CIVE 519 - Irrigation Water Management

FALL 2024

Lecture 22

*Mapping ET_a using a land surface energy balance model based on **S**urface **A**erodynamic **T**emperature*

(SAT, T_o)

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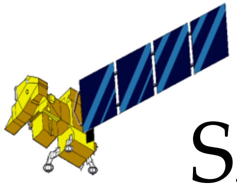
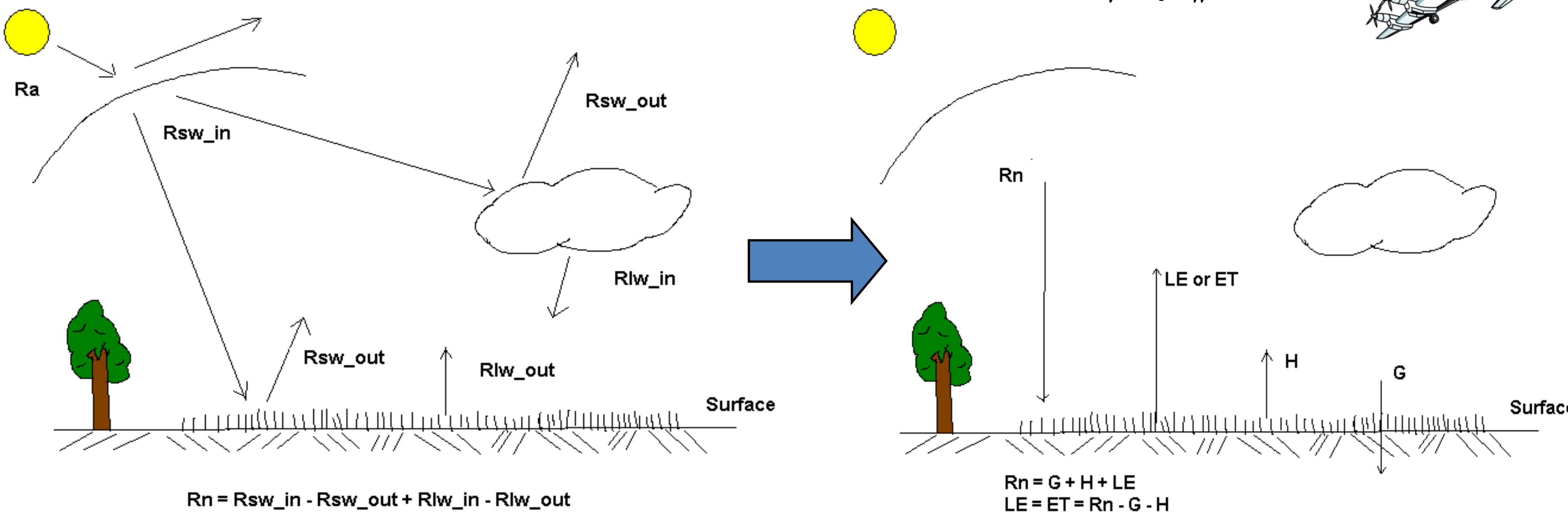


SAT-based Land Surface Energy Balance:

Surface Aerodynamic Temperature (SAT) model

$$LE = R_n - G - H$$

$$ET = \frac{c \times LE}{\lambda_v \times \rho_w}$$



$$R_n = (1- \alpha)R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow}$$

$$R_n = (1-\alpha)R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

$$G = f(VI, R_n)$$

$$\mathbf{H = \rho_a \ c_{pa} \ (T_o - T_a) / r_{ah}}$$

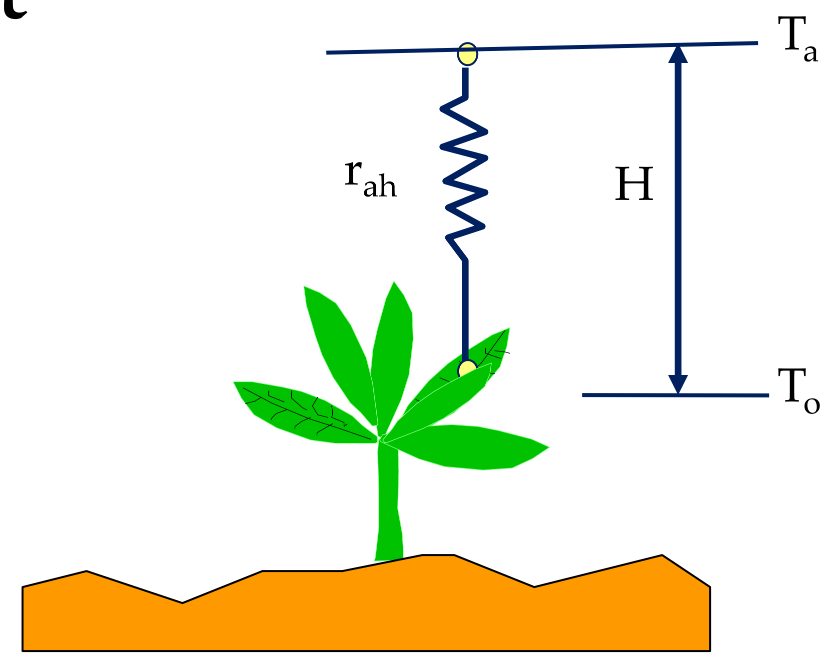
Problem Statement

$$H = \rho_a \, C_{pa} \, (T_o - T_a) \, / \, r_{ah}$$

$$H = \rho_a \, C_{pa} \, (T_s - T_a) \, / \, r_{ah}$$

***T_o = aerodynamic surface temperature*, °C**

T_s = radiometric surface temperature, °C



Use of radiometric surface temperature in standard bulk aerodynamic resistant equations for computing heat fluxes has not been successful in general. This has been attributed to the significant differences existing between the radiative and the so-called "***aerodynamic***" temperature of the surface (Kustas et al., 2001).

Estimating the sensible heat flux (*H*) over sparse vegetation from thermal infrared temperature requires an estimate of the excess resistance r_r to the aerodynamic resistance (Troufleau et al., 1997).

H estimated using T_{aero} (or T_o)

Estimating sensible heat flux, H, by using a "surface-air temperature difference" is commonly expressed in resistance form:

$$H = \rho C_p \frac{T_{AERO} - T_A}{R_A} \tag{1}$$

T_{AERO} is the aerodynamic surface temperature of the surface, T_A is the near-surface air temperature, ρ is air density, C_P is the specific heat of air, and R_A is the aerodynamic resistance (Huband & Monteith, 1986). Radiometric temperature observations, $T_R(\theta)$, at viewing angle θ from satellites offer the possibility of mapping surface heat fluxes on a regional scale if $T_R(\theta)$ can be related to T_{AERO}.

Excess resistance added to compensate for the difference between T_o and T_s (or T_r)

that the existing theory, which addresses this issue, does not adequately account for differences between $T_R(\theta)$ and T_{AERO} observed experimentally. Instead, they have compounded the problem by including an "excess resistance" term determined empirically to account for the non-equivalence of T_{AERO} and $T_R(\theta)$. This yields an expression with the following form (e.g. Stewart *et al.*, 1994):

$$H = \rho C_p \frac{T_R(\theta) - T_A}{R_A + R_{EX}} \tag{2}$$

R_{EX} is the excess resistance, and has been related to the ratio of roughness lengths for momentum, z_{OM}, and heat, z_{OH}, and the friction velocity u_* having the form (e.g. Stewart *et al.*, 1994):

$$R_{EX} = k^{-1} \ln\left(\frac{z_{OM}}{z_{OH}}\right) u_*^{-1} \tag{3}$$

where $k \approx 0.4$ is von Karman's constant. This definition addresses the fact that momentum and heat transport from the roughness elements differ (Brutsaert, 1982), but is just one of several that have been developed (e.g. Stewart *et al.*, 1994; McNaughton & Van den Hurk, 1995).

Adding a ‘β’ term to compensate

Chehbouni et al. (1997) compared the differences between radiative and inverted aerodynamic temperature to the differences between radiative and air temperature for grass and mesquite patches. The comparison showed that despite some scatters, especially for the mesquite site, that differences between the aerodynamic and radiative surface temperatures showed that the deviation of T_s from T_o grew as the magnitude of T_s grew. This model assumes that the relationship is not linear. Their results allow formulating sensible heat flux (H) using the surface radiative temperature (T_s).

$$H = \rho_a Cp\, \beta \left(\frac{T_s - T_a}{r_{ah}} \right)$$

$$\beta = \frac{1}{\exp\left(\frac{L}{L - LAI} \right) - 1}$$

L is an empirical factor and it is site specific. In Chehbouni’s case, L was found to be 2.5 through least square regression.

Adjusting factor ‘β’ approach:

$H = \rho_a \ C_{pa} (T_o - T_a) / r_{ah}$

$H = \rho_a \ C_{pa} \beta (T_s - T_a) / r_{ah}$

β = 1 / EXP(L/(L-LAI)-1)

$$\beta = \frac{T_o - T_a}{T_s - T_a}$$

Chehbouni et al. (2006)

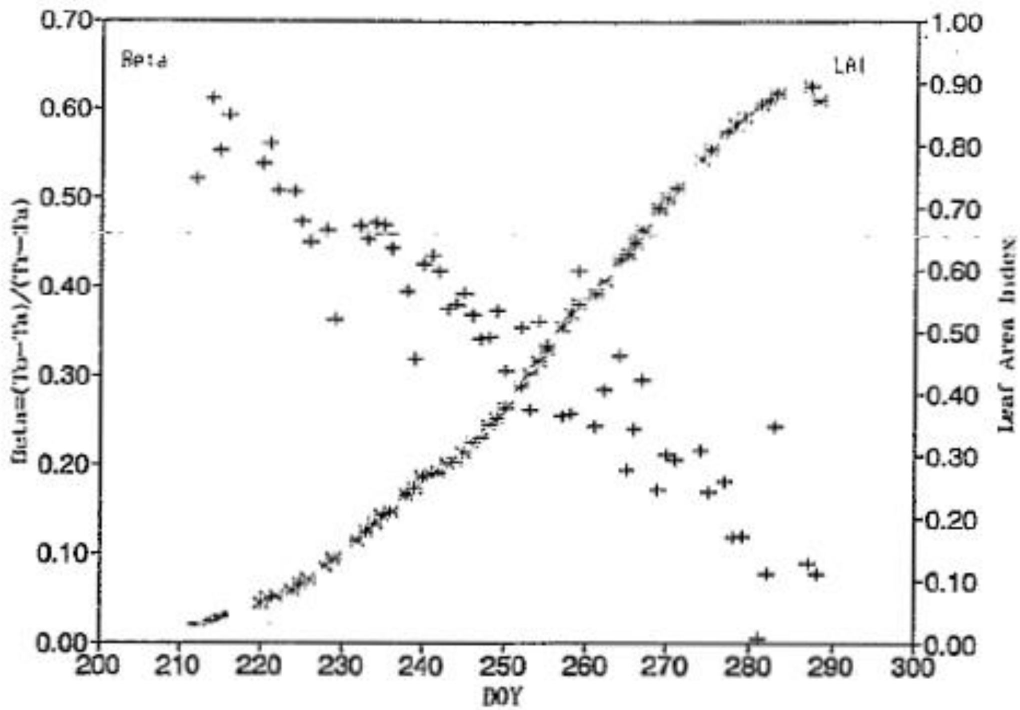
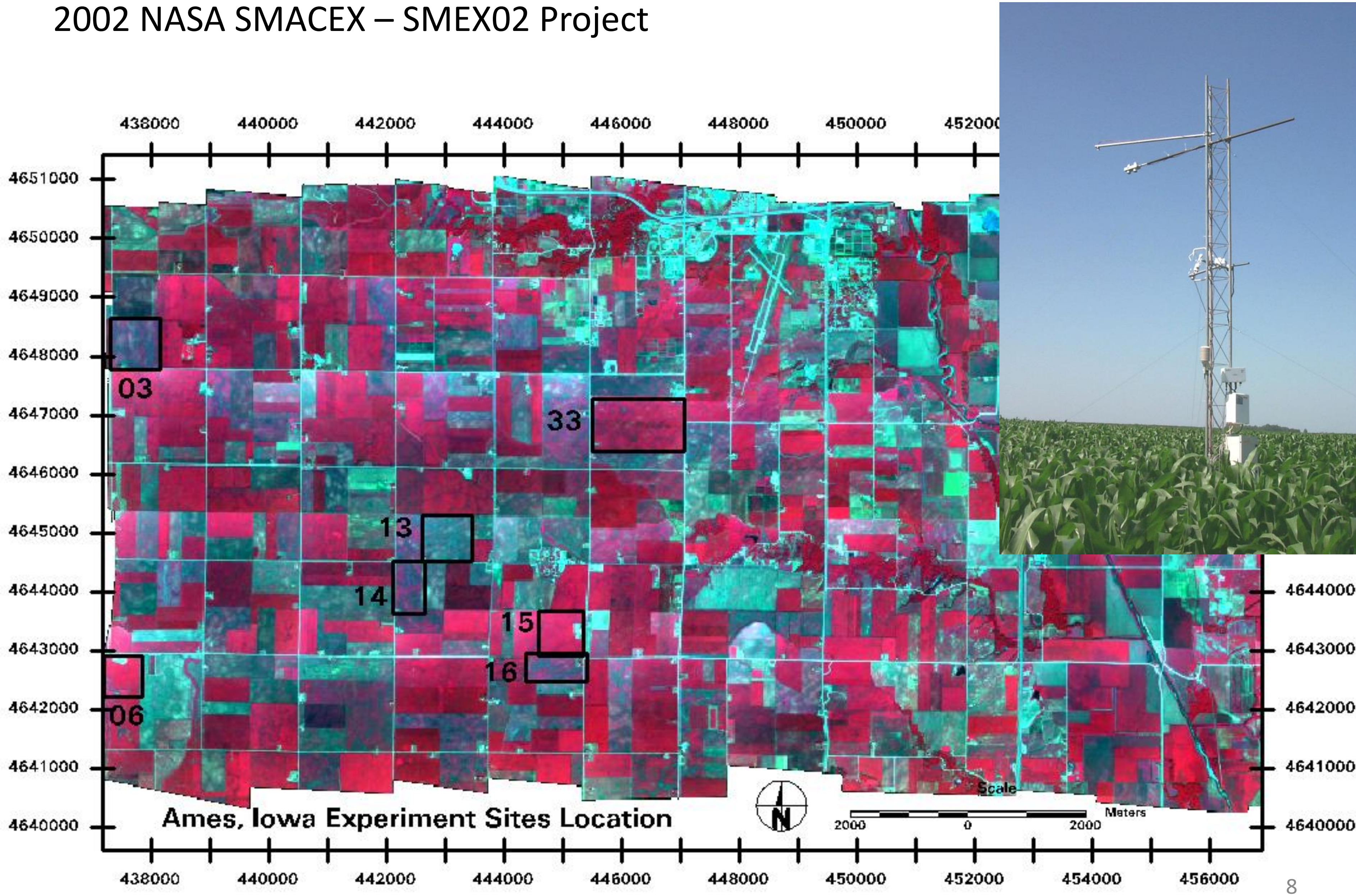


Figure 3. Comparison between the multitemporal behavior of the coefficient β values and the leaf area index.

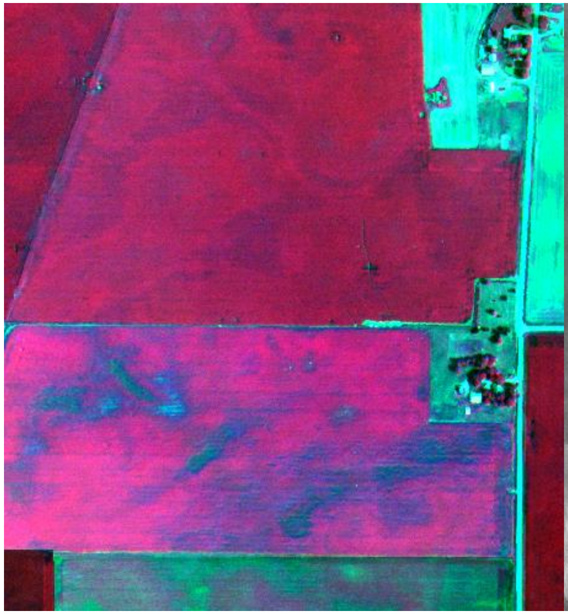
SAT (T_o) estimation over Corn and Soybean Fields (Iowa)

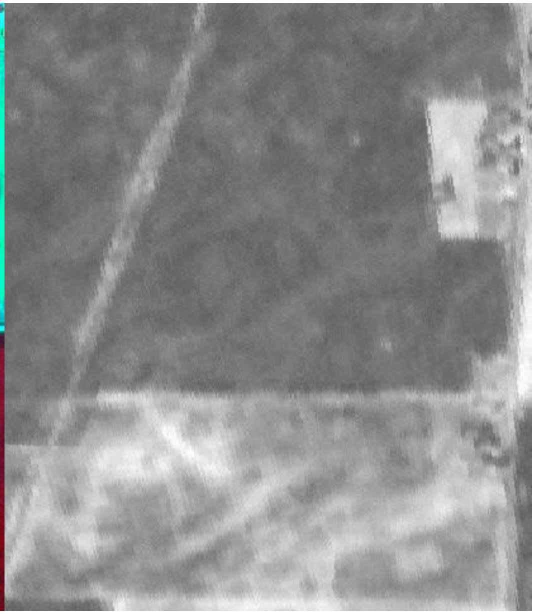
2002 NASA SMACEX – SMEX02 Project

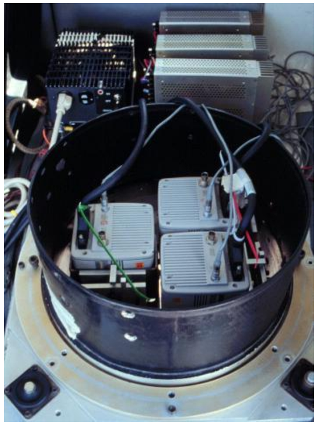


Airborne RS Imagery

Corn and Soybean fields (St 15, 16), DOY 182







reflectance

Temperature

Surface Aerodynamic Temperature (T_o) based Energy Balance (SAT-EB)

$$\mathbf{LE = R_n - G - H}$$

$$R_n = (1-\alpha)R_s + \varepsilon_a \sigma T_a^{\ 4} - \varepsilon_s \sigma T_s^{\ 4}$$

$$\alpha = 0.512\,RED + 0.418\,NIR$$

$$G = ((0.3324 - 0.024\ \mathrm{LAI}) \times (0.8155 - (0.3032\ \ln(\mathrm{LAI})))) \times R_n$$

$$\mathrm{LAI}_{\_RS} = (4 * \mathrm{OSAVI} - 0.8) * (1 + 4.73\mathrm{E}{-6} * \mathrm{EXP}\,[15.64 * \mathrm{OSAVI}])$$

$$OSAVI = \frac{(NIR - RED)(1+L)}{(NIR + RED + L)} \qquad L = 0.16$$

$$T_o = \left(\frac{H \times r_{ah}}{\rho_a\ Cp}\right) + T_a$$

$$\mathbf{H = \rho_a\ Cp_a\ (T_o - T_a) / r_{ah}}$$

$$\mathbf{T_o = 0.534\ T_s + 0.39\ T_a + 0.224\ LAI - 0.192\ U + 1.68}$$

where temperature units are in °C, LAI in $m^2\ m^{-2}$, and U in $m\ s^{-1}$.

The linear model resulted with a goodness of fit value of 0.77. In Iowa the crops (corn and soybean) were slightly water stressed and the LAI range varied from 0.3 to 5.0 $m^2\ m^{-2}$.

Chávez J.L., C.M.U. Neale, L.E. Hipps, J.H. Prueger, and W.P. Kustas. (2005). Comparing aircraft-based remotely sensed energy balance fluxes with eddy covariance tower data using heat flux source area functions. J. of Hydrometeorology, AMS, 6(6):923-940.

Anderson, M.C., C.M.U. Neale, F. Li, J.M. Norman, W. P. Kustas, H. Jayanthi, and J. Chavez (2004). Upscaling ground observations of vegetation water content, canopy height, and leaf area index during SMEX02 using aircraft and Landsat imagery. Remote Sensing of Environment, 92:447-464.

Surface Aerodynamic Resistance and friction velocity corrected for atmospheric stability

$$r_{ah} = \frac{\ln\left(\frac{z_m - d}{Z_{oh}}\right) - \psi_h\left(\frac{Z_m - d}{L}\right) + \psi_h\left(\frac{Z_{oh}}{L}\right)}{u_* \, k}$$

$$u_* = \frac{u \, k}{\ln\left(\frac{z_m - d}{Z_{om}}\right) - \psi_m\left(\frac{Z_m - d}{L}\right) + \psi_m\left(\frac{Z_{om}}{L}\right)}$$

Instantaneous LE (ET_i) and daily ET

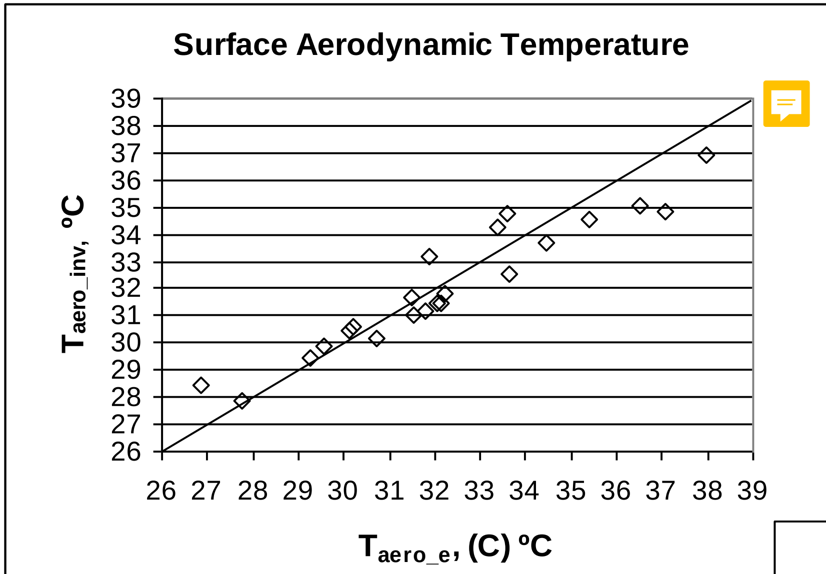
$$LE\ (W/m^2) = R_n - G - H$$

$$ET_i\,(mm/hr) = 3{,}600\,\frac{LE}{\lambda_v\,\rho_w}$$

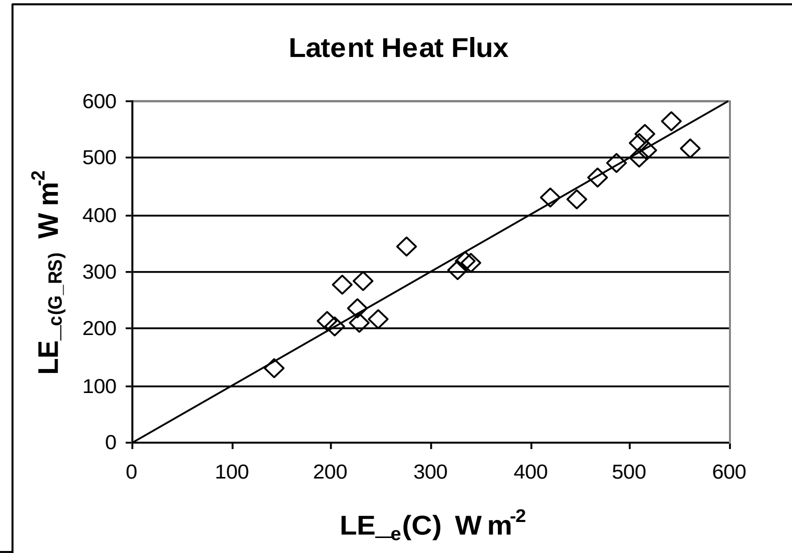
$$ET_rF = \frac{ET_i}{ET_{r\_i}}$$

$$ET_d = ET_rF \times ET_{r\_d}$$

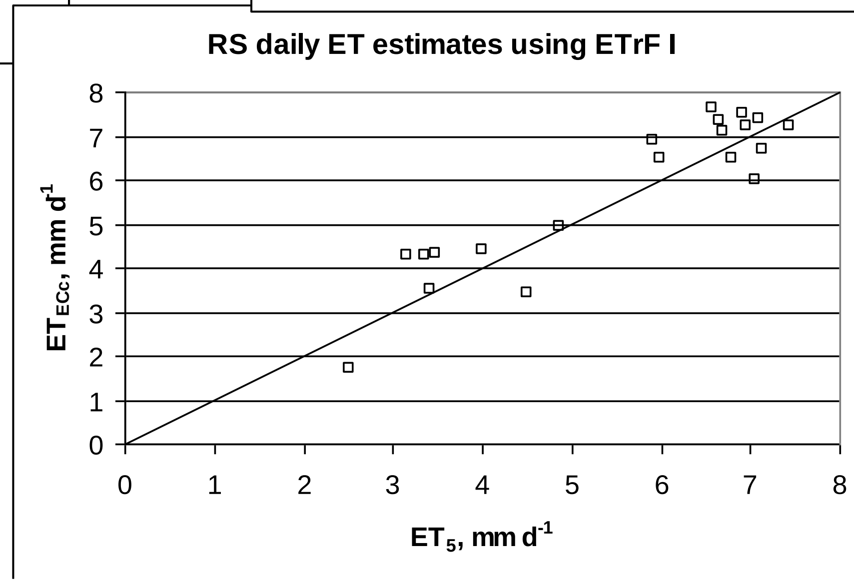
Daily ET from SAT, T_o



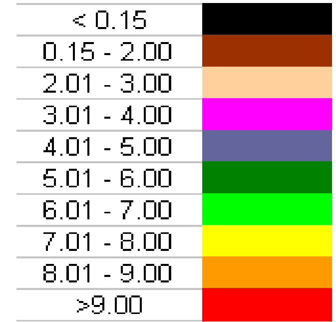
MBE = 0.2 ºC, RMSE = 0.9 ºC

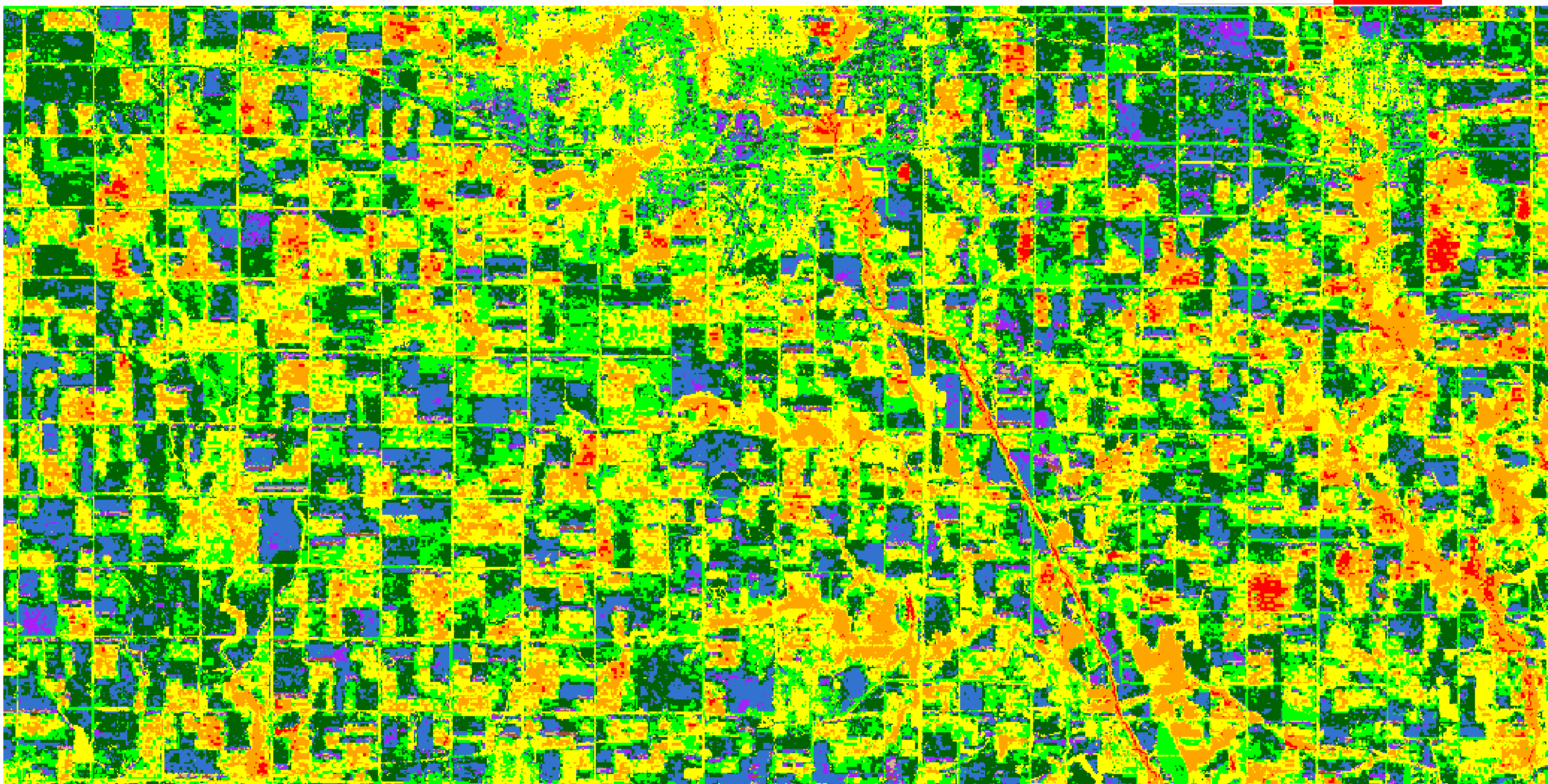


	ET_5 mm d^{-1}
MBE	-0.22
RMSE	0.68
Slope	0.96
Intercept	0.47
R^2	0.85



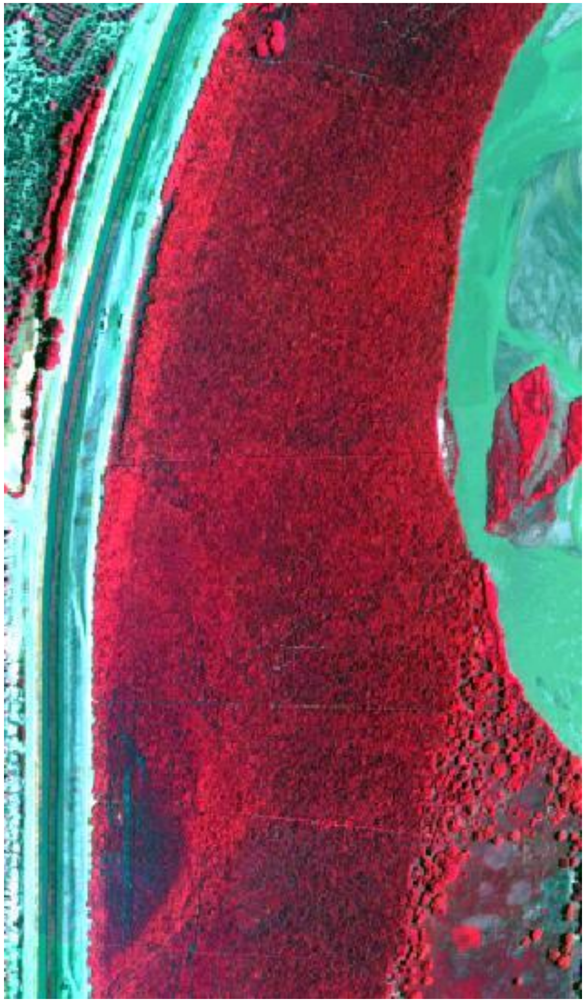
ET_d (mm/d) Map





1,600 m (1 mile)

Modeling SAT (T_o) for Salt Cedar (NM)



Surface Aerodynamic Temperature (SAT, T_o) based ET Mapping: Salt Cedar

- Salt Cedar (Tamarisk pp., ramossissima) in the middle Rio Grande (Bosque del Apache Wildlife Refuge, New Mexico) using eddy covariance systems (EC).The resulting Salt Cedar T_o model (R^2 of 0.99). LAI range was 1.6 - 4.2 $m^2\ m^{-2}$.

- $$\mathbf{T_o = 1.48\ T_s - 0.48\ T_a - 2.47\ LAI - 0.68\ u + 8.32}$$

Chávez J.L., and C.M.U. Neale (2003). Airborne Remote Sensing of Evapotranspiration over Riparian Vegetation in the middle Rio Grande River. Project Report submitted to the U. S. Bureau of Reclamation.

SAT (T_o) modeling for cotton (TX)

LAI = 0.263 Exp(3.813 OSAVI)

Table 1. Correlation of SAT with T_s, T_a, LAI and U using day time values.

	SAT	T_s	T_{a3}	*LAI*	U_3
SAT	1				
T_s	0.708261466	1			
T_{a3}	0.595569925	0.883511372	1		
LAI	-0.103971705	-0.29461358	-0.163677484	1	
U_3	-0.208957883	0.139456115	0.198642474	-0.40842	1

SAT (T_o) based ET Mapping: cotton

- Dryland cotton in the Texas Highplains where a linearly parameterization was performed of T_o to the same variables as in the previous vegetation types (R^2 of 0.70) and also using T_s, T_a, and r_{ah} with improved results (R^2 of 0.76).
- In Texas the cotton was sparse and water stressed and the LAI varied only from 0.2 to 1.3 $m^2\ m^{-2}$.

- $T_o = 0.57\ T_s + 0.14\ T_a + 0.81\ LAI – 0.97\ u + 14.9$

- $T_o = 0.50\ T_s + 0.50\ T_a + 0.15\ r_{ah} - 1.4$

Chávez, J.L., T.A. Howell, P.H. Gowda, K.S. Copeland, and J.H. Prueger (2010a). Surface Aerodynamic Temperature Modeling over Rainfed Cotton. Transactions of the ASABE, 53(3):759-767.

SAT modeling using weighing lysimeters (CO)

Large lysimeter, alfalfa field

ET(mm/h) ➔ LE(W/m²)

H = Rn – G - LE

$$T_o = \left[\frac{H + r_{ah}}{\rho \times cp} \right] + T_a$$

SAT (T_o) modeling: alfalfa, CO

- Alfalfa (somewhat water stressed), in south-east Colorado, was calibrated through a linear model: T_o based on T_s, T_a, LAI, u and r_{ah} as in the cotton case above.

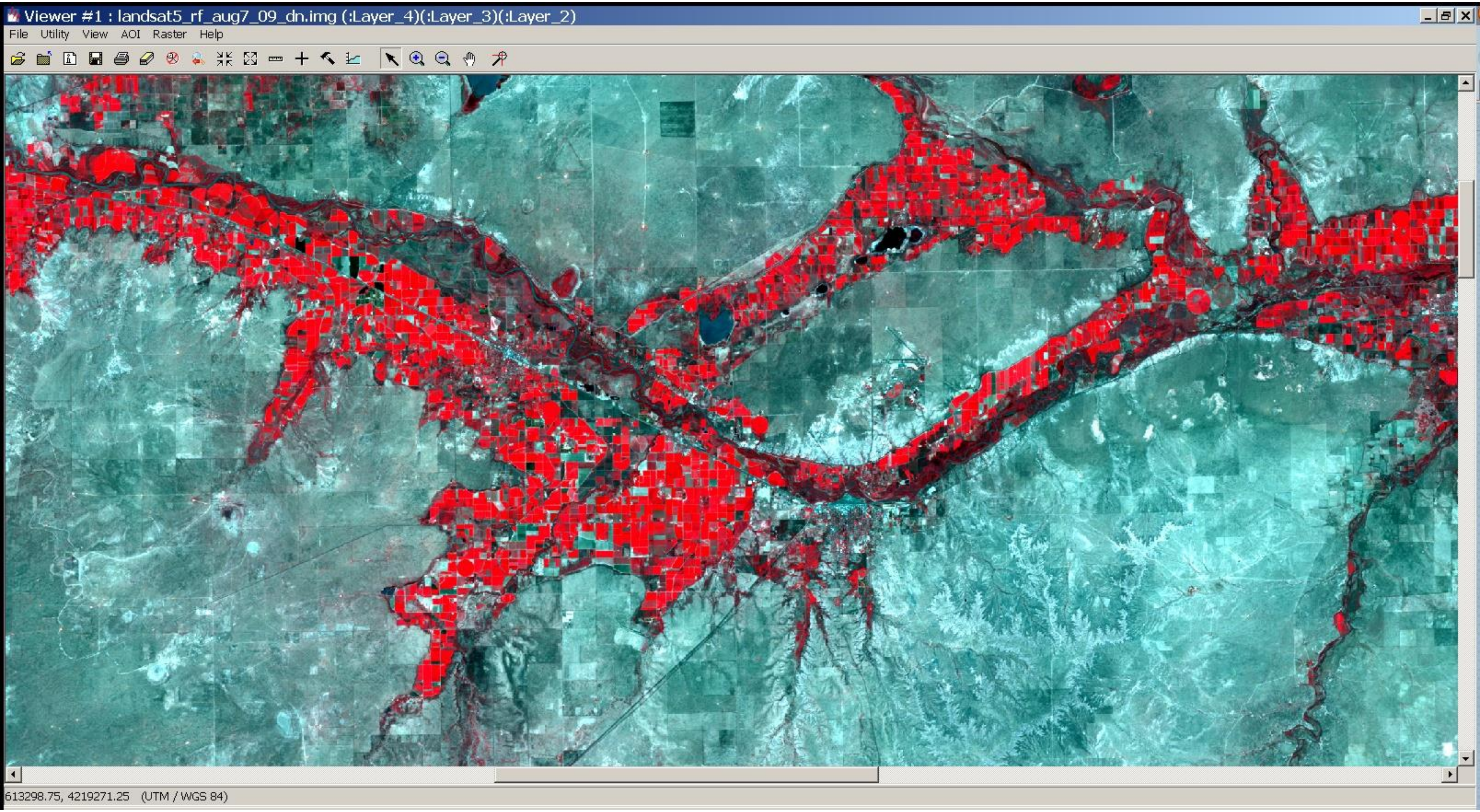
- $T_o = 1.67\ T_s - 0.66\ T_a - 2.33\ LAI – 0.21\ u + 12.3$

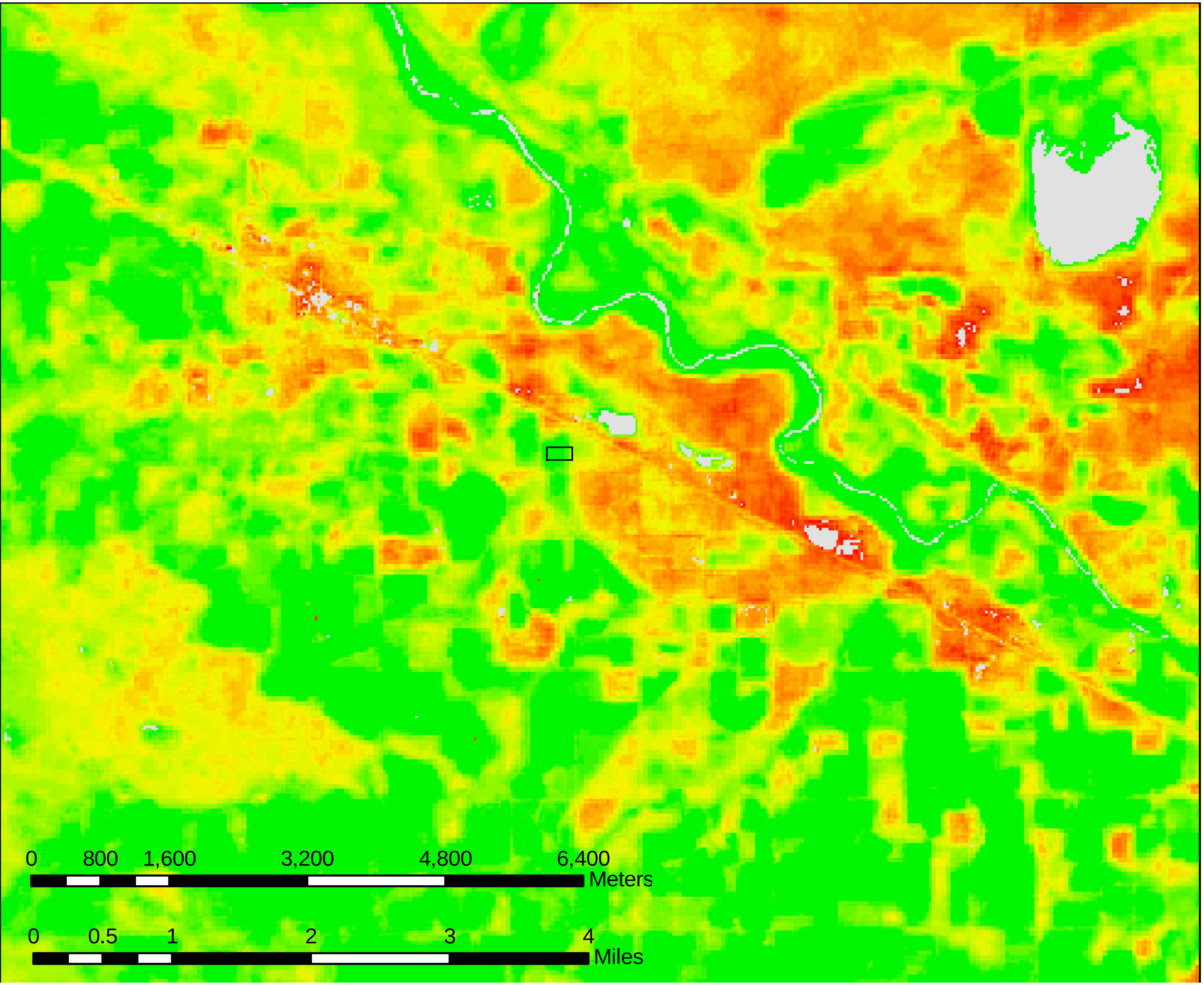
- $T_o = 1.50\ T_s - 0.53\ T_a + 0.052\ r_{ah} + 0.36$

- LAI was large for the alfalfa field (4-5 $m^2\ m^{-2}$), and the goodness of fit was R^2 of 0.97 for both equations

Chávez, J.L., T.A. Howell, D. Straw, P.H. Gowda, L.A. Garcia, S.R. Evett, T.W. Ley, L. Simmons, M. Bartolo, P. Colaizzi, and A.A. Andales (2010b). Surface aerodynamic temperature derived from wind/temperature profile measurements over Cotton and Alfalfa in a Semi-Arid Environment. In Proceedings of the American Society of Civil Engineers (ASCE), World Environmental & Water Resources Congress 2010 (EWRI).

False color Landsat 5 coverage of the Arkansas River Valley near Rocky Ford, La Junta, CO





ETd (mm/d), DOY 187

rf070609_etd.img

Value

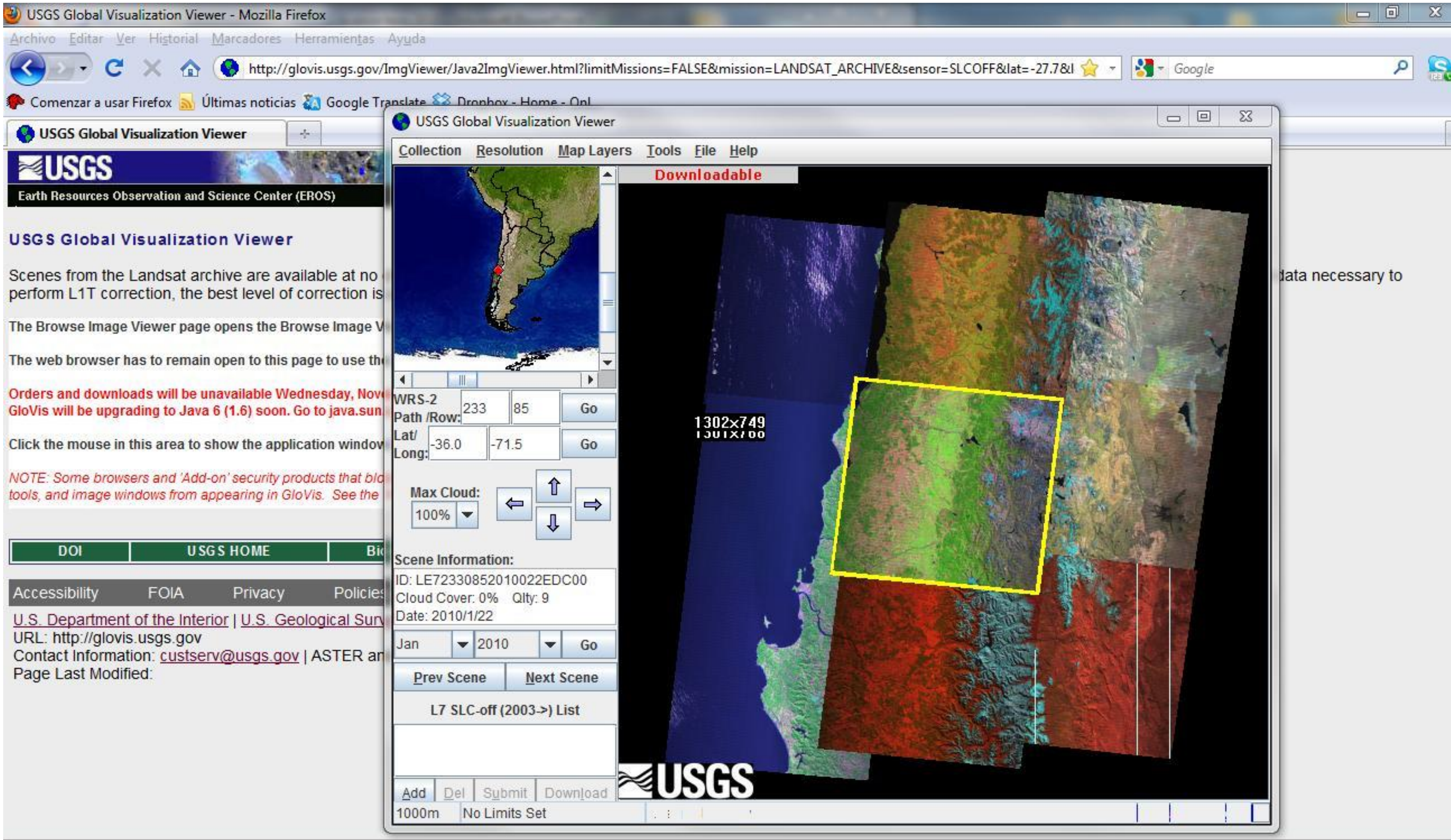
High : 8.0

Low : 0.0

Vineyard Case

Eddy Covariance

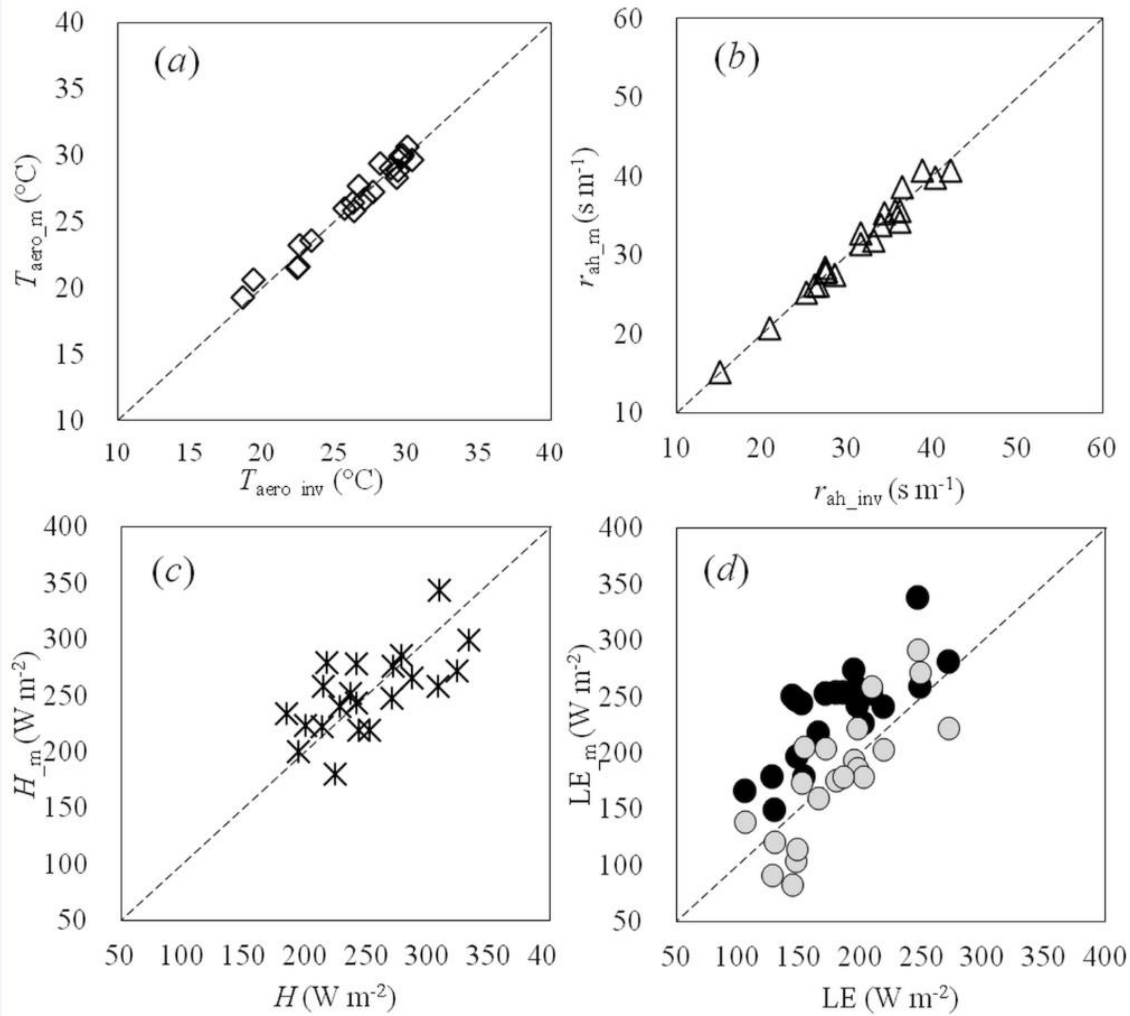
Landsat Scenes (5 TM y 7 ETM+)



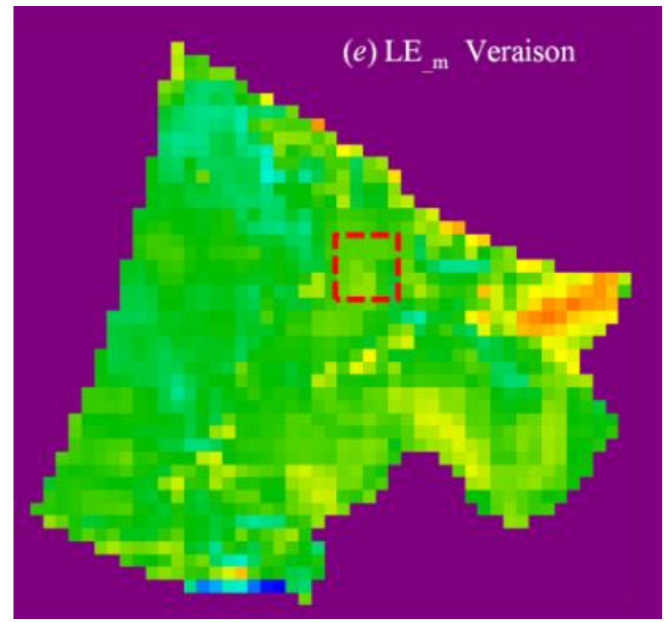
http://glovis.usgs.gov/ImgViewer/Java2ImgViewer.html?limitMissions=FALSE&mission=LANDSAT_ARCHIVE&sensor=SLCOFF&lat=-27.7&lon=-69.7

Modeled Aerodynamic Temperature for the vineyard

$$Taero\_m = 6.75 + 0.161 \cdot Ts + 0.674 \cdot Ta + 1.06 \cdot LAI - 0.84 \cdot u$$



($R^2 = 0.96$)

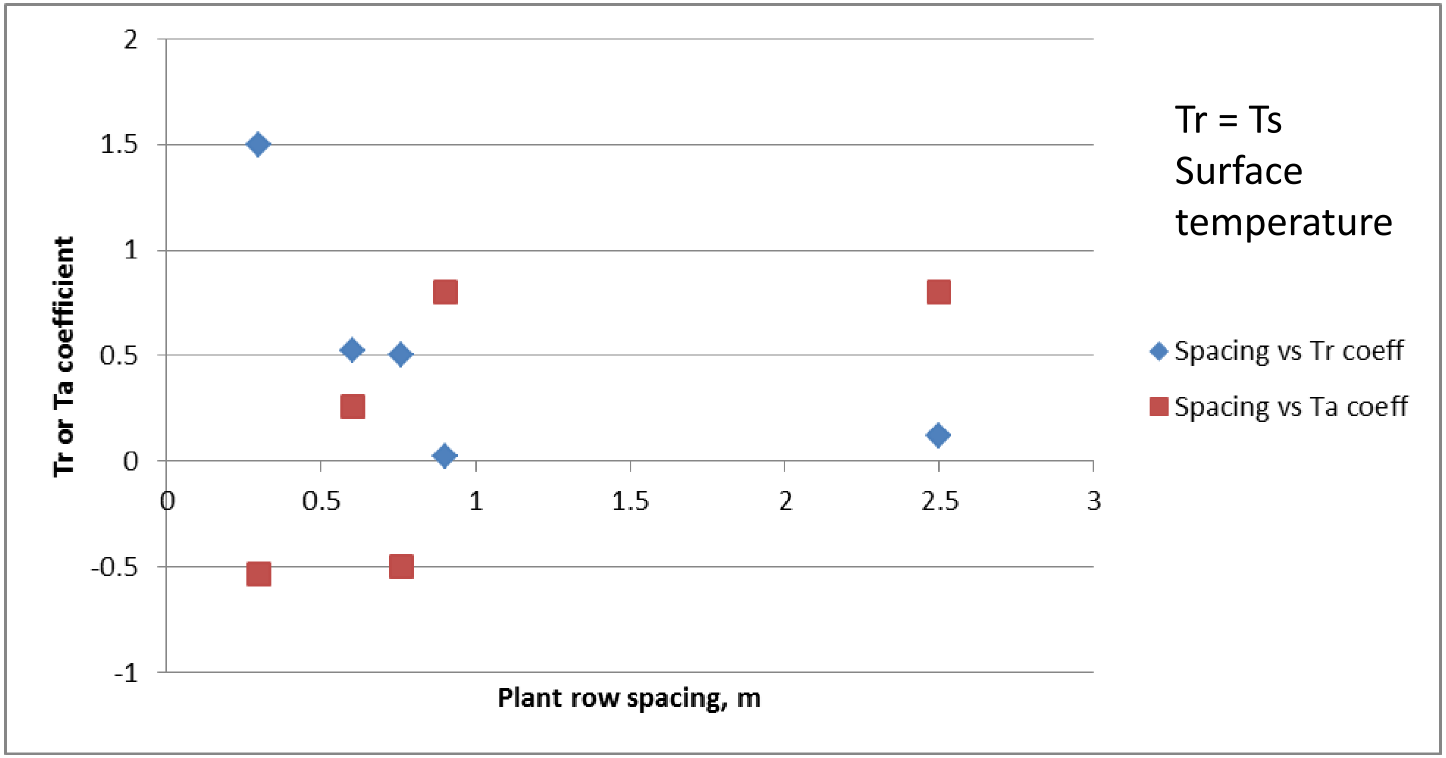


Marcos Carrasco-Benavides, Samuel Ortega-Farías, Luis Morales-Salinas, Carlos Poblete-Echeverría and José L. Chávez. "Calibration and validation of an aerodynamic method to estimate the spatial variability of sensible and latent heat fluxes over a drip-irrigated Merlot vineyard," Int'l Journal of Remote Sensing. Vol. 38, 2017 -- Issue 24, pg 7473-7496.

R^2 = coefficient of determination; Taero_m = average surface aerodynamic temperature modeled (°C); Ts = radiometric temperature obtained from Landsat scenes (°C); Ta = average air temperature (°C); LAI = leaf area index (this value was considered as fix: 1.2 m^2 m^{-2}); u = wind speed at 2 m (m s^{-1})

Coefficients of T_o models

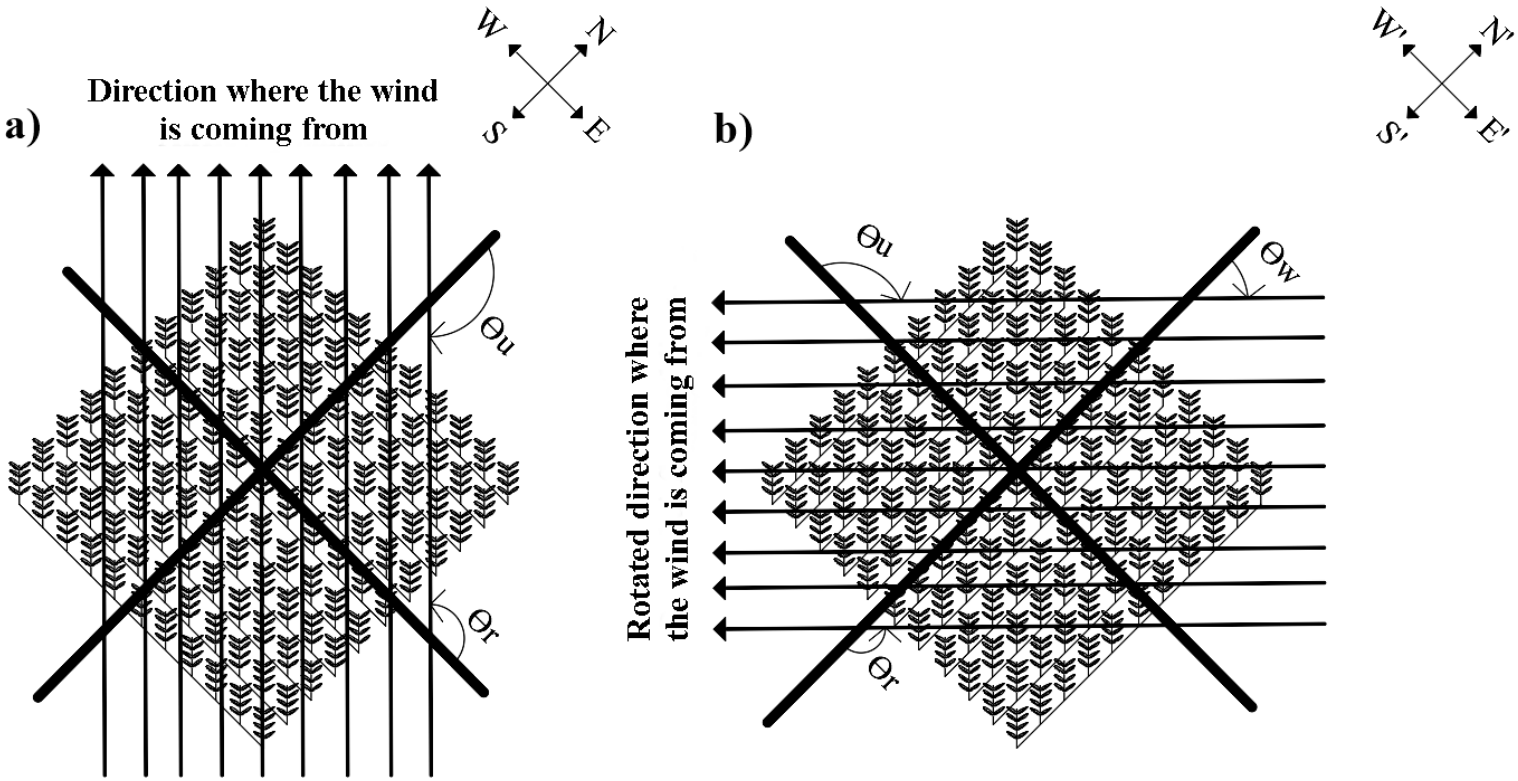
$$T_o = \Omega_1 T_r + \Omega_2 T_a + \Omega_3 LAI + \Omega_4 \, u + \ldots$$



Remarks

- The aerodynamic temperature models based on Tr (Ts), Ta, and LAI seem to perform relatively well for corn and cotton surfaces with LAI > 1.5 m^2/m^2, and larger rates of ETa,
- To models based on Tr (Ts), Ta, and rah seem to perform well for dryland cotton with LAI < 1.5 m^2/m^2,
- There seem to be a relationship between the Tr (Ts) and Ta coefficients and the crop row planting spacing (or density/clumping),
- Further calibration of T_o models should include vegetation percent cover, clumping factor, row spacing, and/or row orientation in relation to wind direction.

Optimized SAT (T_o) Model



Costa-Filho, E., J.L. Chávez, H. Zhang, and A. Andales. 2021. "An Optimized Surface Aerodynamic Temperature Approach to Estimate Maize Sensible Heat Flux and Evapotranspiration," Agricultural and Forest Meteorology, *Volume 311, 15 December 2021, 108683. ISSN 0168-1923, https://doi.org/10.1016/j.agrformet.2021.108683*

Optimized SAT (T_o) Model

$$T_o = \beta_o + \beta_1 f_c + \beta_2 T_a + \beta_3 T_s + \beta_4 r_p$$

Model	LAI (m^2/m^2)	n	r^2	RMSE (°C)*	β_o	β_1	β_2	β_3	β_4
SToR	0.85 < LAI ≤ 5.0	419	0.96	1.13	0.000	1.205	0.407	0.631	0.498
OpToR	0.85 < LAI ≤ 1.5	46	0.99	1.09	3.295	-8.742	0.571	0.529	0.806
	1.5 < LAI ≤ 2.5	87	0.99	0.70	6.491	-9.168	0.485	0.575	-0.16
	2.5 < LAI ≤ 3.5	79	0.96	1.19	0.000	4.708	0.350	0.580	0.086
	3.5 < LAI ≤ 5.0	207	0.94	0.94	5.014	-1.911	0.443	0.509	0.115

where r_p (s/m) is the turbulent mixing row resistance. The r_p resistance term is calculated when wind speed exceeds zero and requires directional wind data

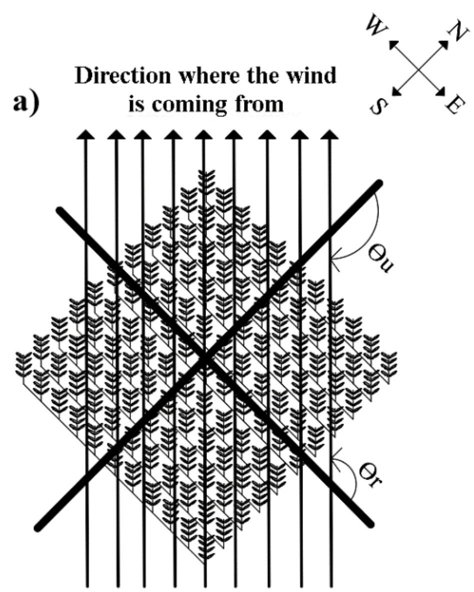
Turbulent mixing row resistance (r_p)

$$\boldsymbol{r_p = \tau \frac{1}{U}}, \qquad \boldsymbol{U > 0}$$

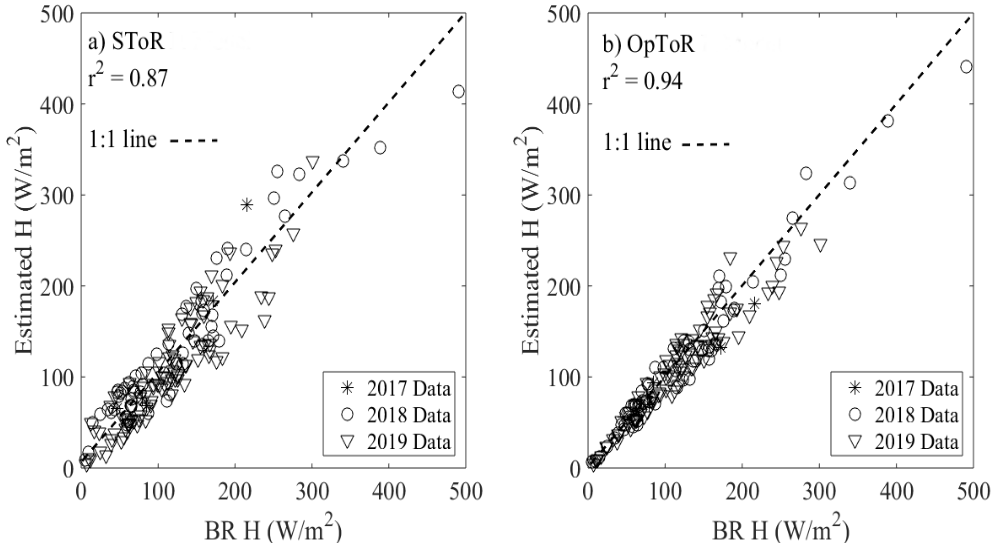
where, U is wind speed (m/s), τ is equivalent to the proportional factor related to the scalar from which the resistance term is associated. In this formulation, the scalar is the wind direction. The factor τ will be referred to as the relative wind direction factor (dimensionless) regarding the crop row layout (i.e., normalized wind direction factor).

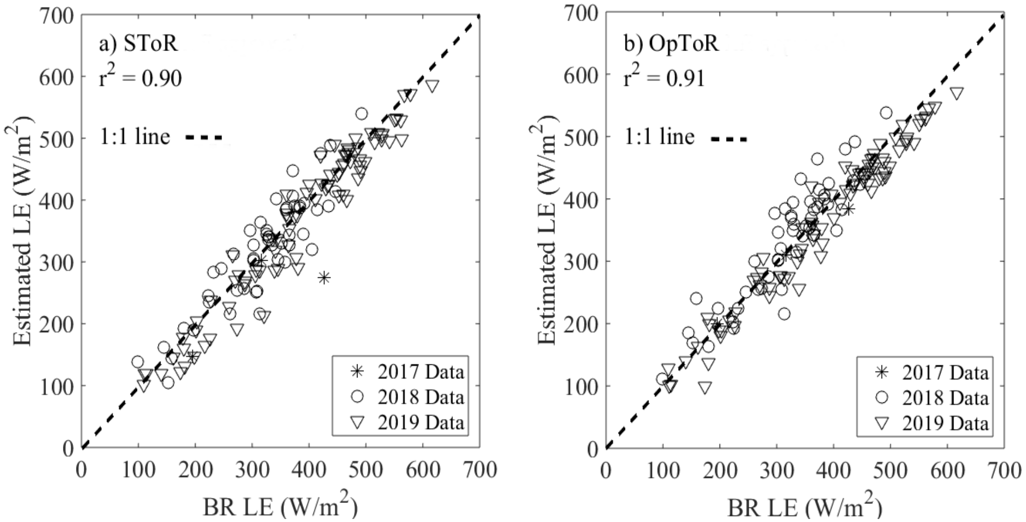
$$\tau = \frac{\theta_u}{\theta_r}$$

where, θ_u and θ_r are the wind direction and the relative wind direction to the crop row in degrees, respectively.



Optimized T_o model H and ET





LE Statistics	SToR Model	OpToR Model
MBE (W/m²)	-11	-6
RMSE (W/m²)	38	35
MBE (%)	-3.1%	-1.8%
RMSE (%)	10.7%	9.7%
n	138	138