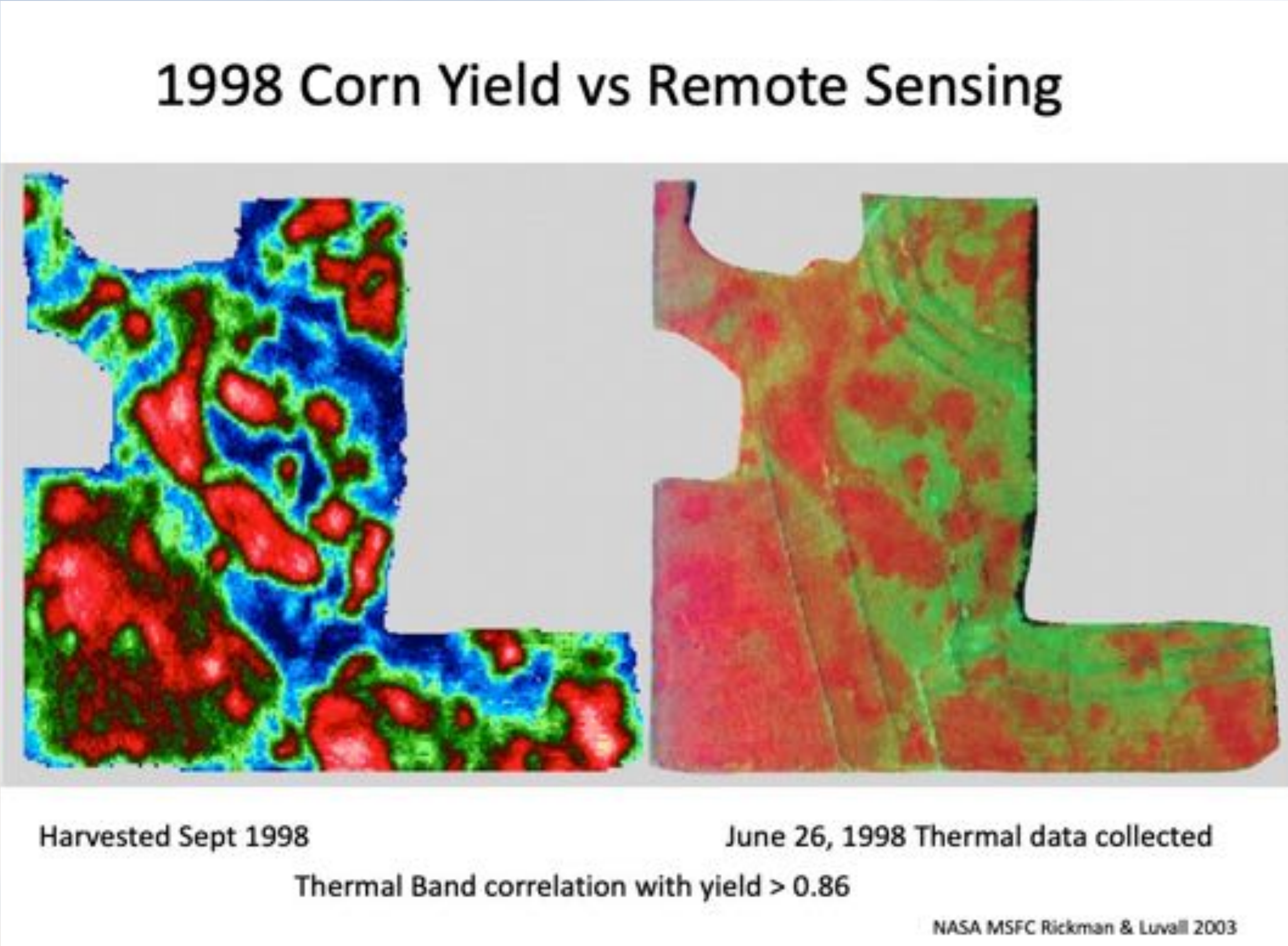


" ***We conclude from the simulations that, in agreement with the ecosystem exergy theory***, succession from non-vegetated land to forests will increase the energy dissipation, through an enhanced evapotranspiration and surface length, whilst reducing the ecosystem's dependence on unpredictable factors for its energy dissipation."

"***This is confirmed by the observational data. Dissipation increased*** in this study with increasing maturity or naturalness of major land use classes (forests > agricultural landscape and gardens > buildings). In addition, more mature (medium-aged and old) pine (in Brasschaat) and poplar (Gorsem) stands dissipated more energy than young forests. "

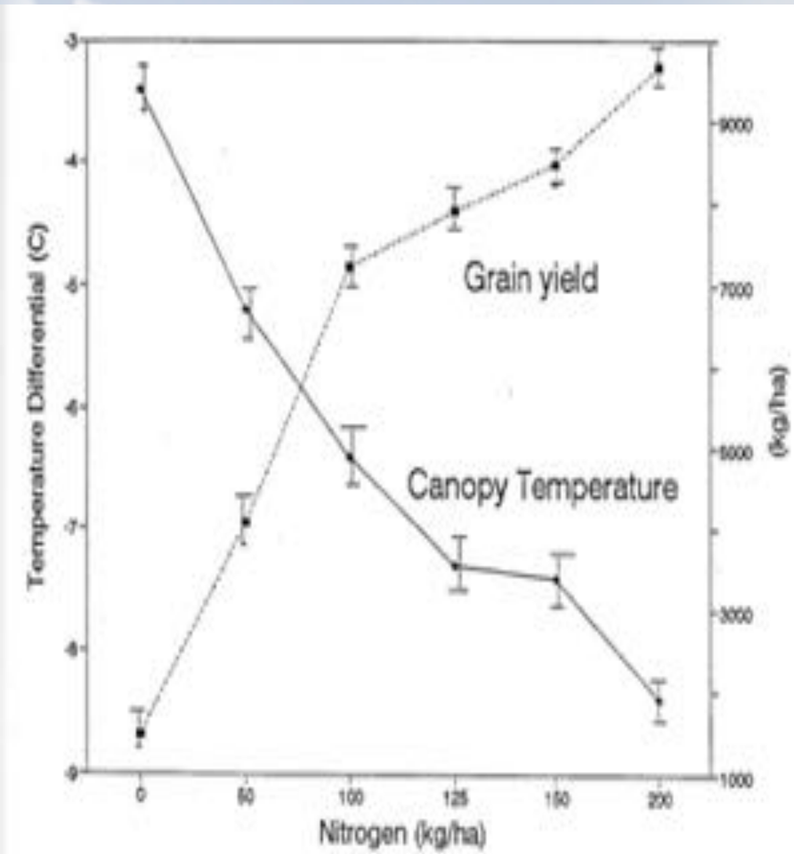
[1]Maes et al., 2011

Airborne ATLAS 5m Thermal Data

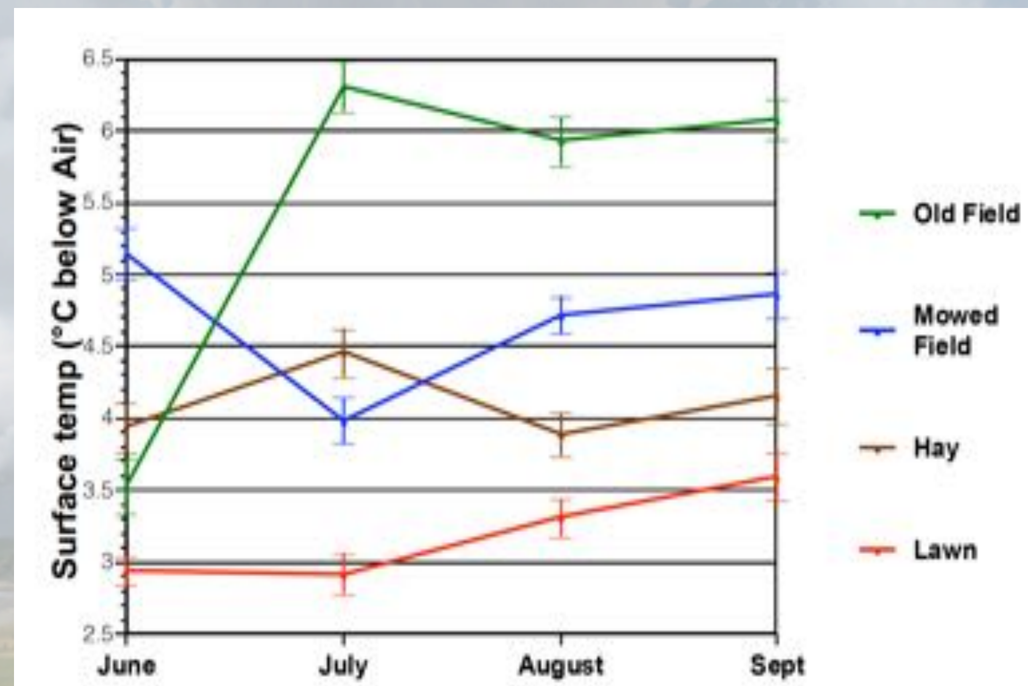


Early Field Studies

Changes in canopy temperature differential of corn as a function of nitrogen level and grain yield.

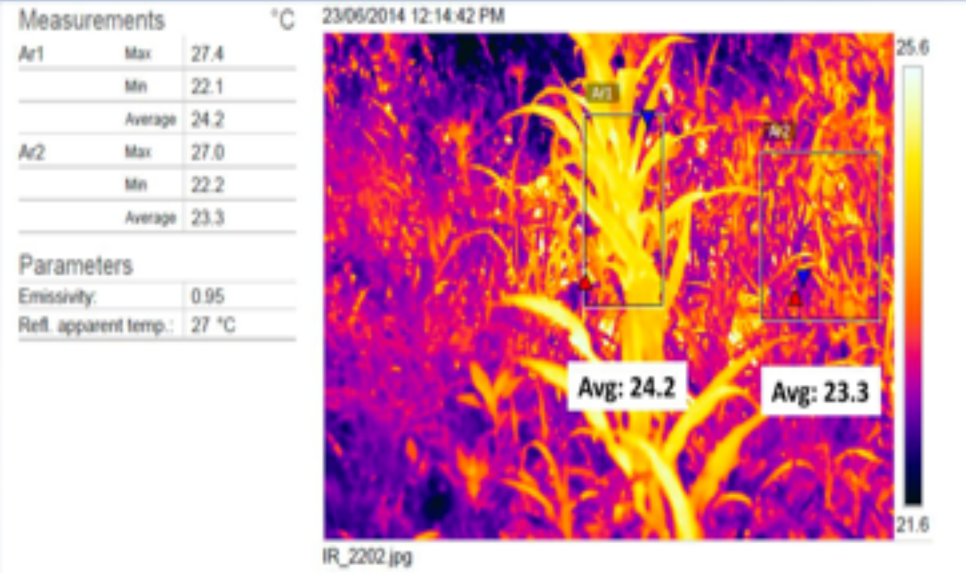


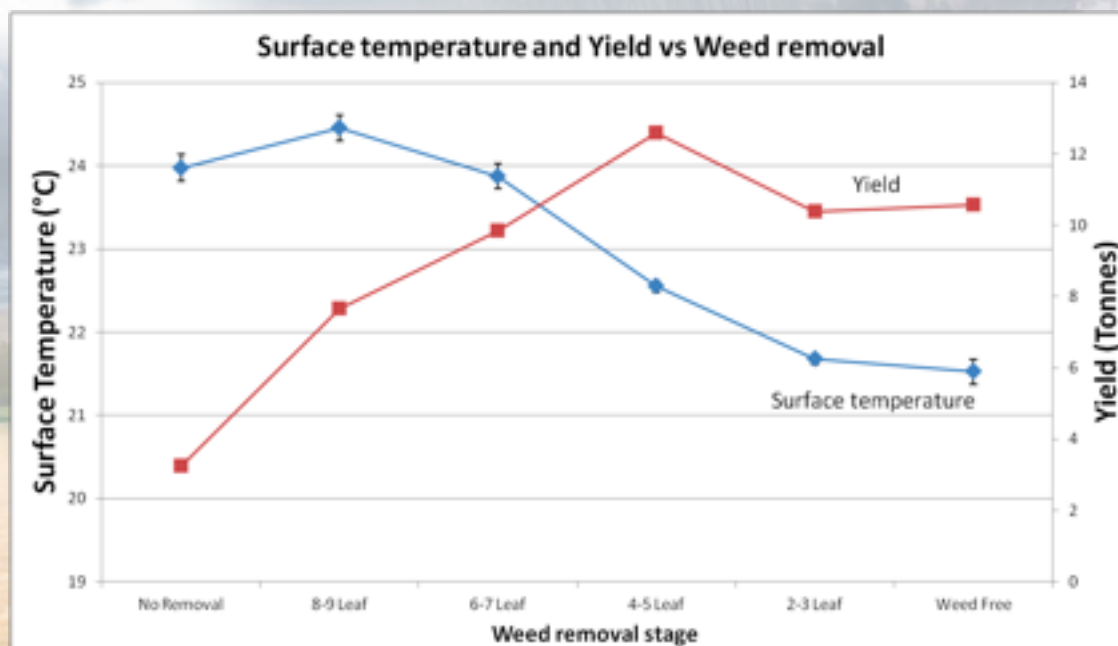
Surface - air temperature differential for various fields



Arkbari 1995

Corn Field Trials Where the Corn is Stressed With an Analog Weed (wheat)

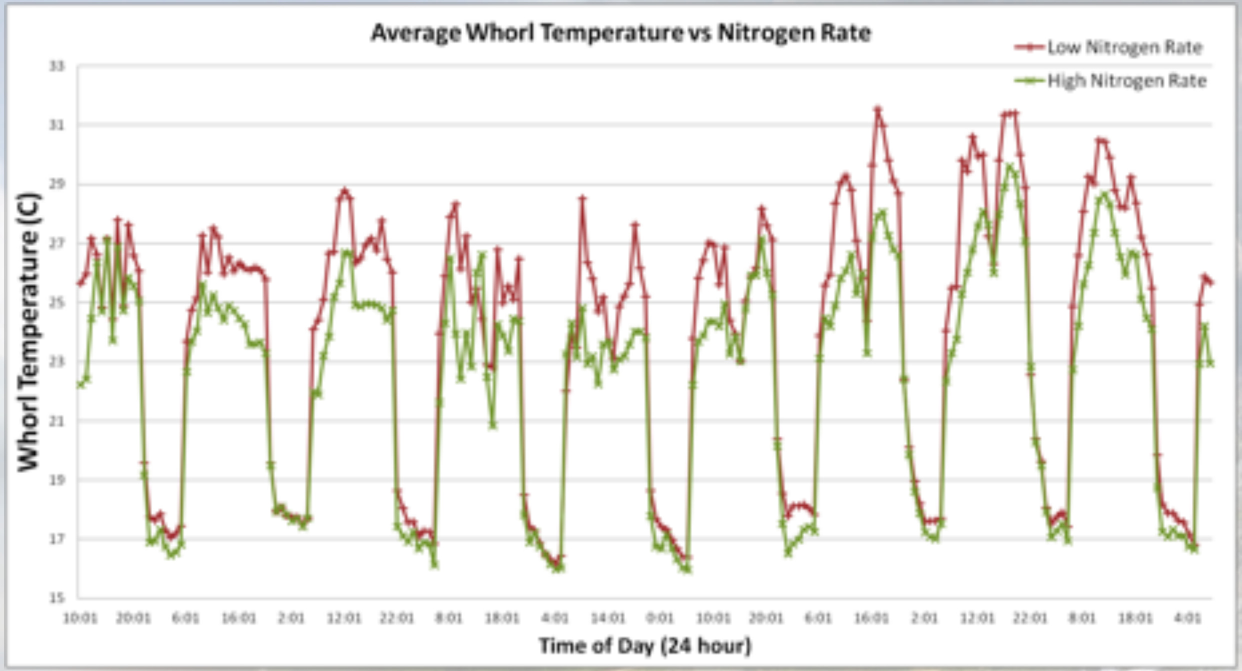




Lawrence 2016

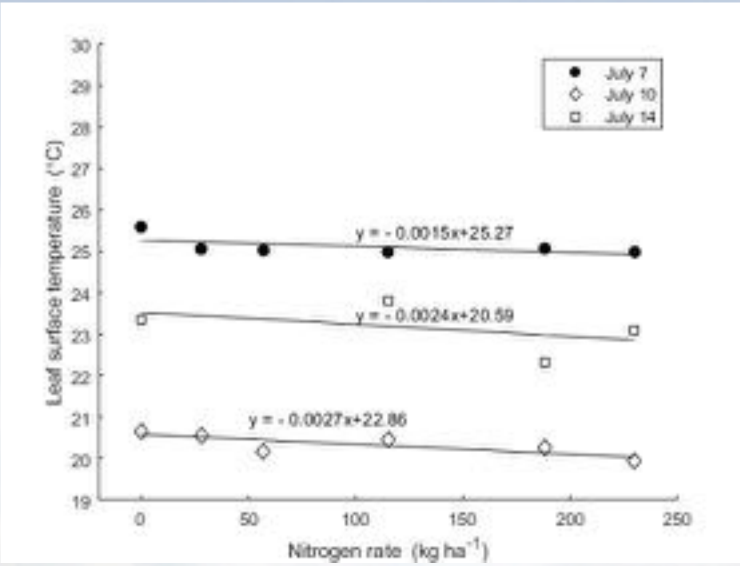
Greenhouse Nitrogen Trials

Leaf Whorl Thermocouple Temperature Measurments

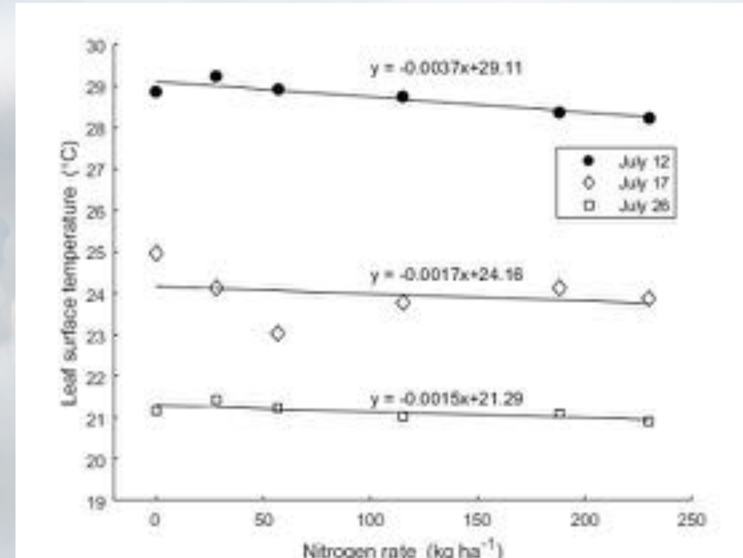


Lawrence 2016

Field Studies -The mean leaf surface temperature as influenced by nitrogen rate in July over different years

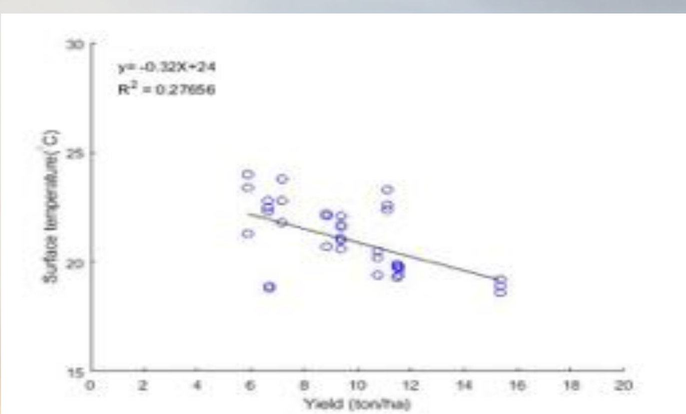


2016

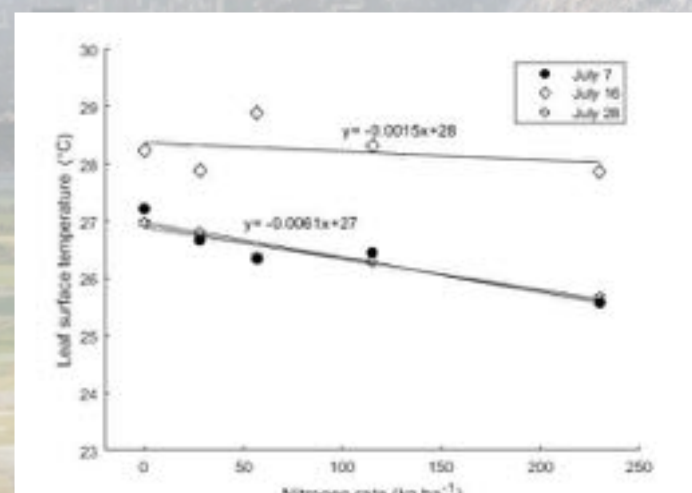


2017

Decreasing surface temperature with nitrogen rate increase and yield increase



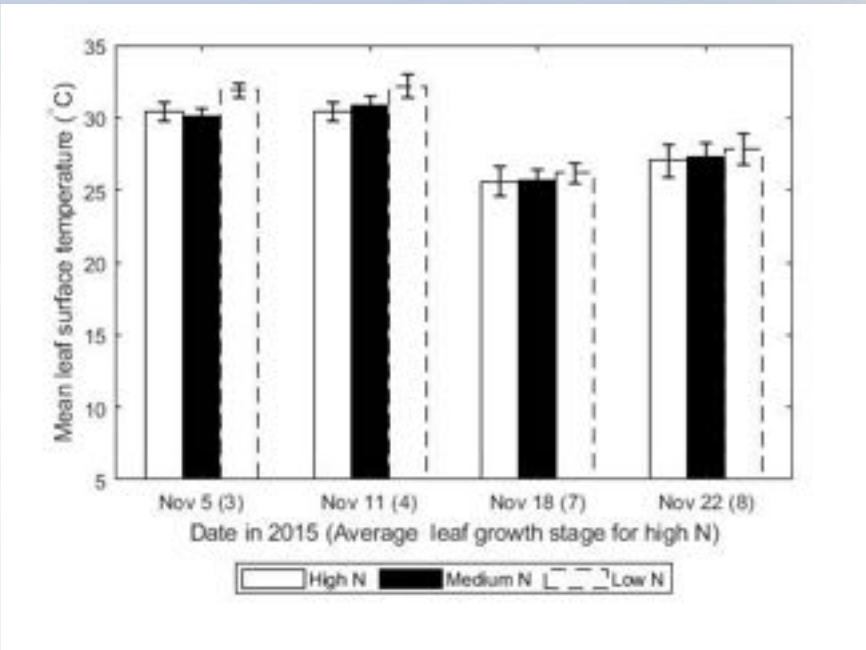
Alzaben 2020

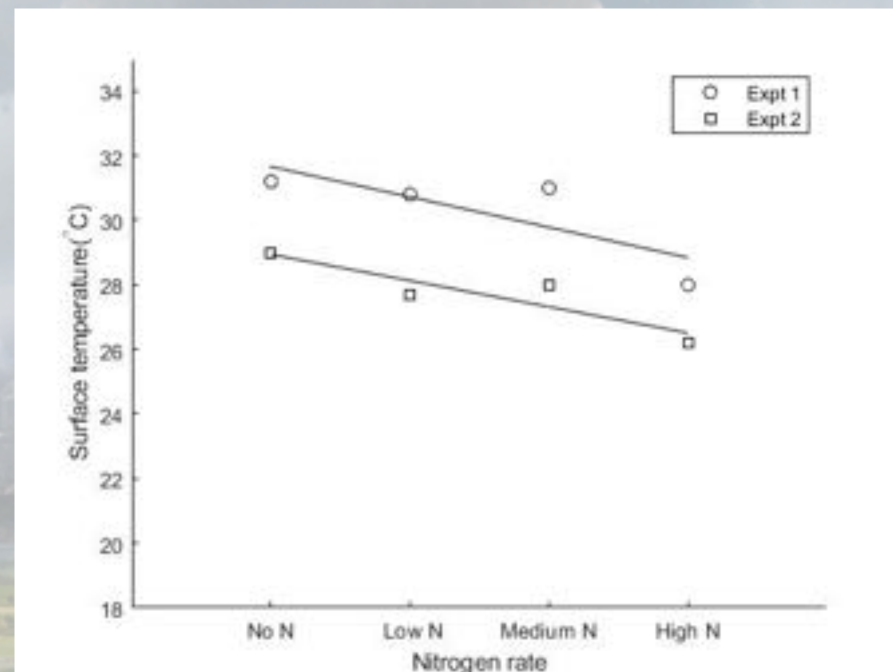


2019

Greenhouse Studies

The average leaf surface temperature decreases with increasing nitrogen rate from a thermal camera data

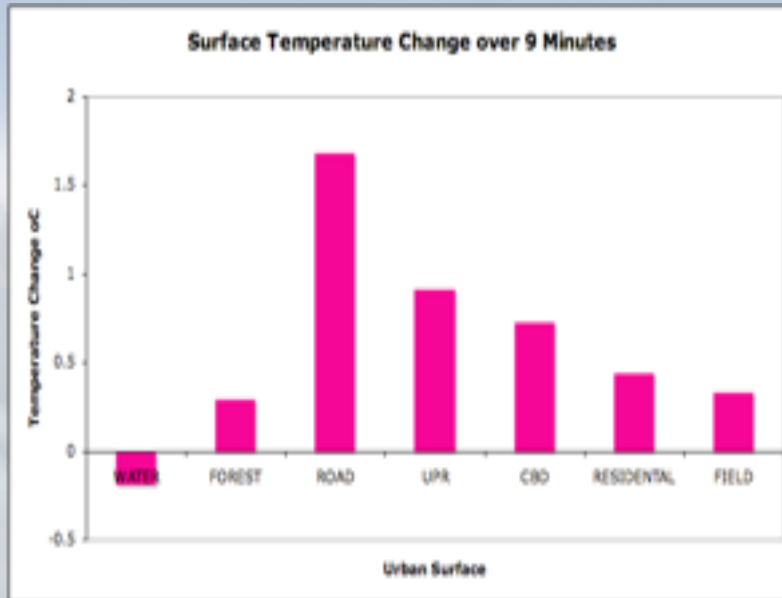


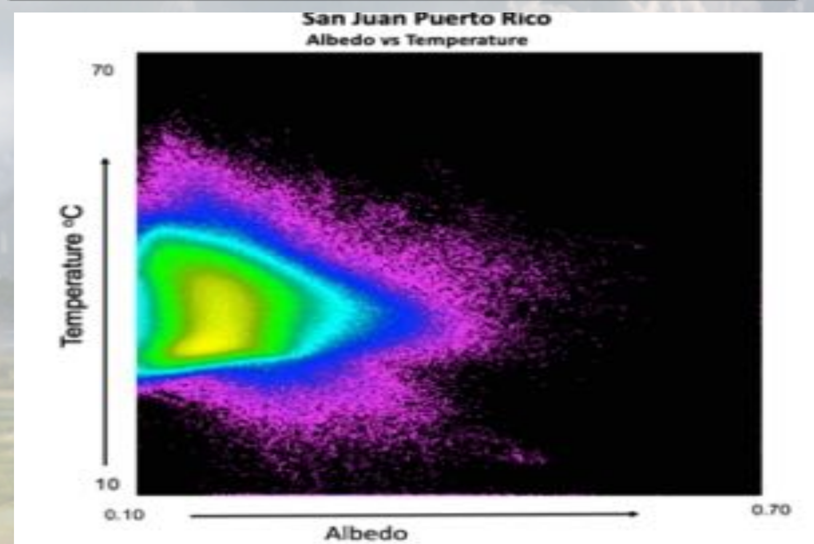


Surface temperature decreased with increasing supplied nitrogen rate

Alzaben 2020

5 m Resolution ATLAS Thermal Data (2004) from San Jaun, PR





An “energy fingerprint” of urban surfaces in Puerto Rico. The unique “energy print” represents how the surface is processing energy and can be used to provide a functional classification of urban surfaces which drive the microclimate important in vector borne disease habitat. (Luvall 2018)

*Both managed and natural ecosystems, develop so as to degrade **exergy** more effectively, as revealed by surface temperature measurements, according to the exergy destruction principle.*[1]

*Thus the ecosystem **T, Rn/K***, ***TRN** and the **Beta Index** are excellent indicators of ecological integrity that can be formulated from first principles of thermodynamics and physics. The required measurements can be measured using thermal* remote sensing*[2].

The potential for these methods to be used globally for ecosystem functional classification, health/integrity, fire recovery, restoration, & biodiversity is apparent. In agriculture systems the ability to estimate yield and optium nitrogen fertilizer levels will provide significant enhancement to the ability to manage these ecosystems.

With current the ECOSTRESS thermal data products and planned HyTES European field campaigns this summer along with the future Trishnia, SBG and LSTM satellite missions, there are significant pontienal for application of these techniques for studying natural & managed ecosystems.

*albedo is also required

[1]Prigogine 1977;Kay 1991; Schneider & Kay 1994;Kay et al., 2001;Fraser & Kay 2004;Schneider & Sagan 2006

[2]Luvall & Holbo 1989;Holbo & Luvall 1989;Luvall et al.; 1990;Akbari 1995;Maes et al., 2011;Lawrence 2016;Hamberg 2020;Alzaben 2020

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