Evapotranspiration Workshop: New Technologies 
and Methods for estimating ET

Use of Remote Sensing to estimate ET

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Presentation Outline

- Energy balance based methods:
  - One source models
    - function of surface radiometric temperature ($T_s$),
    - function of surface aerodynamic temperature ($T_o$),
    - function of a linear relationship between $dT$ and $T_s$,
  - Two source model

- Reflectance-based crop coefficient method
- Fractional vegetation ground cover-based method
- Crop water stress index & Water deficit index based
- Dimensionless temperature method
Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object.
Remote Sensing of ET

Remote sensing of ET is the estimation of vegetation/crop actual evapotranspiration rates using remotely sensed surface characteristics (reflectance, temperature), a processing algorithm, and weather data.
SURFACE ENERGY BALANCE

\[ R_n = R_{sw\_in} - R_{sw\_out} + R_{lw\_in} - R_{lw\_out} \]

\[ R_n = G + H + LE \]

\[ LE = ET = R_n - G - H \]
Net Radiation, $R_n$

\[ R_n = (1 - \alpha) R_{sw\downarrow} + R_{L\downarrow} - R_{L\uparrow} \]

- Albedo, $\alpha$
- Reflectance, $\rho_{\lambda}$
- Radiance, $L_{\lambda}$
- RED, NIR, VIS bands images
- NDVI, OSAVI, LAI
- Thermal image
- $\varepsilon_o$
- $T_{sfc}$
- $T_{bb}$
- $fc$
- $R_{n}$
- LE
- H
- G
Soil Heat Flux, $G$

$G = 0.35 \, R_{n,SOIL}$  \hspace{1cm} (Choudhury et al., 1987)

$G = ((T_s - 273.15) \, (0.0038 + 0.0074 \, \alpha) \, (1 - 0.98 \, \text{NDVI}^4)) \, R_n$  \hspace{1cm} (Bastiaanssen, 2000)

$G = [(0.3324 - 0.024 \, \text{LAI}) \, (0.8155 - 0.3032 \, \text{Ln(LAI)})] \, R_n$  \hspace{1cm} (Chávez et al., 2005)
One Source: Sensible Heat Flux (H)

\[ H = \rho \times c_p \times (T_o - T_a) / r_{ah} \]

\( r_{ah} \) = the aerodynamic resistance to heat transport (s/m),
\( c_p \) is the specific heat capacity of the air (1004 J/kg/K),
\( \rho \) is air density (kg/m\(^3\)),
\( T_o \) = surface aerodynamic temperature (K),
\( T_a \) = air temperature (K)

\[ r_{ah} = \ln\left(\frac{z_a}{z_{om}}\right) \ln\left(\frac{z_a - d}{z_{oh}}\right) \]

\[ \frac{u \times k^2}{d + Z_{oh}, T_o} \]

\[ H = \rho \times c_p \times (T_s - T_a) / r_{ah} \]

\( T_s \) = surface radiometric temperature (K)
ET estimation over Corn and Soybean Fields (Iowa)
2002 NASA SMACEX – SMEX02
Iowa $T_{aero}$ or $T_o$ (SAT) modeling for Corn and Soybeans

$$T_{aero} \text{ or } T_o = 0.534 \, T_s + 0.39 \, T_a + 0.224 \, \text{LAI} - 0.192 \, U + 1.68$$

Chávez et al. (2005)

where temperature units are in °C, LAI in m² m⁻², and U in m s⁻¹.
24 Hour ET (ET_d, mm/d) Map
DOY 182
One Source: SEBAL

- Surface Energy Balance Algorithm for Land
- Developed by
  - Dr. Wim Bastiaanssen, The Netherlands
- Applied to Satellite imagery:
  - energy balance is applied at each “pixel” to map spatial variation

- reflectance of light energy (VIS, NIR),
- vegetation indices (combination of VIS bands),
- surface temperature (thermal band),
- relative variation in surface temperature (dT) to estimate H,
- horizontal wind speed (from a weather station)
Satellite Images used in SEBAL

- SEBAL needs both short wave (VIS) and thermal (TIR) bands

- SEBAL can use images from:
  NASA-Landsat 5 (30 m VIS and 120 m TIR, each 16 days),
  Scene size: 170 km x 185 km (106 mi x 115 mi), swath 185 km, since 1984. Altitude of 705.3 km (438.3 mi)

- On November 18, 2011, image acquisitions were suspended for a period of 90 days, due to fluctuations in the performance of a critical amplifier that is part of the satellite's transmission system. Suspension period extended 90 more days.
The Landsat Data Continuity Mission (LDCM) is the next-generation Landsat satellite and is expected to be launched Jan. 2013. This mission will ensure the continued acquisition and availability of Landsat-like data.
Hyperspectral Infrared Image (HyspIRI) Satellite

The HyspIRI mission includes:
- an imaging spectrometer (VSWIR: 380 nm - 2500 nm) in 10 nm contiguous bands
- and a multispectral imager measuring from 3 to 12 μm in the mid and thermal infrared (TIR).
- spatial resolution of 60 m.
- The VSWIR will have a revisit of 19 days and the TIR will have a revisit of 5 days.
- 30 km swath
- Launch scheduled for mid 2014
HyspIRI-TIR provides ET data every 5 days, allows weekly-monthly measurement
And expectation for a cloud-free scene (typically 1 in every 3 data takes)
SEBAL: Sensible Heat Flux (H)

\[ H = \frac{(\rho \times c_p \times dT)}{r_{ah}} \]

\(dT = \text{the near surface temperature difference (K)}\)

\[ r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right)}{u* \times k}\]
Surface Temperature Image

White – cold
(18-22 ºC)

Dark red – hot
(35-49 ºC)

\[ dT = T_o - T_a \]

\[ dT = b + a T_s \]

\[ H = (\rho \times c_p \times dT) / r_{ah} \]
SEBAL: dT function definition

\[ dT = b + a T_s \]

SEBAL fixes dT at 2 “anchor” pixels:

- At the “cold/wet” pixel (water body):

- At the “hot” pixel (bare soil):

\[ H = \frac{\rho \times c_p \times dT}{r_{ah}} \quad \rightarrow \quad LE = R_n - G - H \]
METRIC

- Mapping Evapotranspiration at High Resolution using Internalized Calibration

- Main developers: Dr. Richard Allen, Dr. Mashiro Tasumi, and Dr. Ricardo Trezza.

- METRIC is an extension of SEBAL.
METRIC: Concepts

- METRIC does not assume $H = 0$ at the wet/cold pixel,
- METRIC does not assume $LE = R_n - G$ at the dry/hot pixel,
- METRIC selects extreme pixels in only agricultural areas,
- METRIC uses $ET_r F$ (not EF) to extrapolate instantaneous to daily ET values,
- METRIC needs high quality weather data on an hourly or shorter time step and relies on the accuracy of $ET_r$ estimates.

Where: $ET_r = \text{alfalfa reference ET (ASCE EWRI, 2005)}$

$ET_r F = \text{alfalfa reference ET fraction}$
Soil Heat Flux (G)

Tasumi (2003):

\[
\frac{G}{R_n} = 0.05 + 0.15 e^{-0.52 \text{LAI}}, \quad \text{for LAI} \geq 0.5
\]

\[
\frac{G}{R_n} = 1.8 \frac{(T_s - 273.15)}{R_n} + 0.084, \quad \text{for LAI} < 0.5
\]
Instantaneous LE ($ET_i$) and daily ET

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

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

$$ET_r F = \frac{ET_i}{ET_{r_i}}$$

$$ET_d = ET_r F \times ET_{r_d}$$
One Source: ReSET (Remote Sensing of ET)

Elhaddad & Garcia (2008)

- ReSET expands upon SEBAL and takes into consideration the spatial variability in weather parameters over a region by using data from multiple weather stations.

- ReSET interpolates between the available weather stations in time and space taking into consideration the spatiotemporal variability of the available weather data by generating surfaces of wind run and ET_r between weather stations.

- ReSET model second enhancement is the ability to calculate the cumulative ET over time between the dates of the available Landsat scenes.
ReSET: Satellite Based ET Modeling

Network of weather stations

ET Model
ReSET: Crop coefficient ($K_c$) generation for Corn using LS 2001, 2004, 2006

The equation used is:

\[ y = 2 \times 10^{-13}x^4 - 9 \times 10^{-10}x^3 + 1 \times 10^{-6}x^2 - 0.0002x + 0.2468 \]

\[ R^2 = 0.9545 \]
Two Source Model (TSM)

\[ T_{RAD}(\theta) = \left[ f(\theta)T_C^n + (1 - f(\theta))T_S^n \right]^{1/n} \]
RS of ET$_d$ evaluation with weighing Lysimeters

![Graph showing ET$_d$ values for different locations and crops.

- **Corn**
- **Forage Sorghum**
- **Sorghum Clump**
- **Sorghum Rows**
- **Grass**

The graph includes bars for Lysimeter locations labeled NE, SE, NW, SW, and GRASS, each with different colored bars representing ET$_d$ values.

- **ET$_d_m$**
- **ET$_d_TSM$**
- **ET$_d$_METRIC**
- **ET$_d$_SAT**

**ET, mm/day**
- 0 - 0.8
- 0.8 - 2.0
- 2.0 - 2.4
- 2.4 - 2.7
- 2.7 - 3.0
- 3.0 - 4.4
- 4.4 - 6.1
- 6.1 - 6.5
- 6.5 - 7.1
- 7.1 - 9.9
Reflectance-based Crop Coefficient ET

\[
ET = K_{cr} \times ET_r
\]

For Potatoes:

\[
K_{cr} = 1.085 \times \text{SAVI} + 0.051
\]

For Corn: Neale et al. (1989)

\[
K_{cr} = 1.092 \times \text{NDVI} - 0.053, \text{ for Fruita, CO}
\]

\[
K_{cr} = 1.181 \times \text{NDVI} - 0.026, \text{ for Greeley, CO}
\]

Bausch (1993)

\[
K_{cr} = 1.416 \times \text{SAVI} + 0.017
\]

\[
\text{NDVI} = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}}
\]

Neale, Jayanthi, and Wright (2005)
Vegetation fraction of ground cover based ET

\[ \text{NDVI} \rightarrow f_c \rightarrow K_{cb} \rightarrow \text{ET}_{cb} \text{ Approach} \]

\[ f_c = 1.22 \times \text{NDVI} - 0.21 \]

\[ K_{cb,o} = 1.13 \times f_c + 0.14 \]

\[ \text{ET}_{cb} = K_{cb,o} \times \text{ET}_o \]
Satellite Irrigation Management Support (SIMS)

\[ \text{NDVI} \rightarrow f_c \rightarrow K_{cb} \rightarrow \text{ET}_{cb} \] approach implementation

http://ecocast.arc.nasa.gov/sims/

California Irrigation Management Information System (CIMIS), operated by the California Dept. of Water Resources (CDWR), provides daily estimates of \( \text{ET}_o \) on a 2 km statewide grid.

The system being developed at NASA Ames builds on a prototype ET\(_c\) monitoring and irrigation forecasting system for wine grapes in California developed by NASA and California State University Monterey Bay (CSU Monterey Bay).
TOPS Satellite Irrigation Management Support: $ET_{cb}$
Crop Water Stress Index (CWSI)

Idso (1981)

\[
\text{CWSI} = \frac{dT - dT_{\text{min}}}{dT_{\text{max}} - dT_{\text{min}}}
\]

\[
\text{CWSI} = 1 - \frac{ET_a}{ET_c}
\]

where:

\(dT = T_c - T_a\), canopy – air temperature

\(dT_{\text{min}} = (T_c - T_a)_{\text{min}} = a + b \text{ VPD}\)

\(dT_{\text{min}} = 3.11 - 1.97 \text{ VPD}, \) (Idso, 1981), for corn

\(dT_{\text{min}} = 2.67 - 2.06 \text{ VPD}, \) (Nielsen & Garden, 1987), for corn

\(dT_{\text{max}} = T_c \text{ dryland plot} - T_a\)
Water Deficit Index (WDI) or the Vegetation Index/Temperature (VIT) trapezoid

Moran et al. (1994)

Account for partially vegetated fields

\[ \text{WDI} = 1 - \frac{\text{ET}_a}{\text{ET}_c} \]

\[ \text{WDI} = \frac{\text{dT}_{\text{min}} - \text{dT}_a}{\text{dT}_{\text{min}} - \text{dT}_{\text{max}}} \]

\[ \text{dT}_a = (T_s - T_a)_{\text{actual, RS}} \]

\[ \text{WDI} = \frac{\text{AC}}{\text{AB}} \]
Concluding Remarks

- There are different remote sensing approaches to estimating actual crop water use or ET. However, some perform better under certain conditions,

- All approaches rely on accurate weather data from ground-based weather stations, and accurate calculations of reference (alfalfa or grass) evapotranspiration rates.