Estimating Crop Water Use Using Remote Sensing

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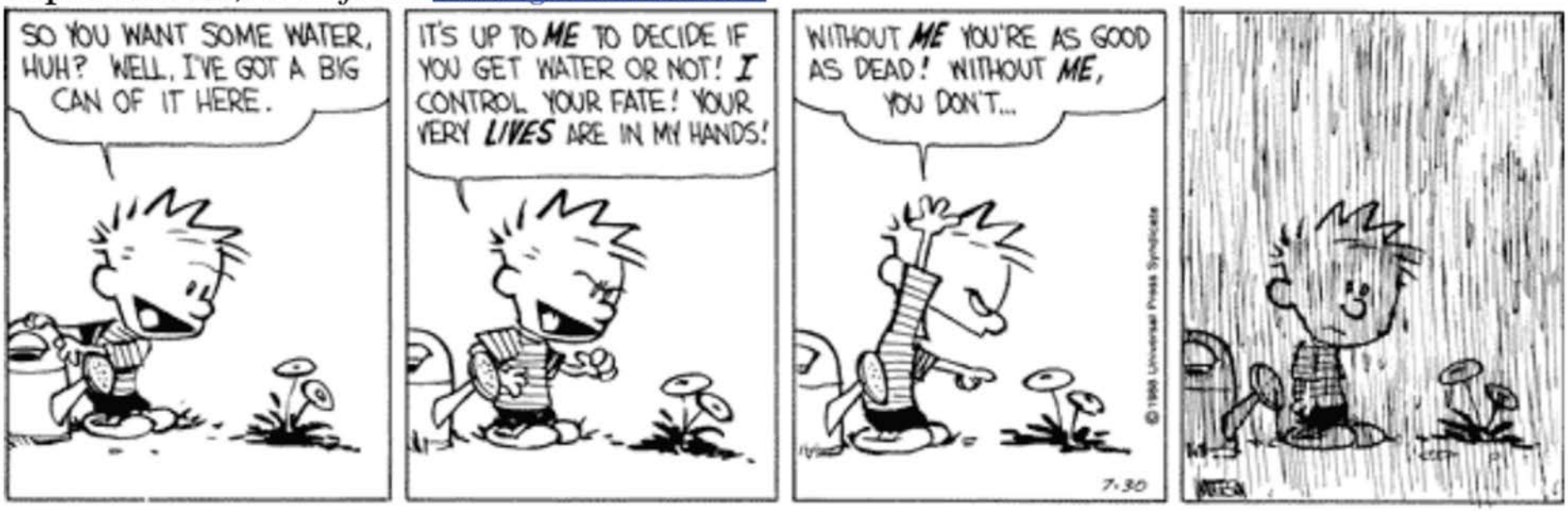
MINNESOTA DEPARTMENT OF AGRICULTURE

Calvin and Hobbes

September 12, 2009 *from* www.gocomics.com



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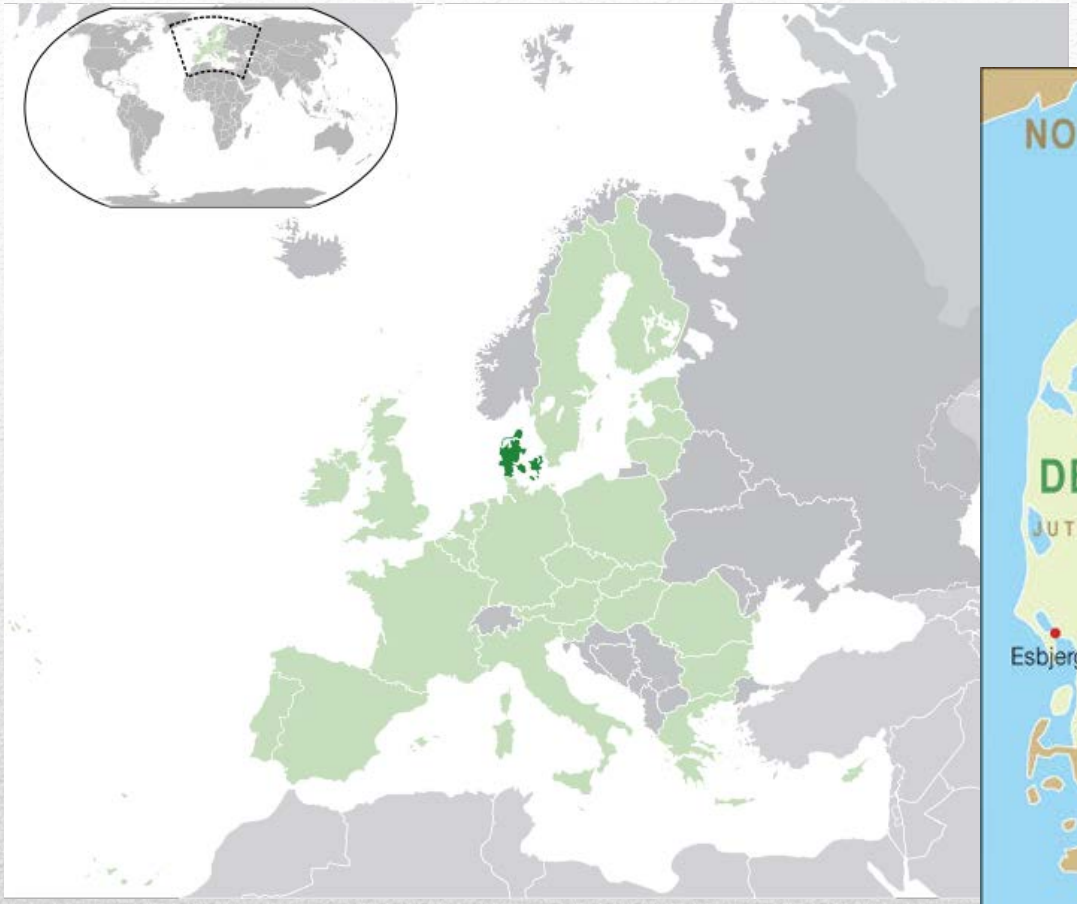


NORWAY
Skagen
Ålborg
SWEDEN
Randers
DENMARK
Århus
JUTLAND PENINSULA
Helsinger
Horsens
Vejle
Fredericia
Roskilde
COPENHAGEN
Kolding
Esbjerg
Odense
ZEALAND
Rønne
Åbenrå
BALTIC SEA
GERMANY
50 km
50 miles
© wordtravels.com

Geography

Denmark

- Population: 5,500,000
- Pop. density: 340/sq mi
- Area: 16,560 sq mi
- Constitutional Monarchy

Montana

- Population: 1.024,000
- Pop. density: 7/sq.mi
- Area: 147,040 sq mi

Fast facts

Denmark in Your Life

…back to the talk: Outline

- Crop water use
- Evapotranspiration estimation
- Applications of evapotranspiration ‘maps’

Acknowledgements

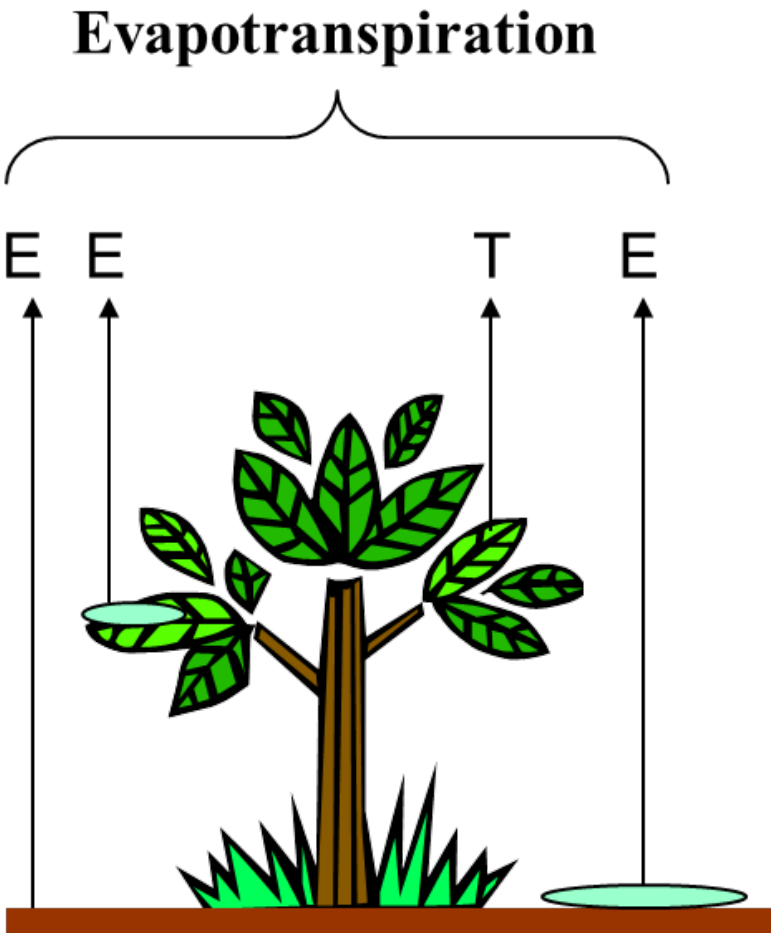
University of Idaho

South Dakota State University
Water Resources Institute

MINNESOTA DEPARTMENT OF AGRICULTURE

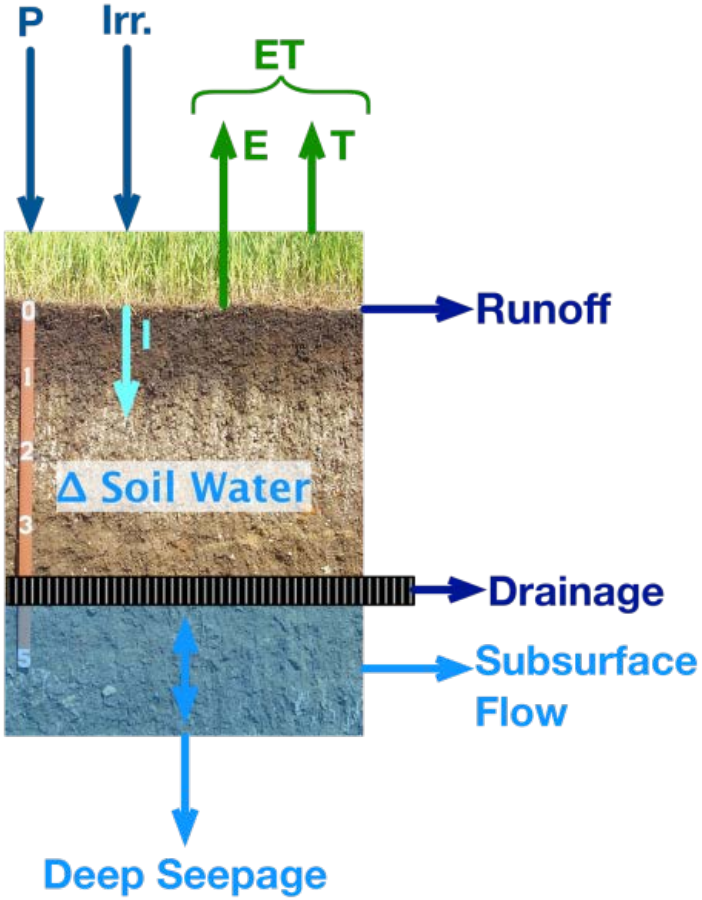
Evapotranspiration (ET)

- Why Estimate ET?
  - Irrigation Scheduling
  - Water Balance Estimations
  - Impacts of Agricultural Production on Surface Water and Groundwater Quality
  - Compare Consumptive Use to Water Rights
  - Aquifer Recharge
  - Crop Yield Forecasting



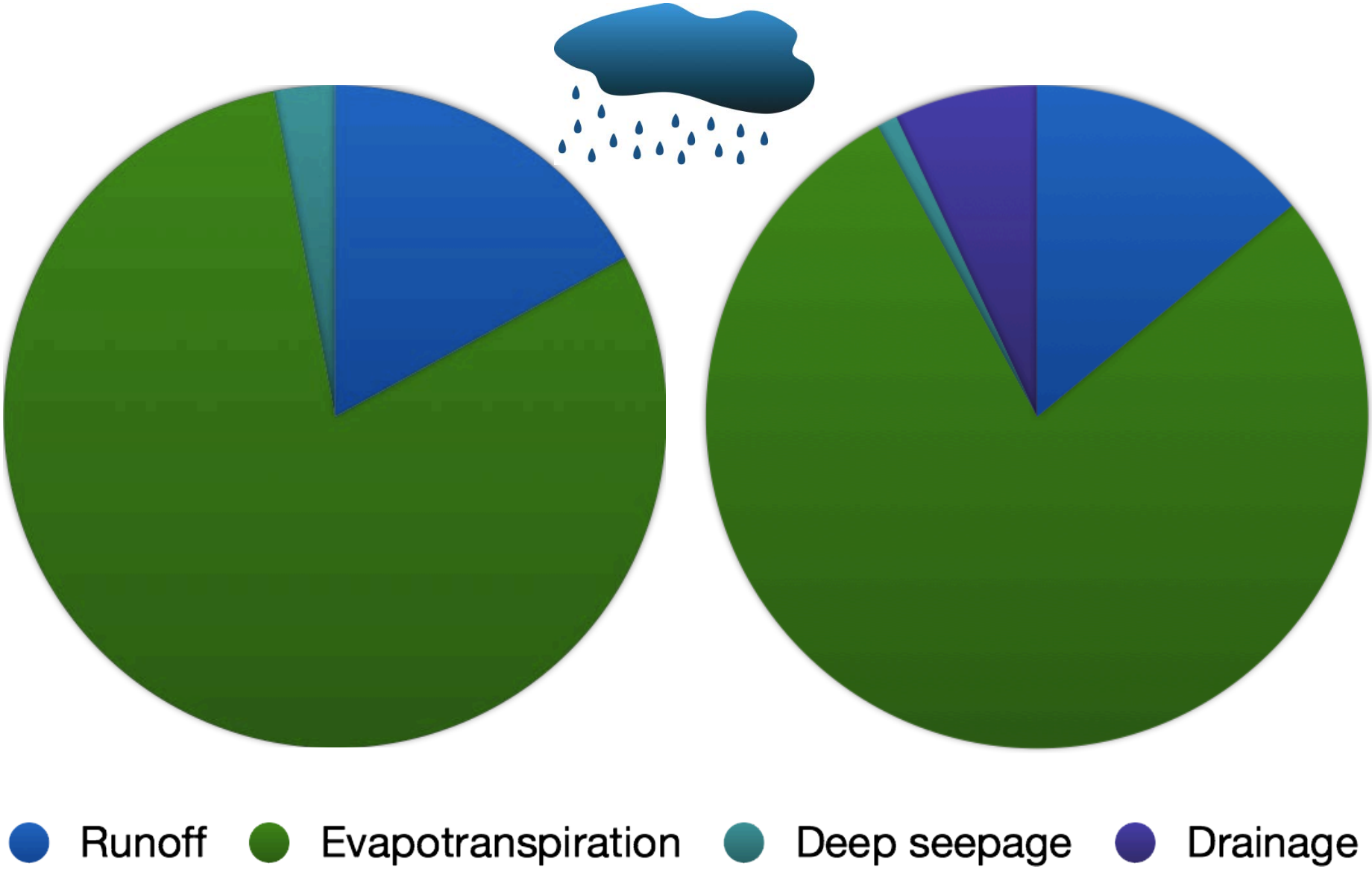
Crop water use is a component of the field water balance

Precipitation + Irrigation = Runoff + ET + Drainage + Storage



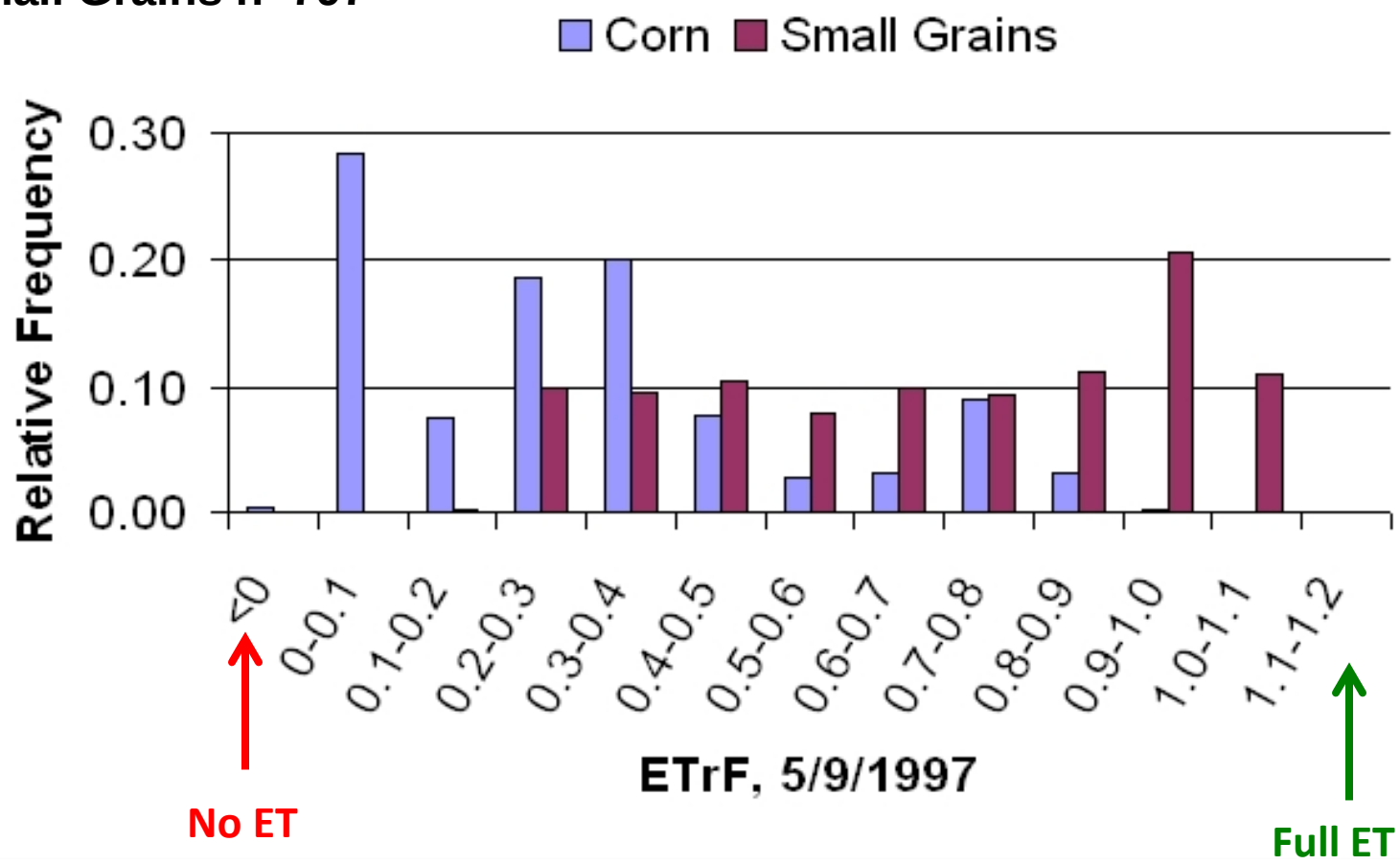
Graphics courtesy of C. Hay, SDSU

ET may consume 70-80% of the water in the field



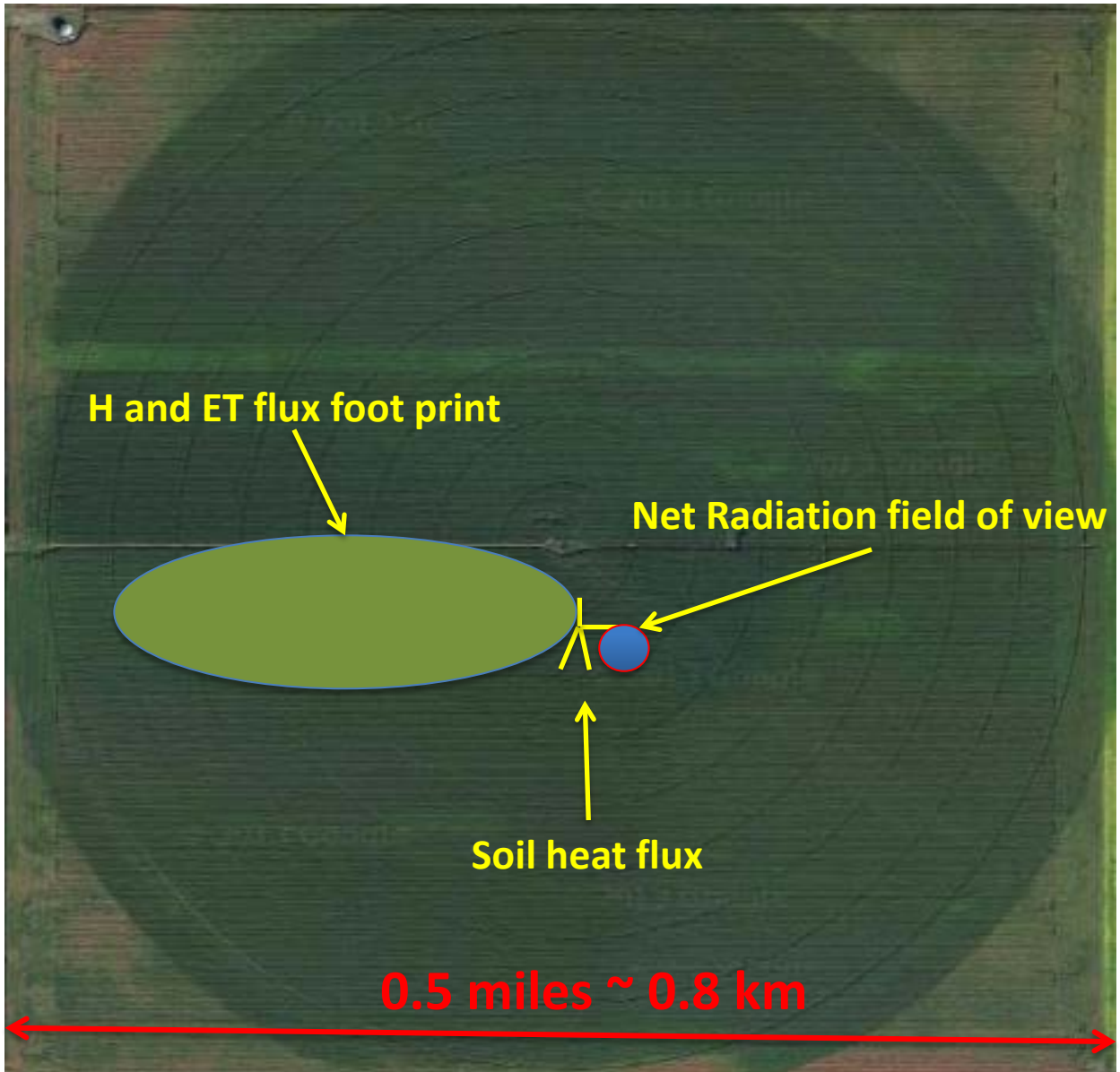
Evapotranspiration varies from field to field

Corn n=900
Small Grains n=797



Fields sampled in the Nebraska Panhandle. Kjaersgaard et al.

Scales of ET Measurement



Calculating ET using an ET index (K_c)

- Atmospheric demand
  - Air temperature
  - Air humidity
  - Net radiation
  - Wind speed

  (via reference crop)

- Plant and soil
  - Type and cultivar
  - Plant density
  - Water availability
  - Fertility status, salinity
  - Soil characteristics

$$ET_{act} = ET_{ref} \times K_c$$

ET Index (fraction of reference ET)

The output from METRIC is commonly stated as ET_rF

$$K_c = ET_rF = \frac{ET_{act}}{ET_{ref}}$$

Reference ET calculation

- Most popular method: Penman-Monteith
- Used for hourly, daily or longer time periods

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

Rn is net radiation
G is soil heat flux
Pa is mean air density at constant pressure
Cp is the specific heat of the air
Δ is the slope of the vapor pressure curve
γ is the psychrometric constant
rs and ra are surface and aerodynamic resistances
es and ea are saturated and actual vapor pressure

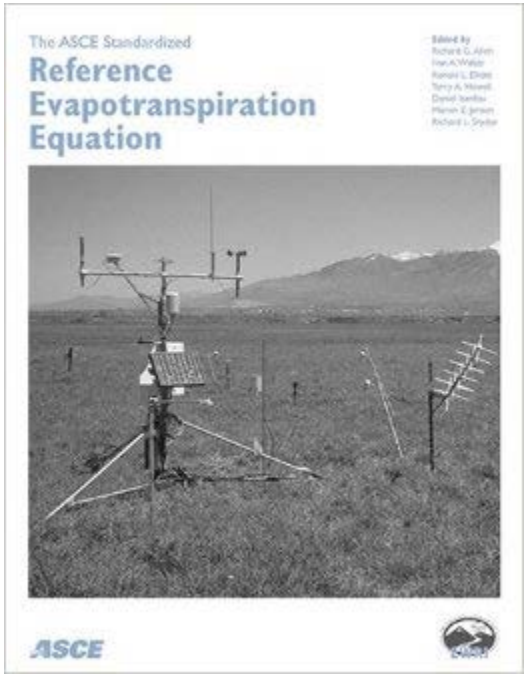
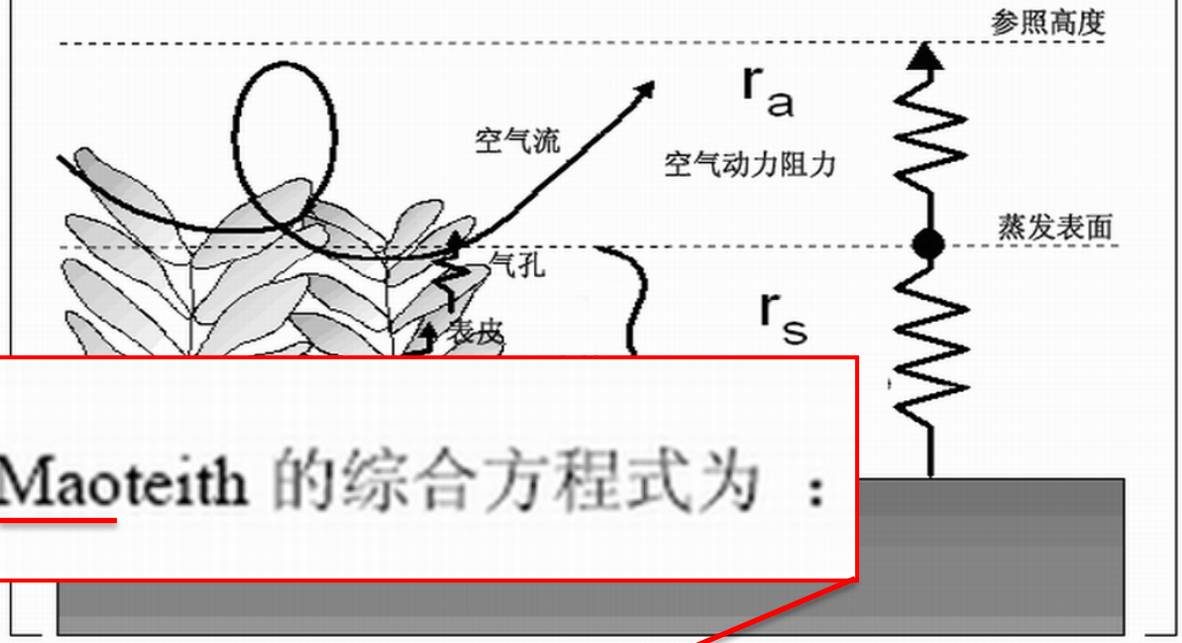


图 7

水汽流中（总）表面阻力和空气动力学阻力的简单示意图（Simplified representation of the (bulk) surface and aerodynamic resistances for water vapour flow）



Penman-Maoteith 的综合方程式为 ：

Penman-Maoteith 的综合方程式为 ：

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \dfrac{e_s - e_a}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \tag{3}$$

式中 R_n 为净辐射；G 为土壤热通量，$(e_s - e_a)$为水汽压差；ρ_a 为常压下的空气平均密度；C_p 空气的比热，Δ代表饱和水汽压与温度关系曲线的斜率，γ为湿度计常数，r_s 是整体表阻力，r_a 为空气动力阻力。公式中的各参数的定义在第三章中给出。

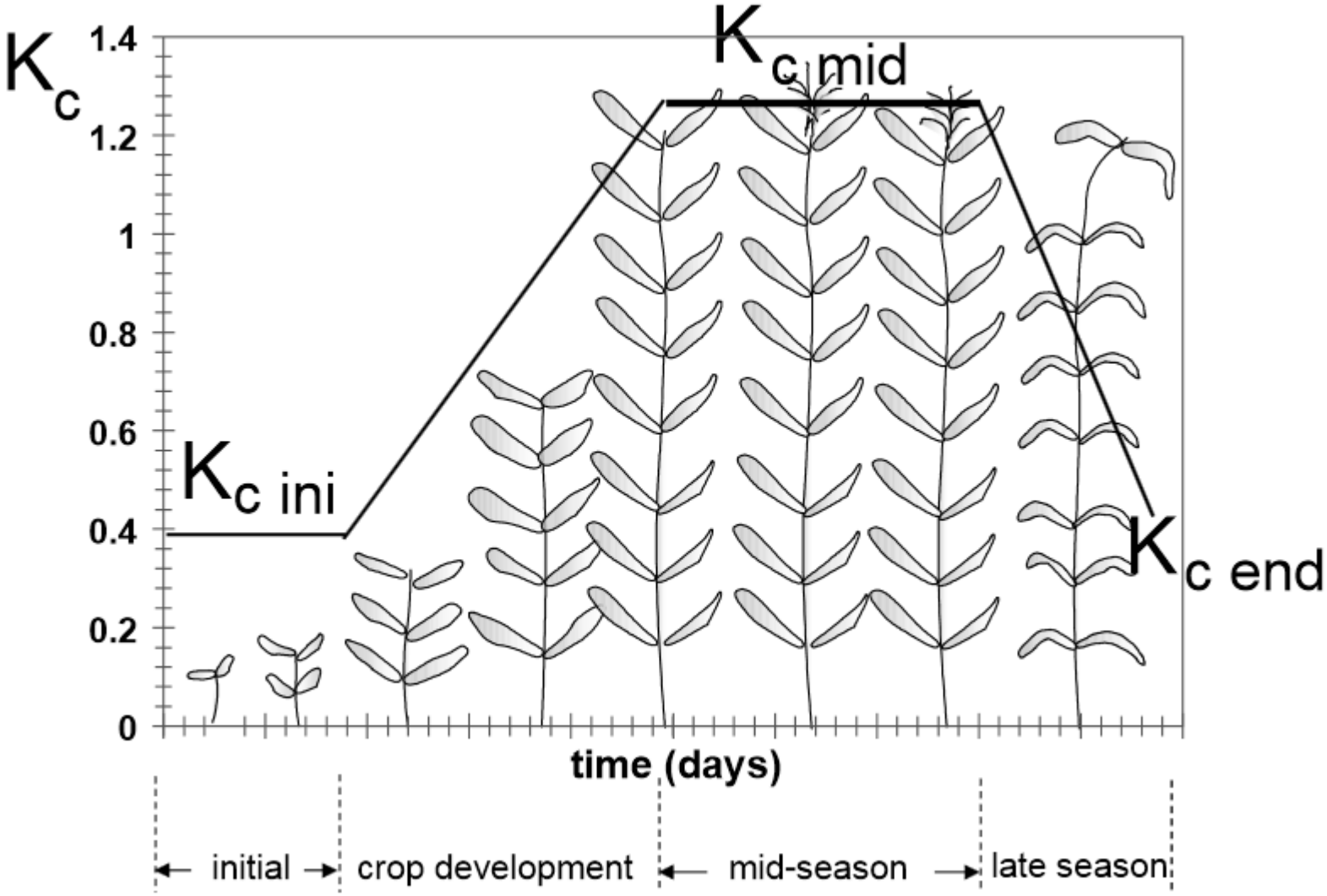
上面所述的 Penman-Maoteith 公式包括了调控能量转换得所有参数和相应的均匀扩展植被潜

Short and tall reference

Tall reference ET_{rs} resembles alfalfa at full cover ~ 50 cm tall

Short reference ET_{os} resembles cool season, actively growing, clipped green grass ~ 12 cm tall

Single crop coefficient



Mean Crop Coefficients, K_c, for Mid-Latitude Crops for use with Alfalfa Reference ET_r as Computed by the *ASCE Standardized Penman-Monteith Reference Method* *

Mean ET Crop Coefficients, K_c

Pct, time from planting to effective cover

Crop	0	10	20	30	40	50	60	70	80	90	100
Spring grain[1]	0.20[2]	0.20	0.20	0.25	0.37	0.50	0.63	0.76	1.00	1.03	1.03
Peas	0.15	0.17	0.19	0.21	0.32	0.42	0.52	0.63	0.73	0.83	0.93
Sugar Beets	0.26	0.26	0.26	0.26	0.26	0.28	0.30	0.38	0.55	0.74	1.03
Potatoes	0.20	0.20	0.20	0.22	0.30	0.41	0.53	0.67	0.73	0.77	0.80
Corn	0.20	0.20	0.20	0.20	0.24	0.34	0.44	0.58	0.72	0.90	1.00
Beans	0.20	0.20	0.22	0.26	0.35	0.45	0.55	0.68	0.83	0.95	0.97
Winter Wheat	0.25	0.25	0.27	0.38	0.60	0.80	0.90	0.96	1.00	1.03	1.03

DT, days after effective cover

Crop	0	10	20	30	40	50	60	70	80	90	100
Spring grain[1]	1.03	1.03	1.03	1.03	0.94	0.50	0.30	0.15	0.10		
Peas	0.93	0.93	0.70	0.54	0.38	0.22	0.12	0.10			
Sugar Beets	1.03	1.03	1.03	1.00	0.97	0.92	0.82	0.74	0.65	0.61	0.56
Potatoes	0.80	0.80	0.76	0.72	0.68	0.63	0.58	0.50	0.38	0.20	0.15
Field Corn	1.00	0.99	0.98	0.95	0.88	0.80	0.72	0.63	0.35	0.18	
Sweet Corn	1.00	0.97	0.94	0.90	0.84	0.70	0.55	0.35	0.20	0.10	
Beans	0.97	0.97	0.94	0.64	0.32	0.15	0.10	0.05			
Winter Wheat	1.03	1.03	1.03	1.03	1.00	0.55	0.25	0.15	0.10		

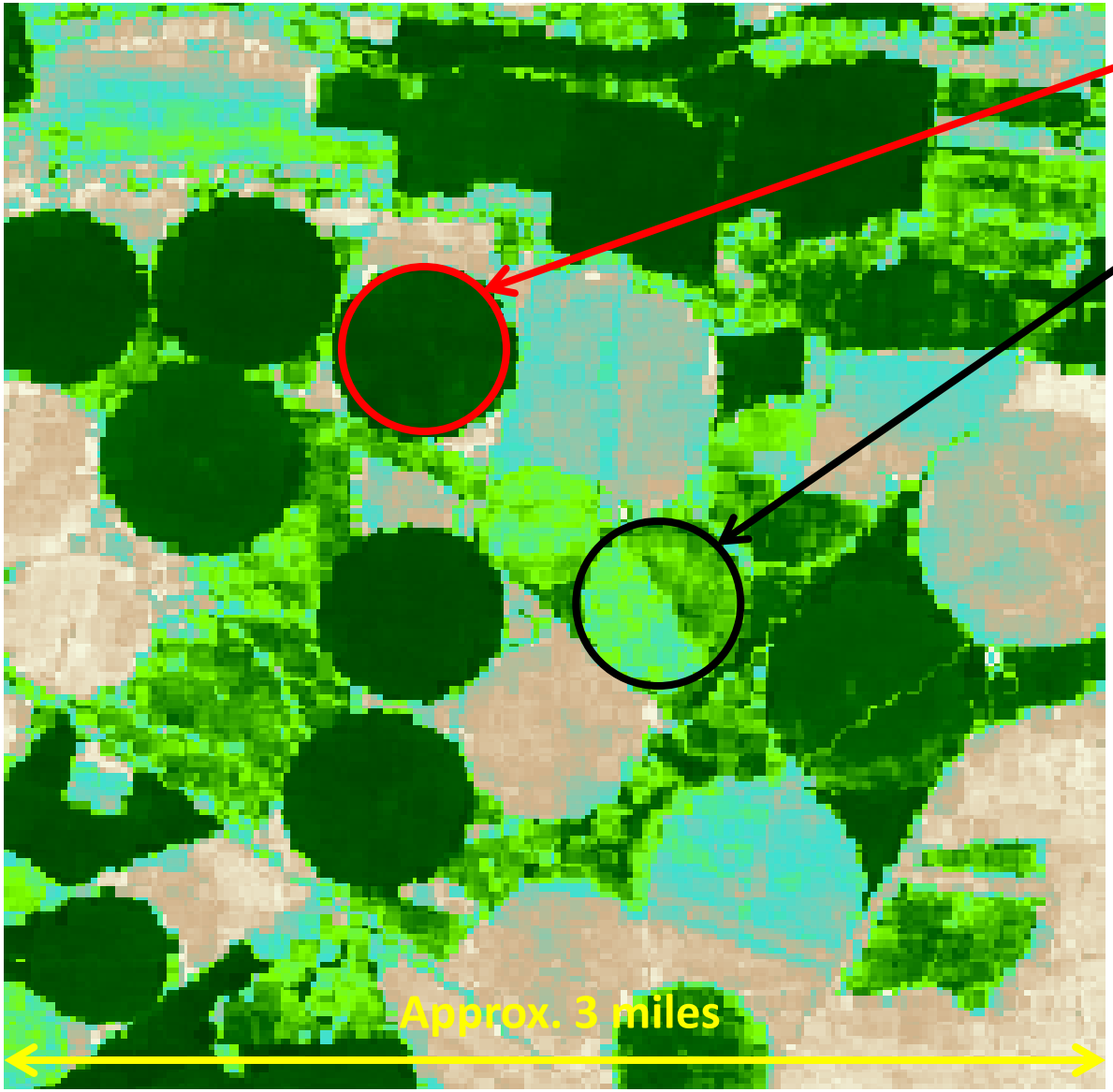
Time from new growth or harvest to harvest (%)

Crop	0	10	20	30	40	50	60	70	80	90	100
Alfalfa (1st cycle)[3]	0.50	0.62	0.73	0.83	0.88	0.94	1.00	1.00	1.00	0.98	0.95
(Intermediate cycles)	0.30	0.40	0.55	0.80	0.94	0.97	1.00	1.00	1.00	0.97	0.94
(Last cycle)	0.30	0.35	0.45	0.53	0.58	0.58	0.54	0.48	0.46	0.44	0.44

Total season (days from beginning of spring growth)

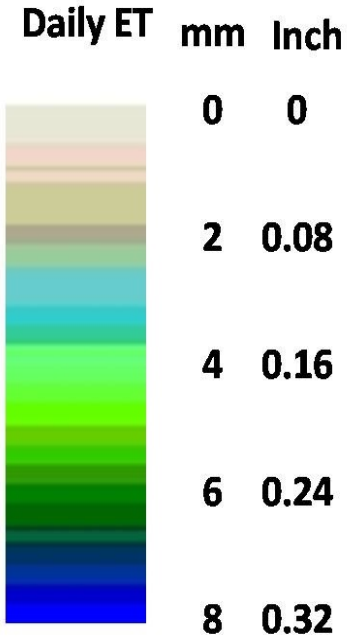
Crop	0	20	40	60	80	100	120	140	160	180	200
Alfalfa	0.45	0.69	0.87	0.88	0.7	0.75	0.88	0.81	0.88	0.71	0.65
(seasonal)	0.44	0.77	0.82	0.86	0.9	0.88	0.85	0.82	0.78	0.66	0.5
(seasonal mean)						**0.85**					
Perennial rye grass (8-15 cm)	0.55	0.66	0.77	0.80	0.80	0.80	0.78	0.76	0.72	0.68	0.55

“Map” of evapotranspiration based on Landsat satellite imagery

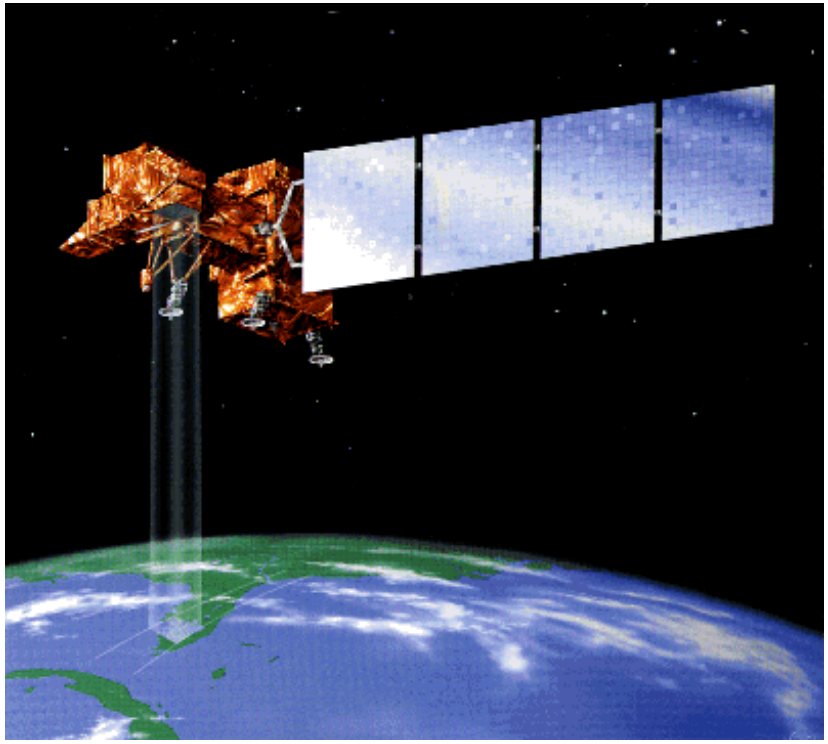


Pivot-irrigated field with a vigorous crop, high ET

The within-field variation in ET is visible



Each Landsat satellite acquires a new image each 16 days for a specific location



Landsat 7

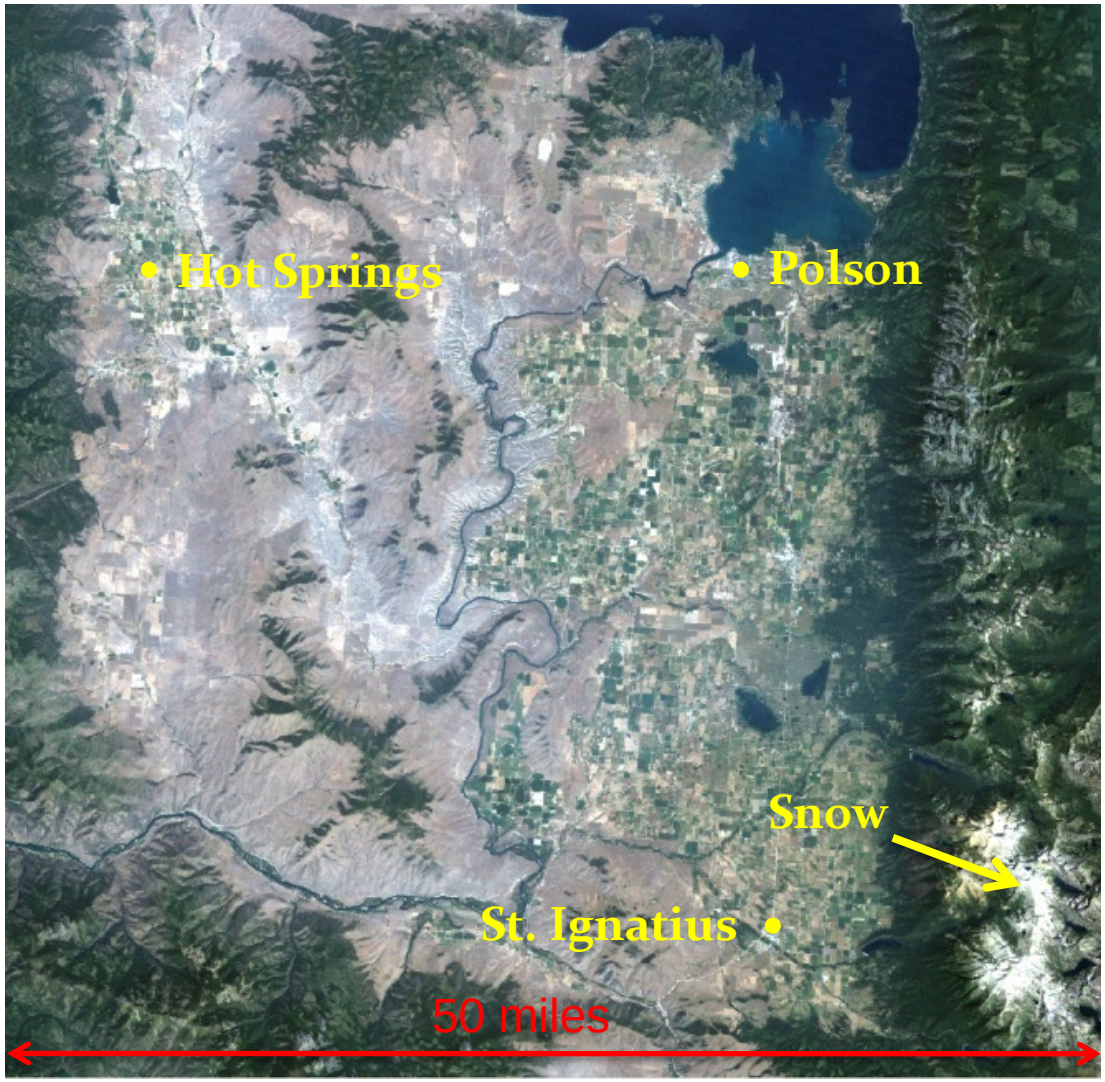
Landsat 5 (discontinued)

Landsat 8

Scale of ET estimation

Example Landsat image:
Mission Valley, MT
Image from 07/16 2007

- Estimates of ET from Landsat
  - Regional coverage (100 miles by 100 miles per image)
  - 90 ft. resolution (allows for capturing within-field and between-field variations in ET)



Categorizing RS-methods to estimate ET

Draft, suggested by the ASCE-EWRI Remote Sensing of Evapotranspiration Task Committee

	Tier 1	Tier 2	Tier 3	Tier 4
Complexity	Low →			High
Method example	Vegetation Index vs. Kc	Scaling ET from surface temp	Routine EB applications	Higher level EB applications
Uncertainty targets	+/- 30%	+/- 20%	+/- 15%	+/- 10%
Application example	Identify irrig. vs. non-irrig. land; local scale ET estimations	National or global surveys of veg. water consumption	Hydrological modeling, Kc development	Water rights management, litigation

YIELDER
YIELDER

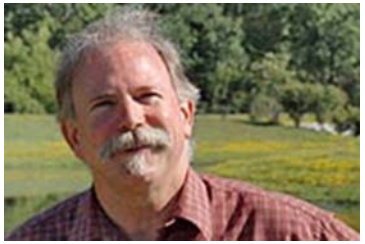
ET “mapping” with SEBAL and METRIC

- Surface Energy Balance Algorithm for Land

  Dr. Wim Bastiaanssen,
  WaterWatch, *The Netherlands*
  – beginning in 1990

- Mapping EvapoTranspiration with high Resolution and Internalized Calibration

  Allen et al,
  University of Idaho, *Kimberly*

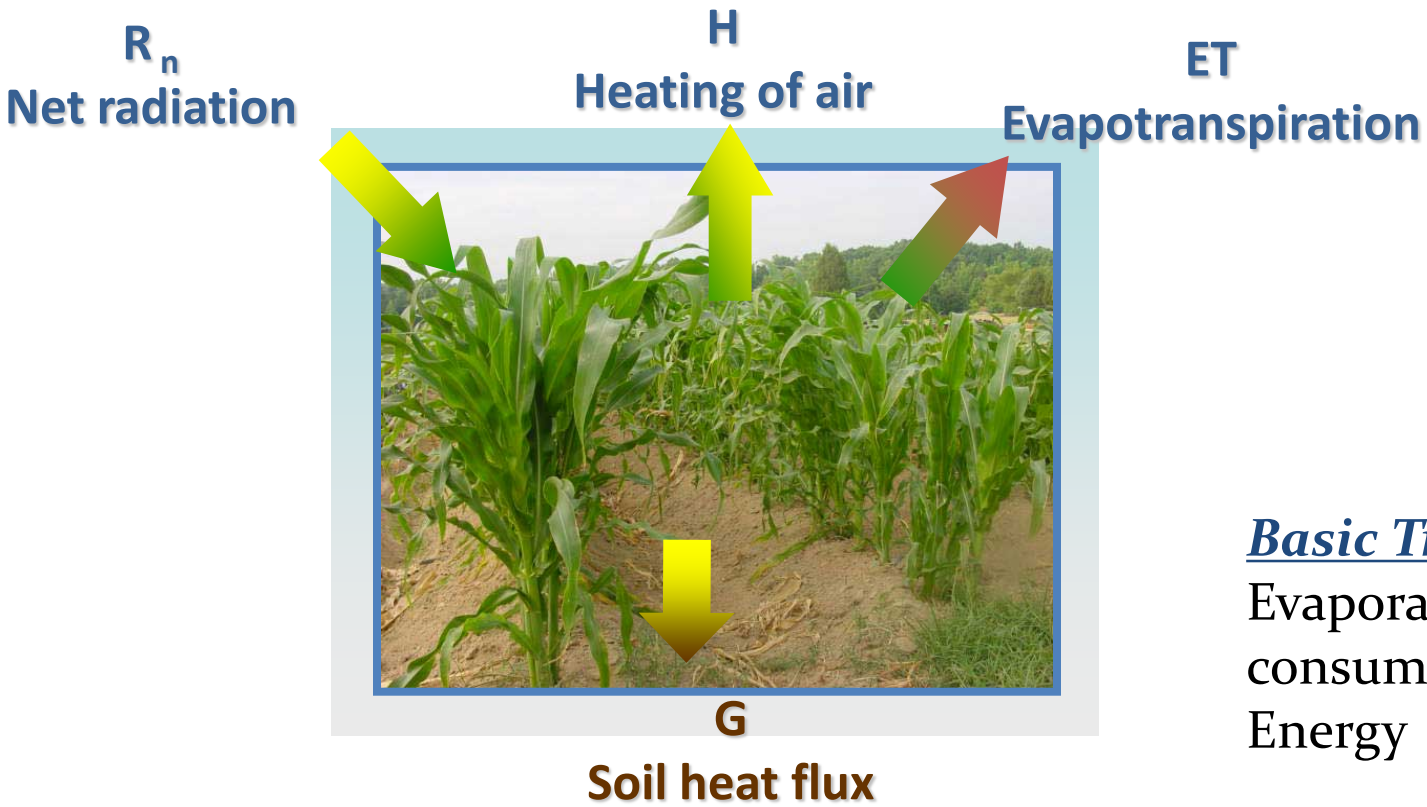


METRIC utilizes shortwave and thermal infrared satellite information

METRIC^{tm} is energy-balance-based ET mapping tied down and partly calibrated using ground-based *reference ET* (from weather data)

METRIC Energy Balance

The satellite can not "see" ET therefore ET is calculated as a "residual" of the energy balance: **$ET = R_n - G - H$**



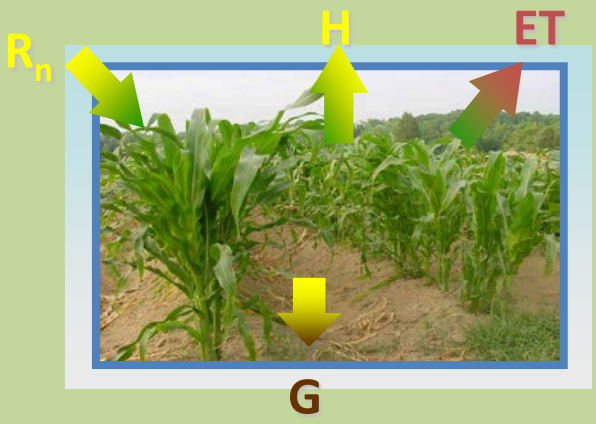
Basic Truth: Evaporation consumes Energy

We can “see” differences in crop water use using the energy balance approach

- soil water shortage (stress)
- plant density
- soil salinity
- fertility deficiencies
- disease
- insect pressures
- weeds
- senescence
- tillage/traffic
- hail/frost

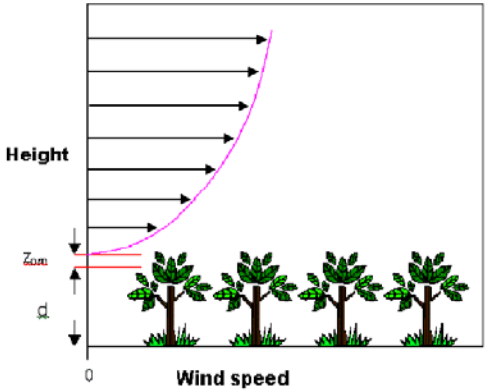
METRIC Energy Balance

- **Net Radiation** (R_n), calculated using
  - Sun-earth geometry
  - *Spectral reflectance* from the surface
  - *Thermal radiance* from the surface
  - Transmissivity of Atmosphere
- **Ground Heat Flux (G)**, Calculated using
  - *Vegetation Amount*
  - *Net radiation*
  - *Thermal radiance*
- **Sensible Heat Flux** (**H**), Calculated using
  - *Thermal radiance*
  - Wind speed
  - Surface cover type and roughness
  - Surface to air temperature difference, dT



underlined terms are obtained from the satellite data

Sensible Heat Flux (H)



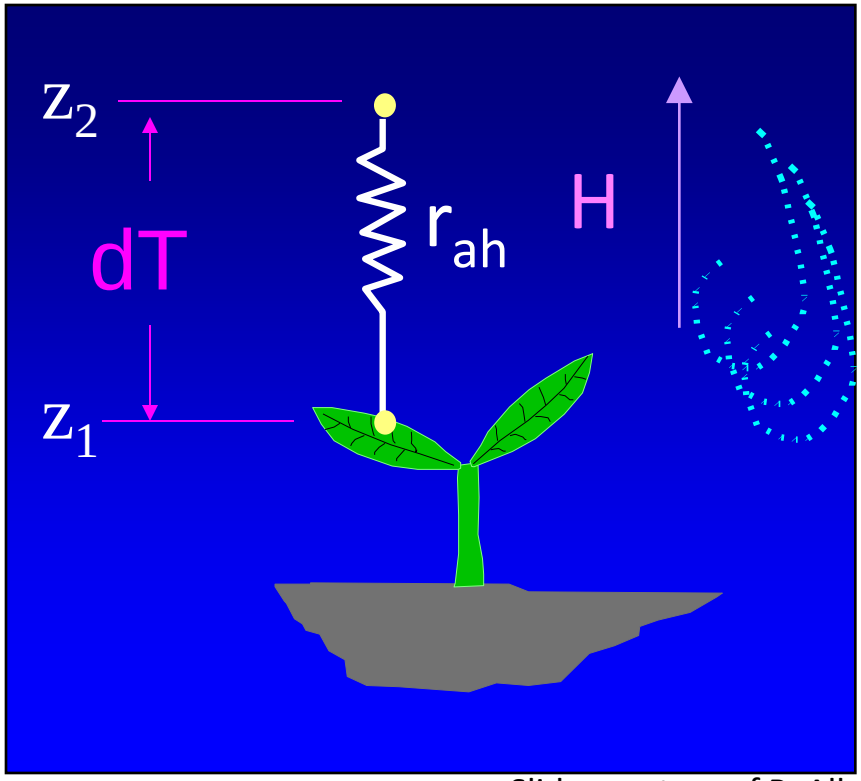
$$H = (\rho \times c_p \times dT) / r_{ah}$$

dT = “floating” near surface temperature difference (K).

r_{ah} = the aerodynamic resistance to heat transport (s/m).

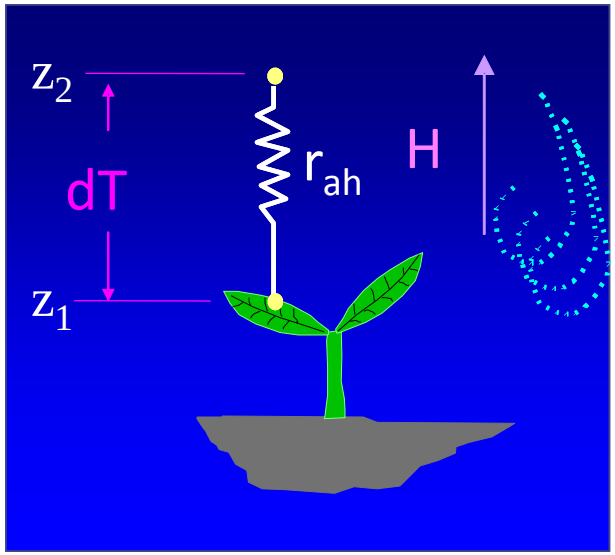
$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_{ns}}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

u_* = friction velocity
k = von Karman constant (0.41)
Ψ = Atmospheric stability corrections for heat transport



Slide courtesy of R. Allen

Near Surface Temperature Difference (dT)



- To compute the sensible heat flux (H), define near surface temperature difference (dT) for each pixel

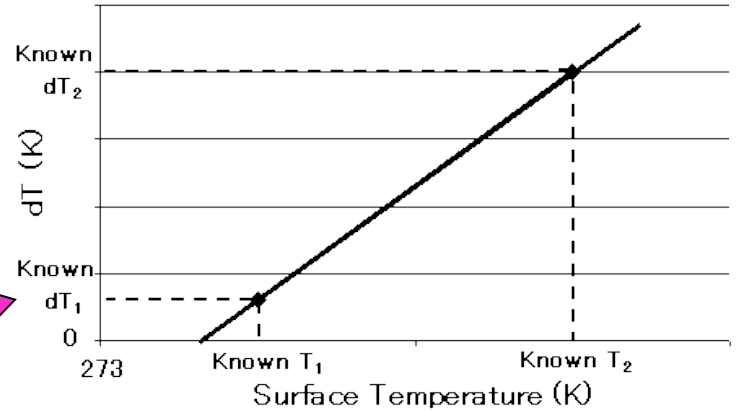
Classical: $dT = T_{surface} - T_{air}$

SEBAL/METRIC: $dT = T_{z1} - T_{z2}$

- T_{air} is unknown and unneeded
- SEBAL and METRIC^{tm} assume a linear relationship between T_s and dT:

$$dT = b + aT_s$$

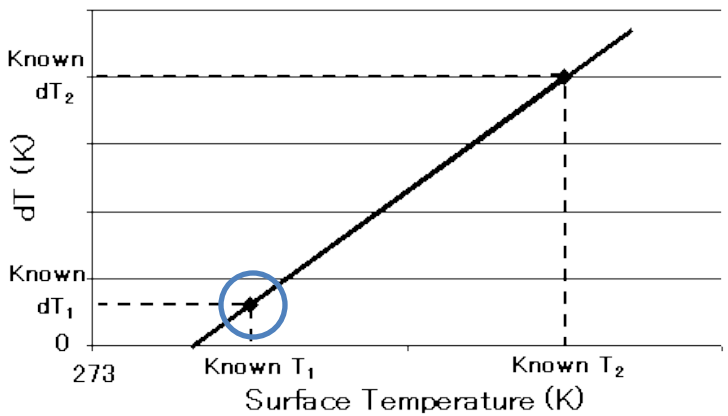
Bastiaanssen ingeniousness



- T_s is used only as an index and can have large bias and does not need to represent aerodynamic surface temperature

Slide courtesy of R. Allen

“Cold” condition



“Cold” condition

- Full cover alfalfa or similar crop
- $H = R_n – G - 1.05\ ET_{ref}$
- $H = \rho c_p\, dT / r_a$

LE ~ 1.05 ET_r
Assumes “wet” fields (just irrigated) can have ET 5 – 10% greater than alfalfa ET_r

Net Radiation

Ground Heat Flux

$$ET_{ref} = \frac{\Delta(R_n - G) + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\lambda}$$

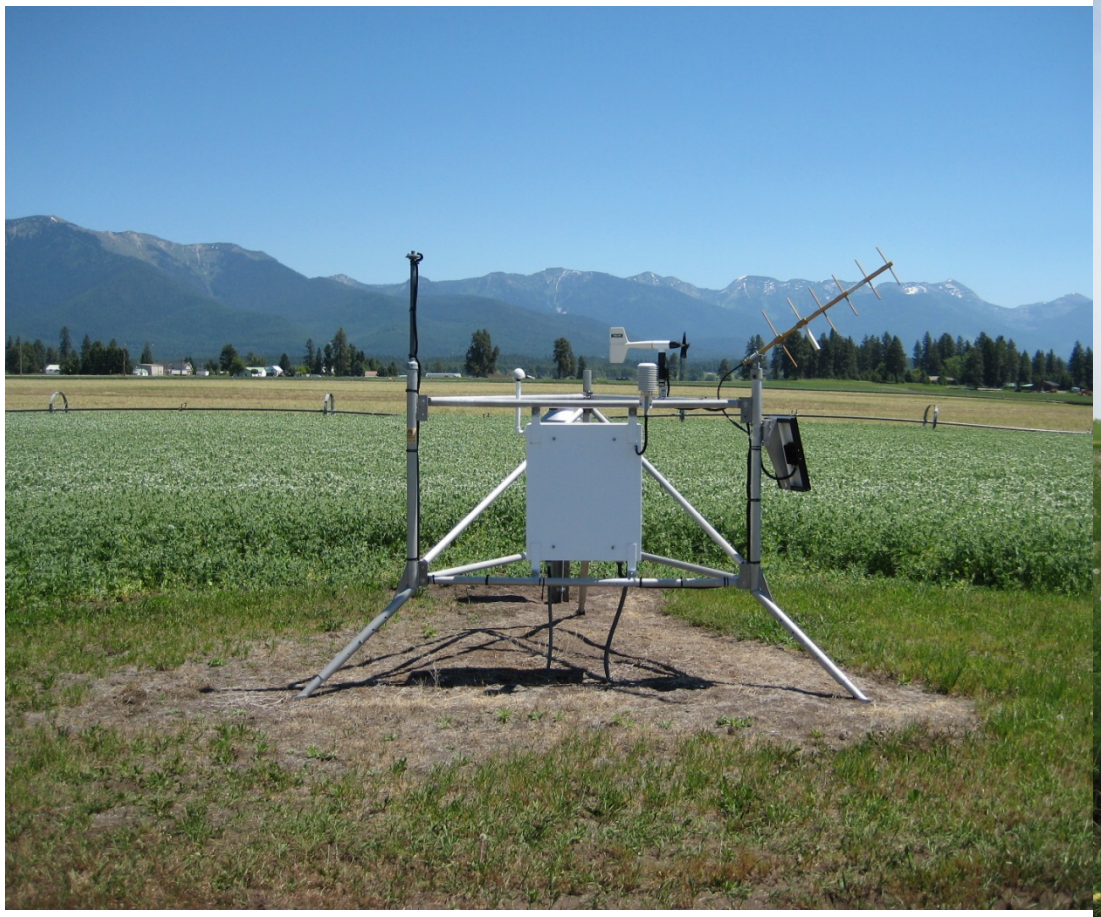
Vapor Pressure

= f(0.5 m ht)

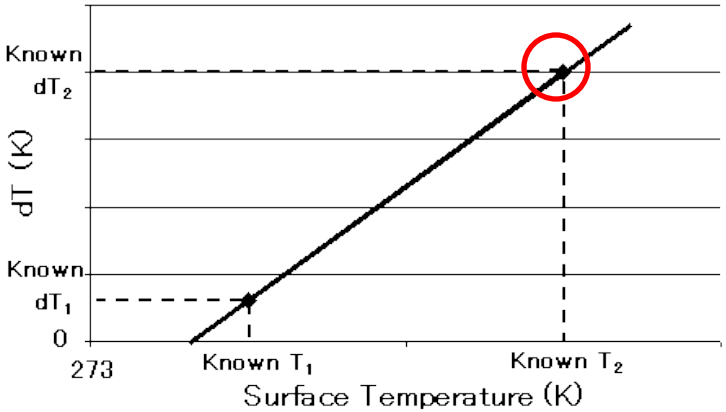
30 s m^{-1}
(daylight)

(ASCE-EWRI, 2005)

Weather data

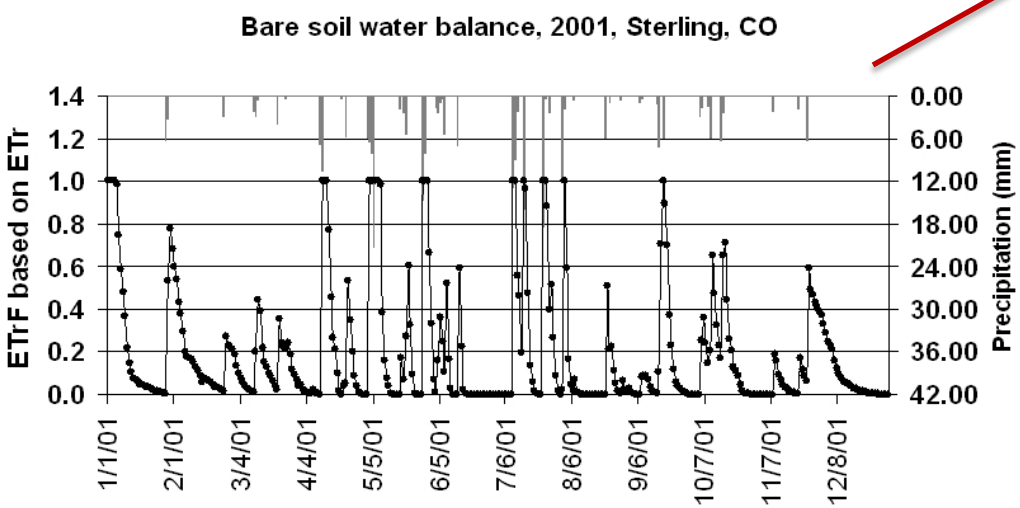


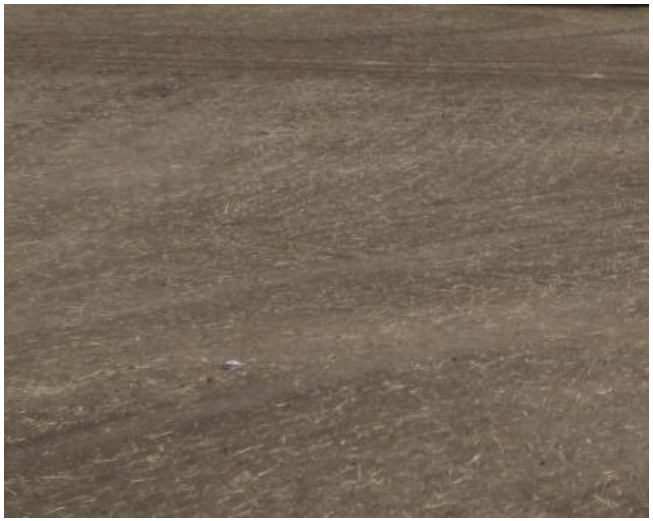
“Hot” condition



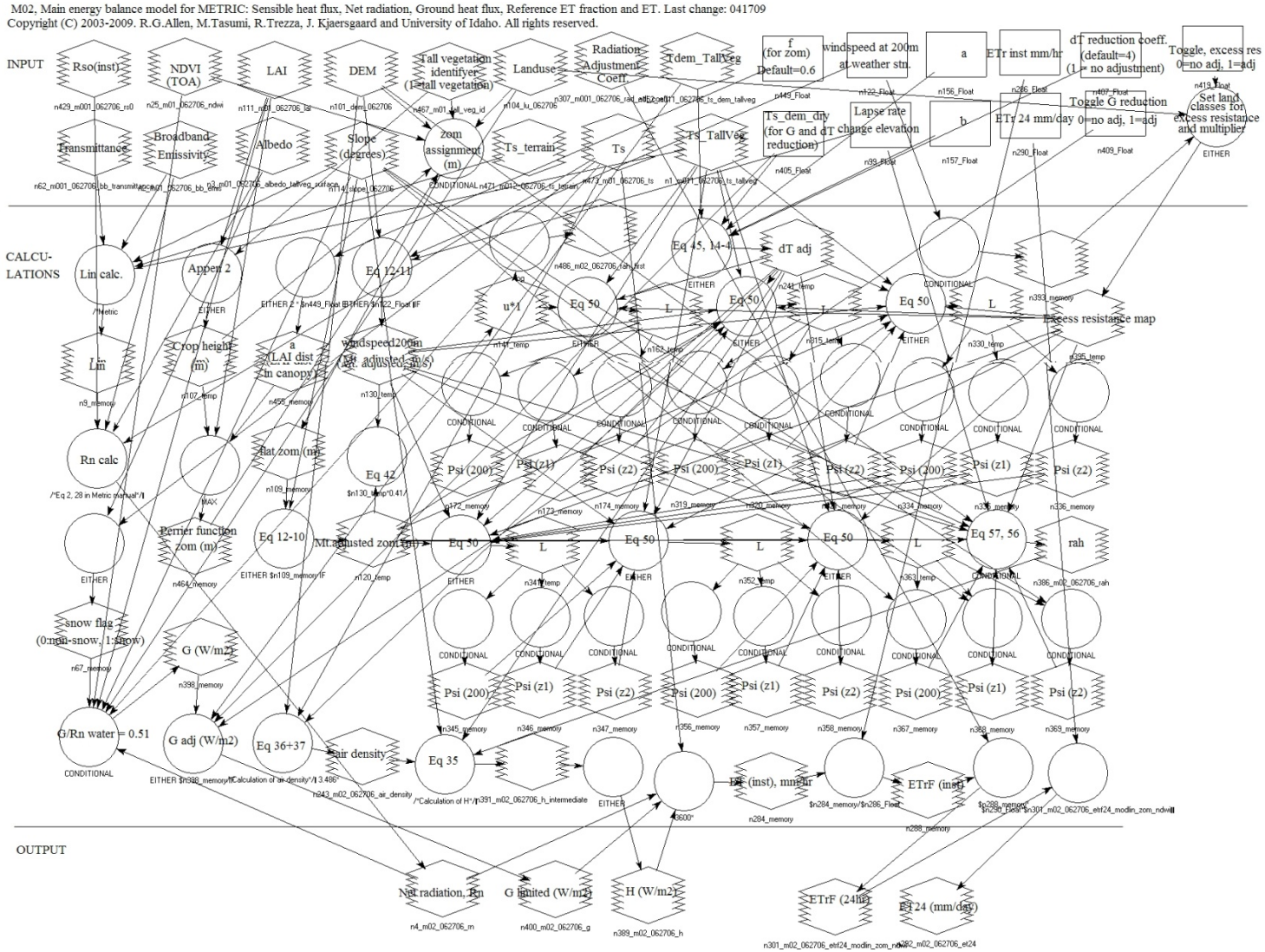
“Hot” condition

- Bare soil
- $H = \rho c_p \, dT / r_a$
- $H = R_n - G - \mathbf{x} \, ET_r$

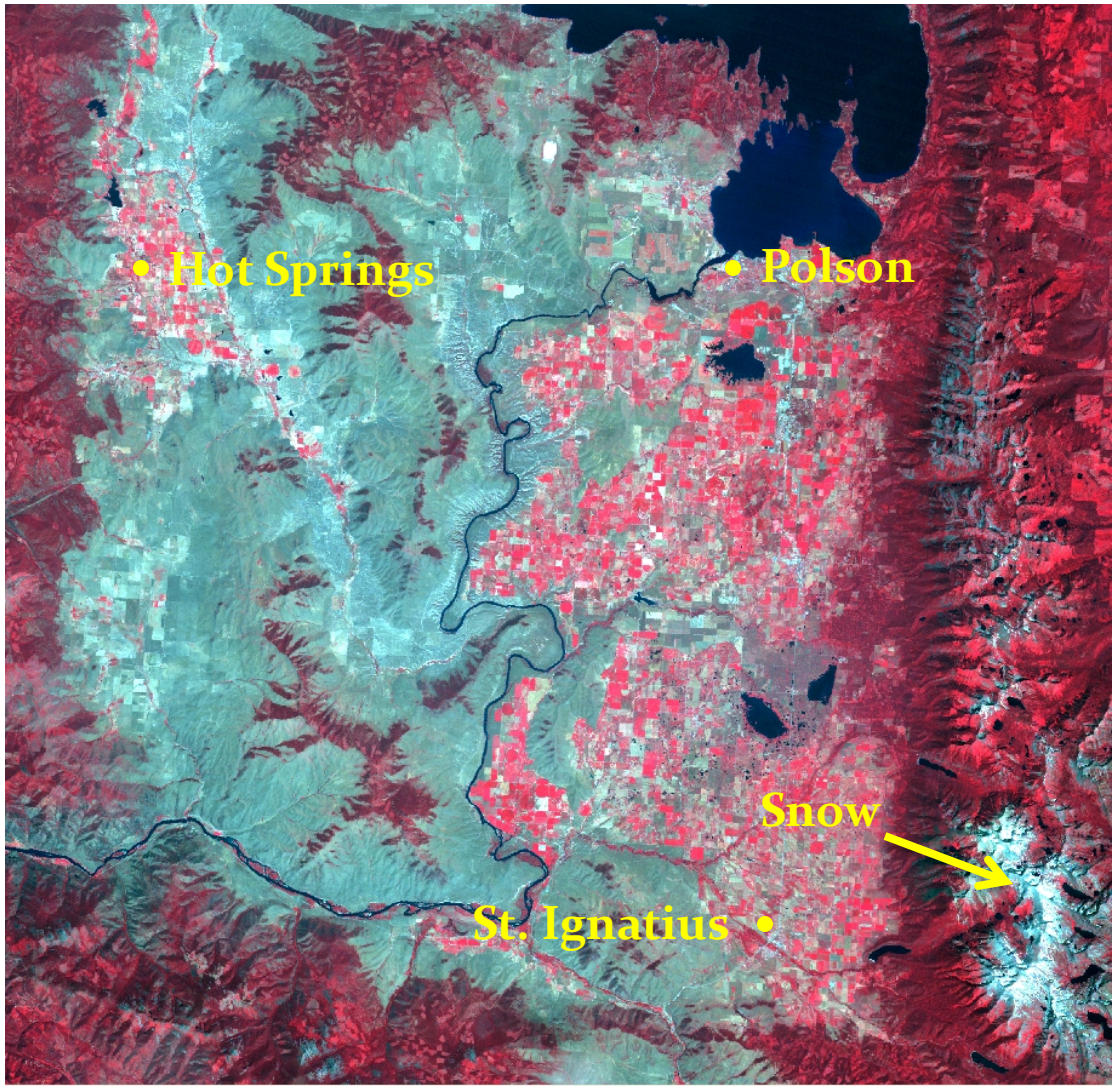




METRIC model



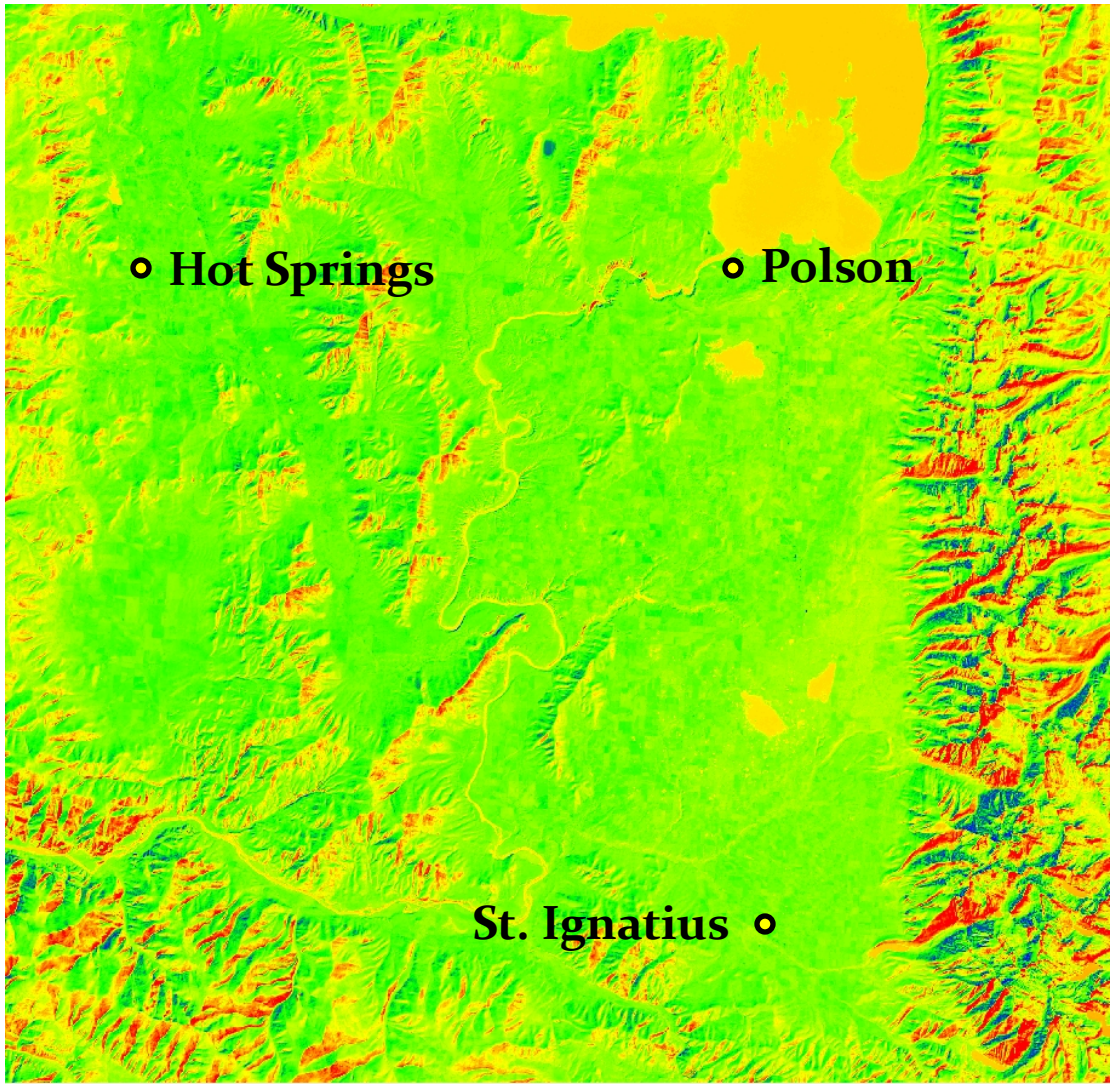
False color image

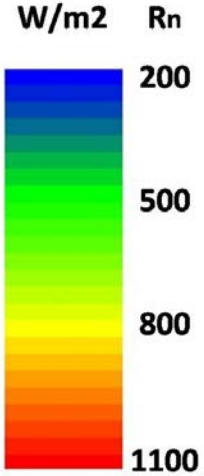


50 miles

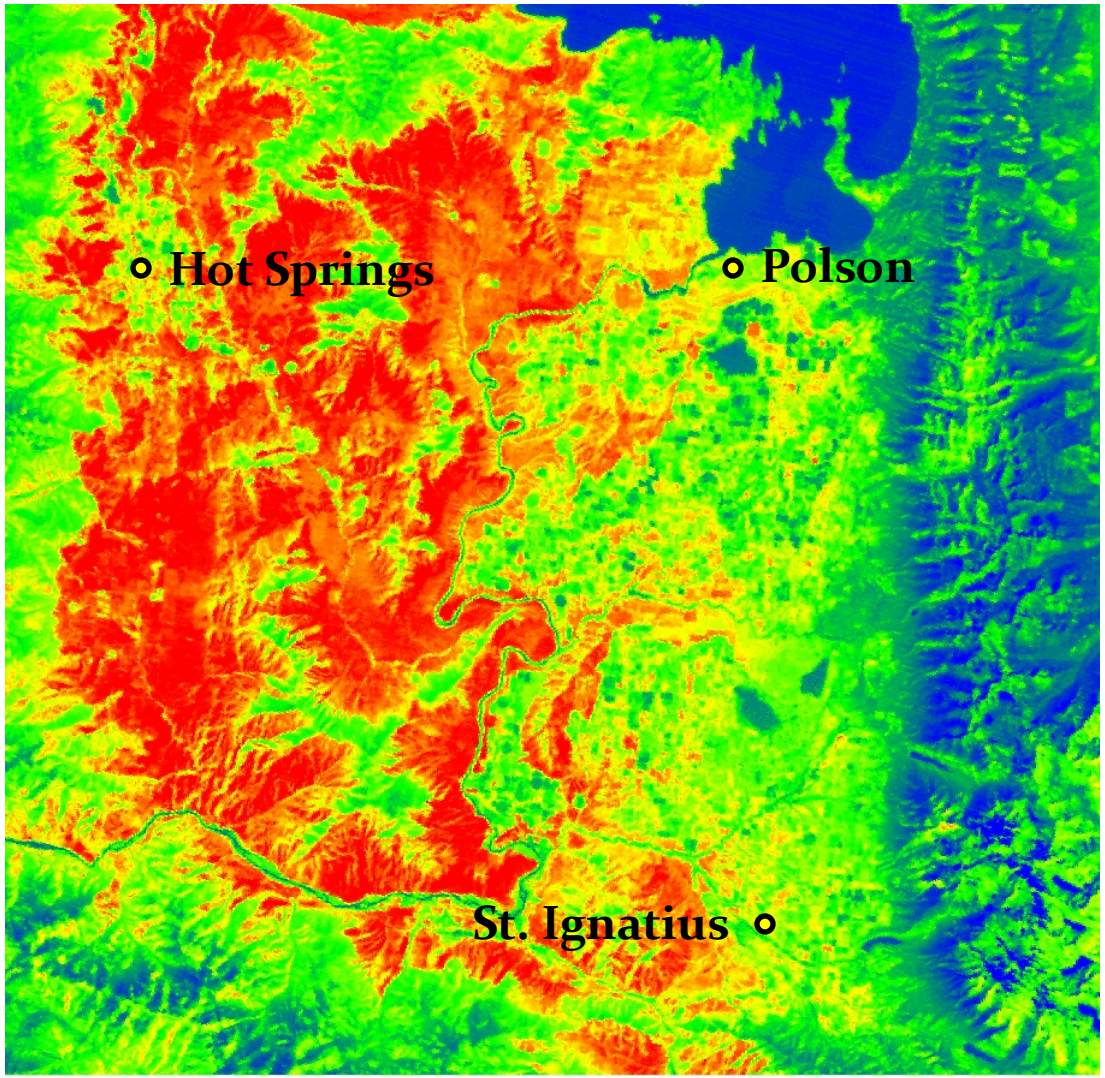
Image from 07/16 2007

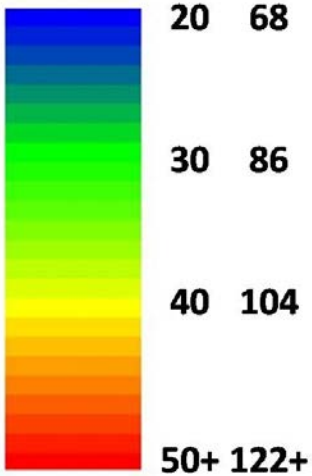
Net Radiation



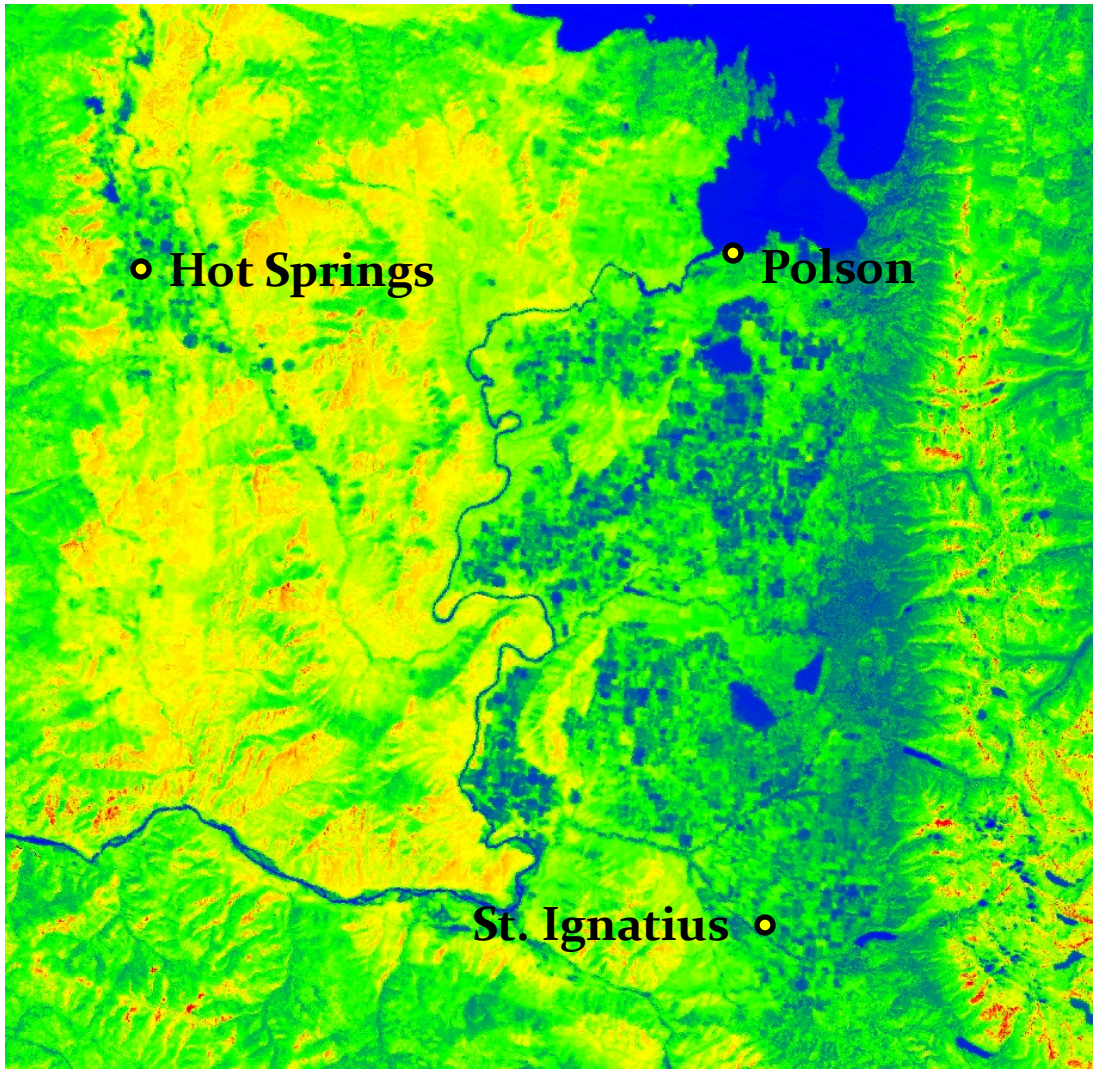


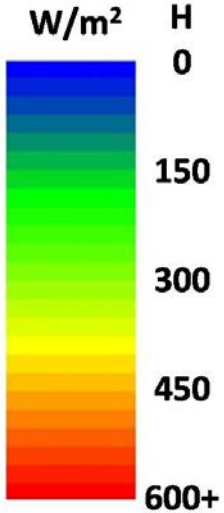
Surface Temperature



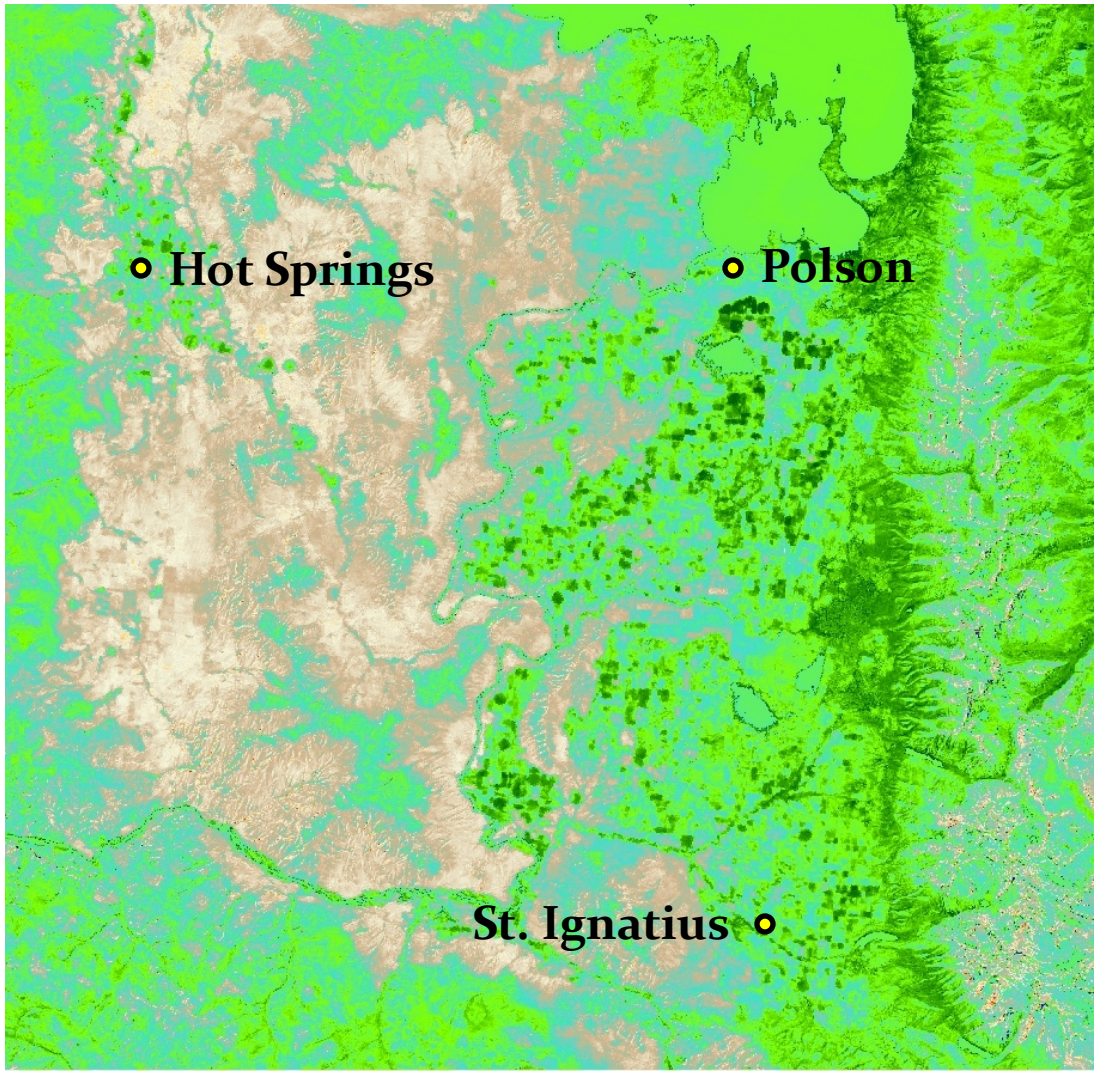


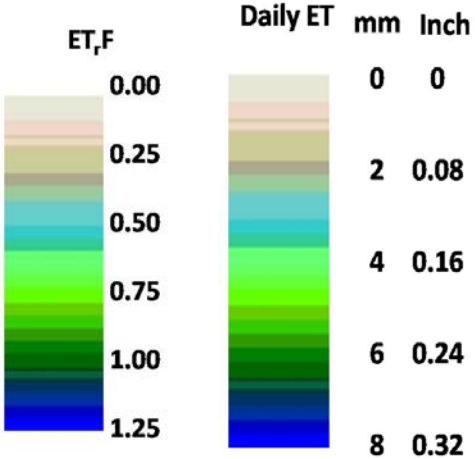
Heat flux to air



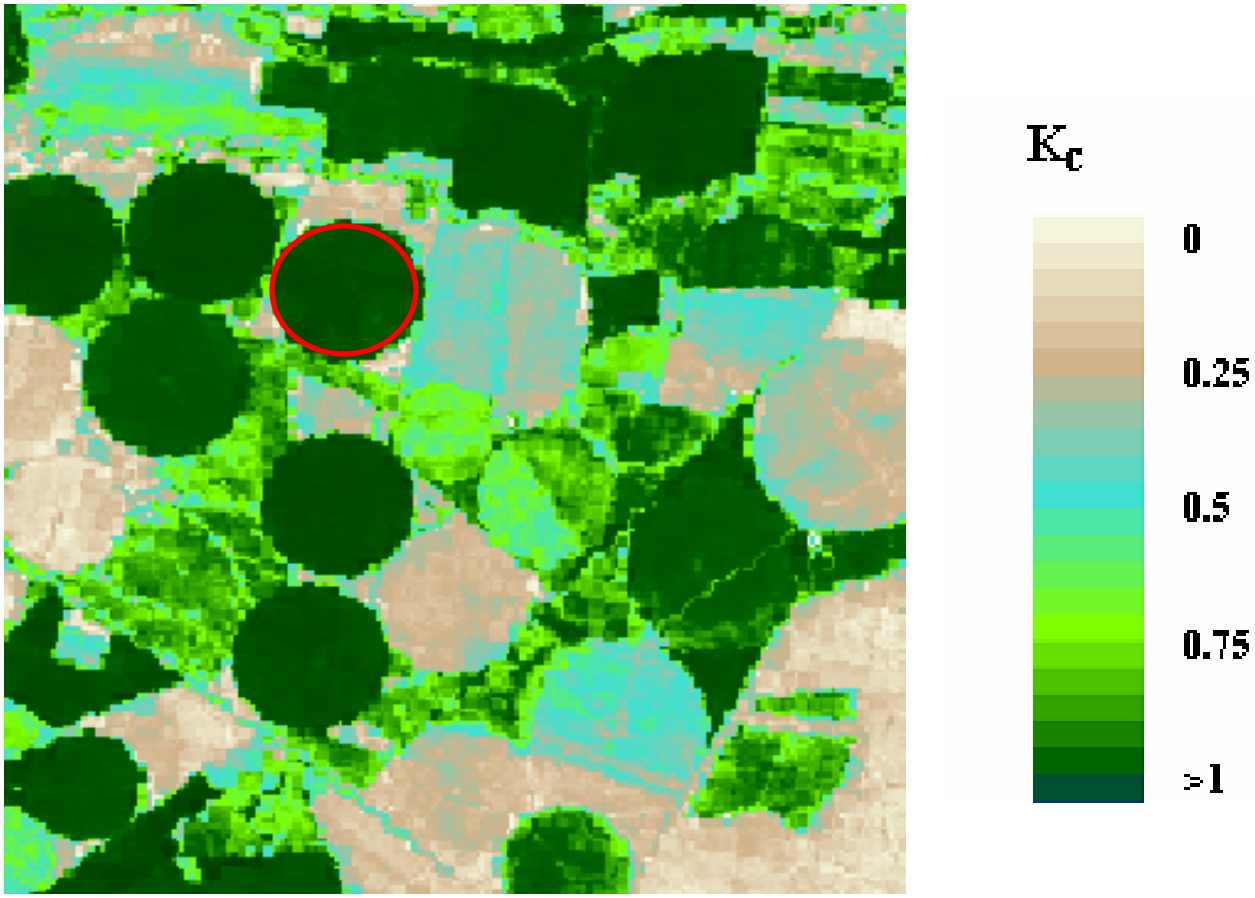


Evapotranspiration

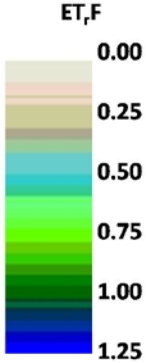


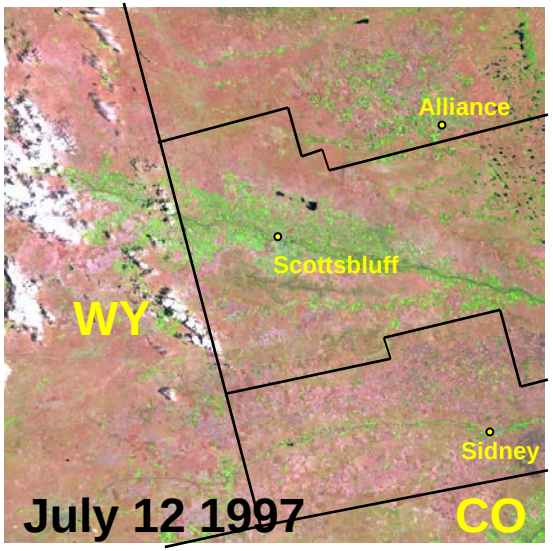


“Maps” of Evapotranspiration



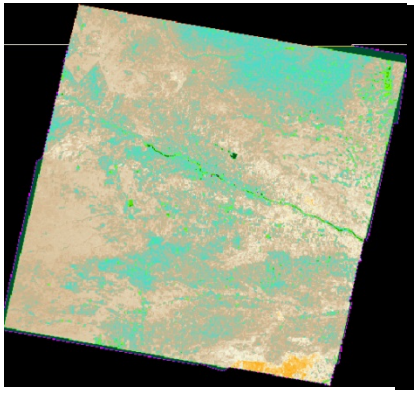
ET_rF during the growing season



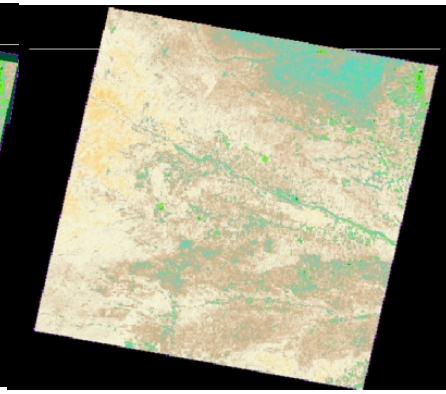


Landsat true color

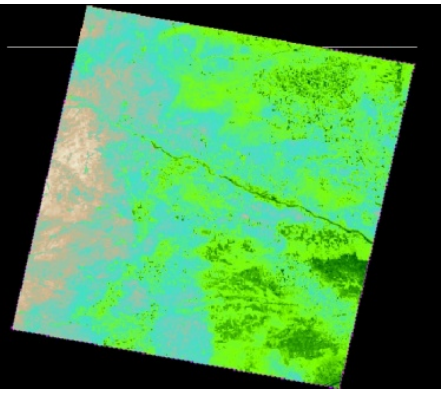
1997 image date ET_rF estimates



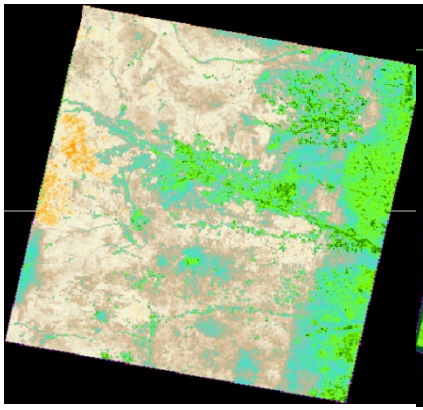
April 23



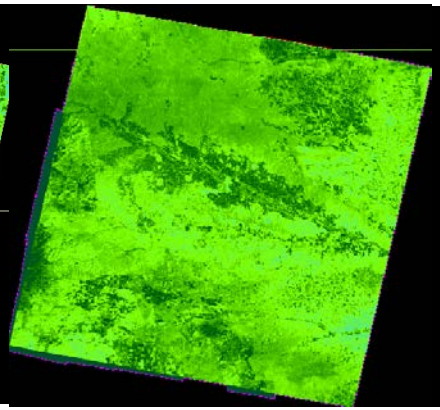
May 9



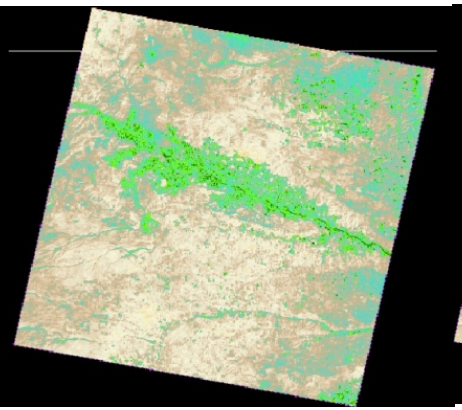
June 26



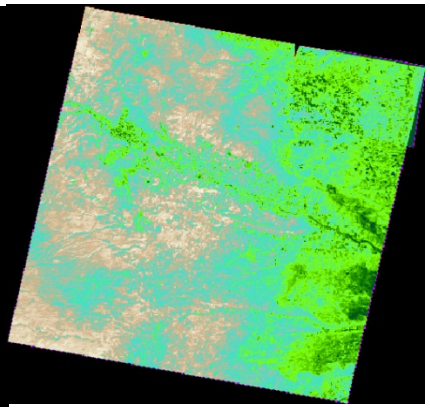
July 12



August 13

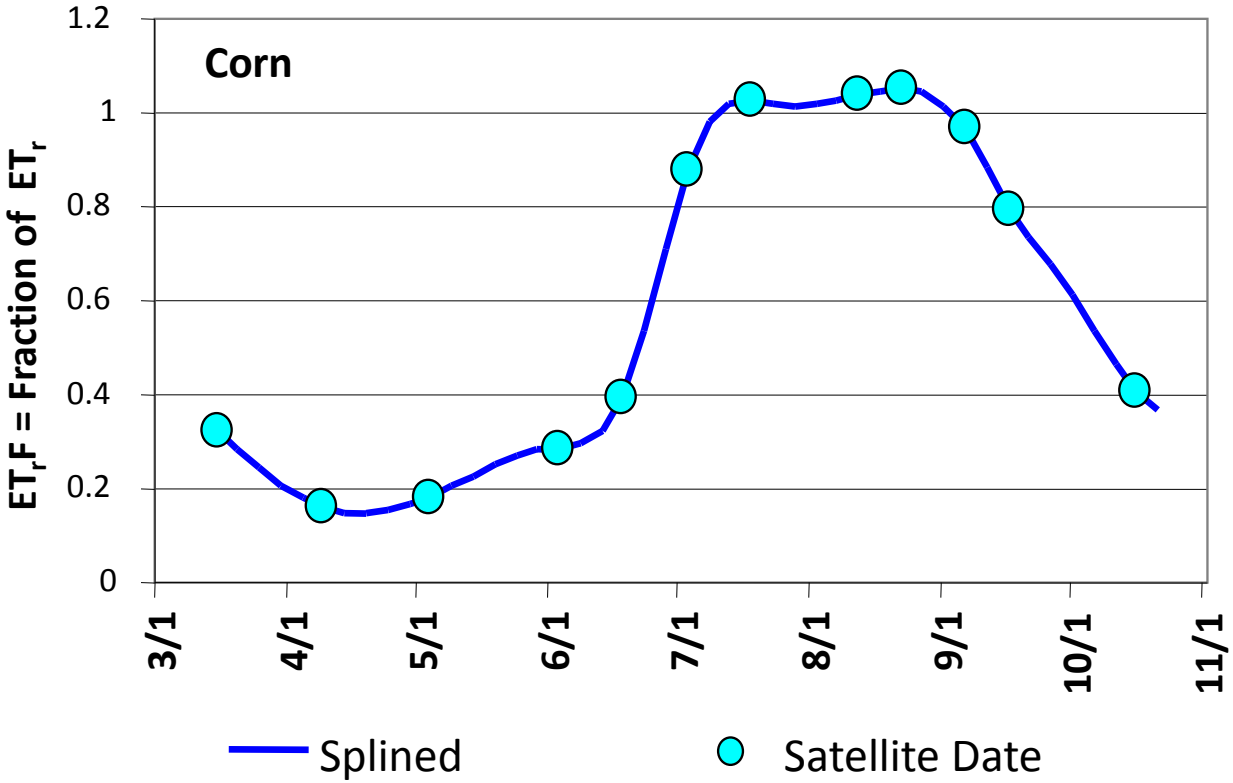


September 30

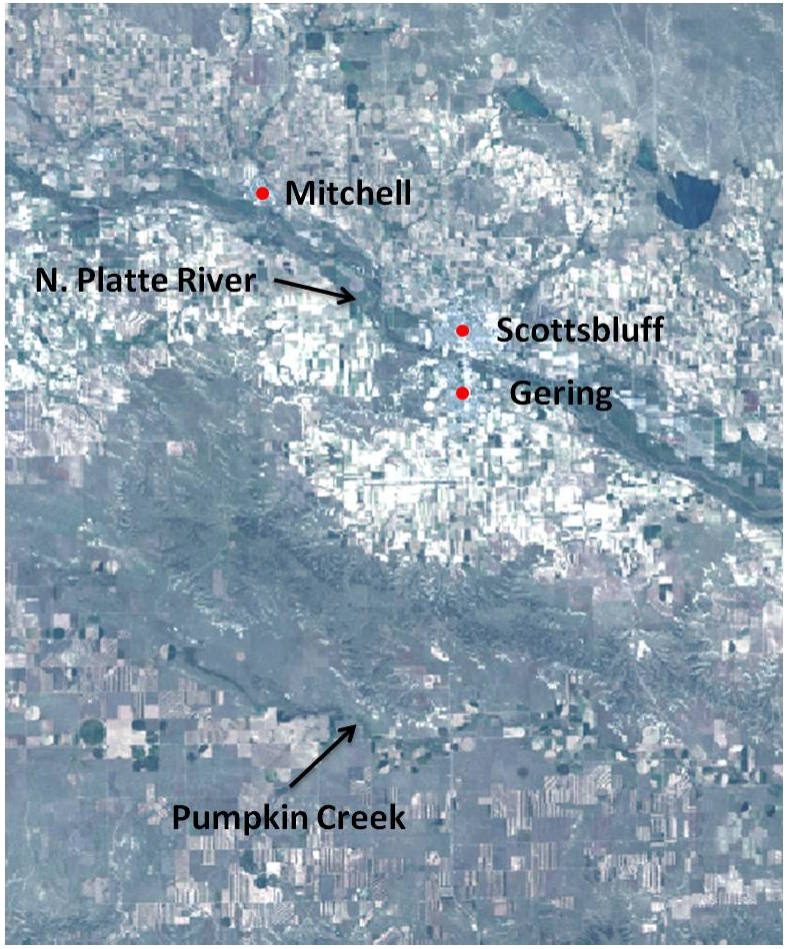


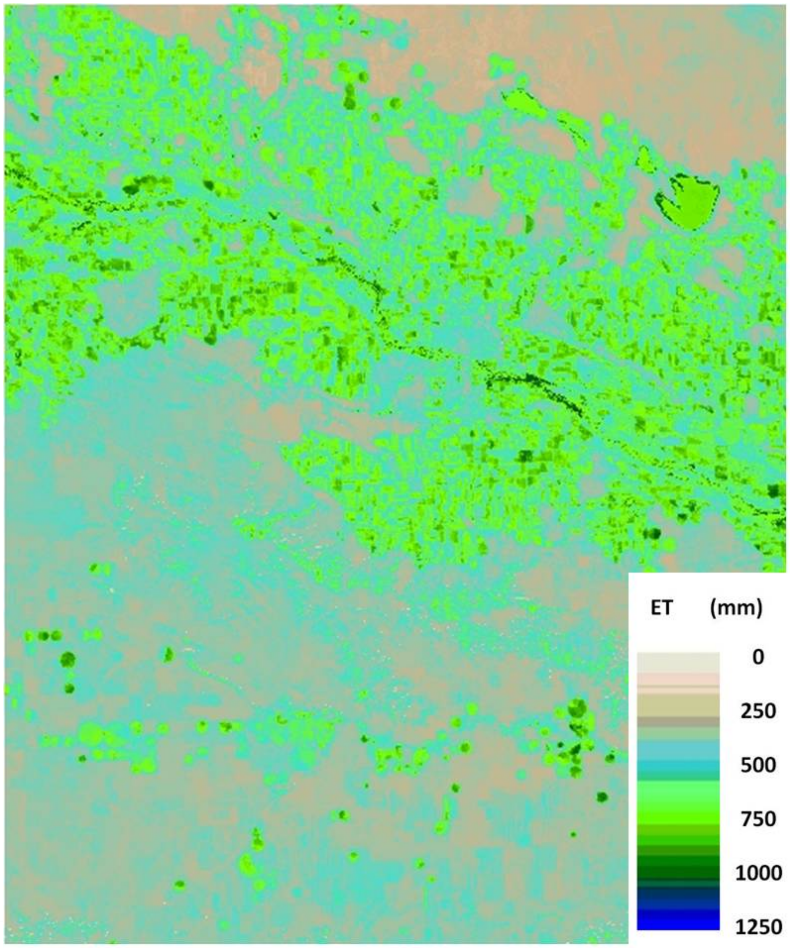
October 16

Interpolation for Monthly or Seasonal ET



Growing season ET





Growing season ET (April 1 – October 31) 1997 near Scottsbluff, NE

ET maps are used where water are in short supply or contested

- Improved Calibration of Hydrologic Models
- Assessments of Consumptive Use (MT)
- Water Rights Management (ID)
- Water Rights Transfers (NV)
- Riparian Invasive Species Water Use (NM)
- Estimate Injury from Water Curtailment (CA)
- Native American Water Rights (OR)
- Hydrologic impacts of subsurface drainage (SD)

BUDGET JUSTIFICATIONS

The United States
Department of the Interior

and Performance Information
Fiscal Year 2015

U.S. GEOLOGICAL SURVEY

NOTICE: These budget justifications are prepared for the Interior, Environment and Related Agencies Appropriations Subcommittees. Approval for release of the justifications prior to their printing in the public record of the Subcommittee hearings may be obtained through the Office of Budget of the Department of the Interior.

USGS FY15 Budget Justifications, page F-28

its provisional products for public release in consistent, user-friendly forms via online interfaces.

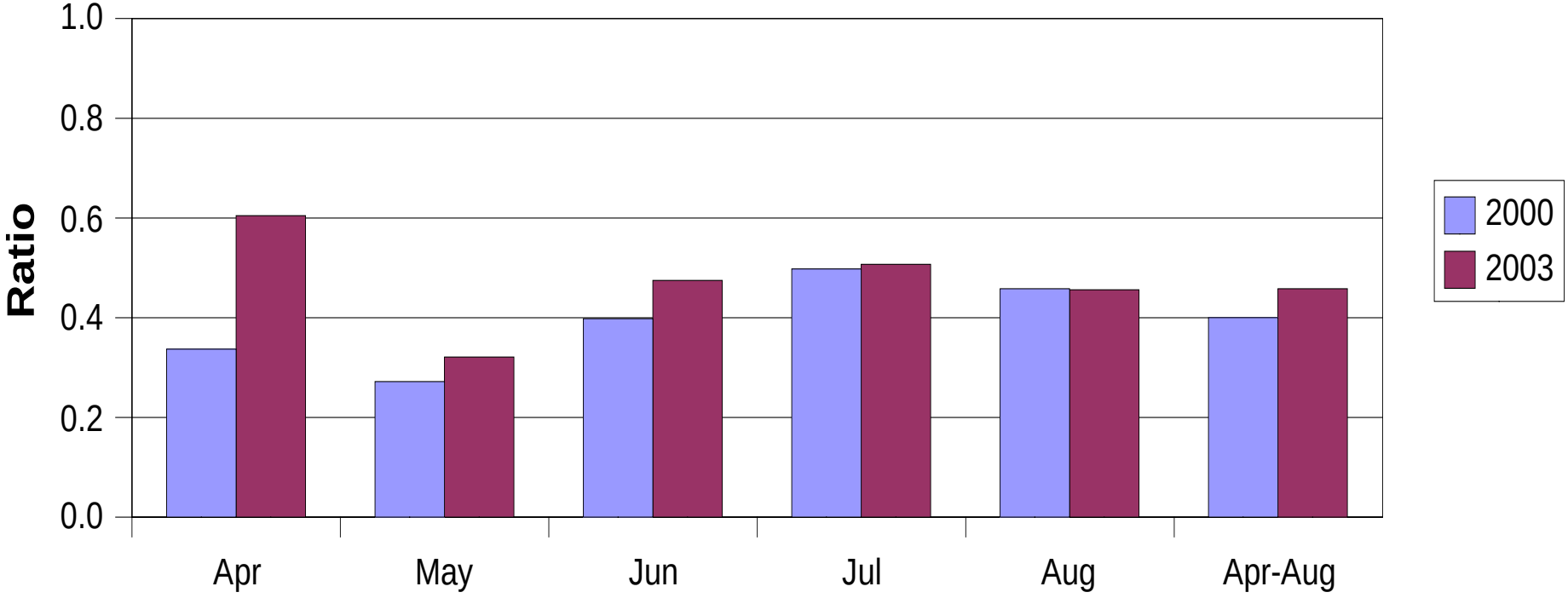
The LRS Program will continue to support the Landsat Science Team in developing Landsat applications that support natural resource management in critical sectors of the Nation's economy. For example, water-resource managers in at least 12 states are using a Landsat-based tool (developed by the University of Idaho and the Idaho Department of Water Resources) for water management and impartial, data-driven adjudication of water rights. The tool, a computer model called METRIC, uses Landsat thermal data to produce water-use maps of irrigated fields more efficiently than using traditional, labor-intensive methods.

The LRS Program is also supporting researchers from the USGS, the University of Maryland, the State

Irrigation District Performance - Idaho

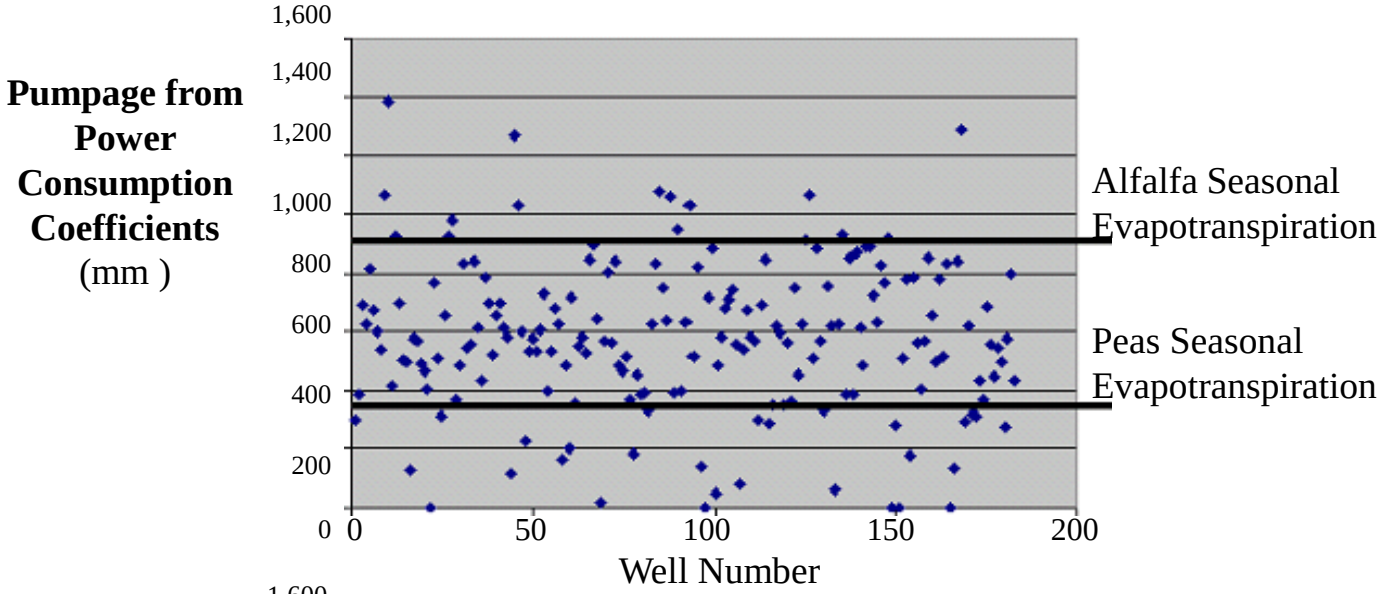
Twin Falls Canal Company, Idaho (200,000 acres)

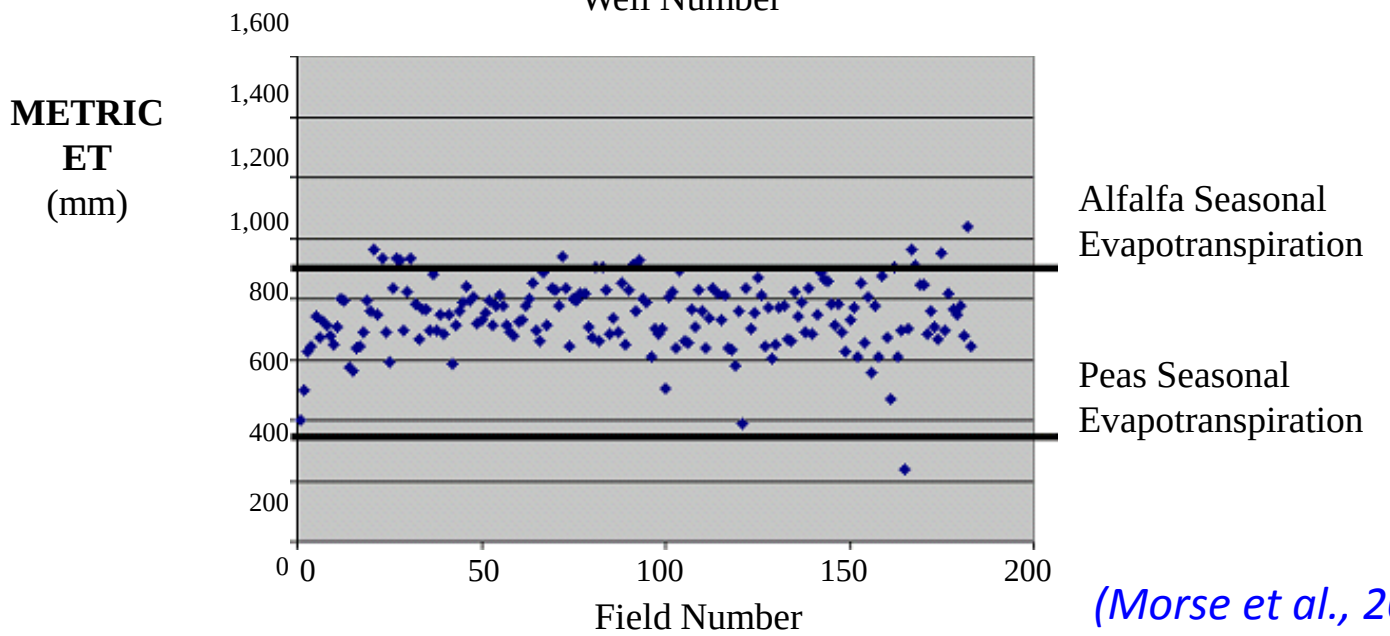
Evapotranspiration as a Ratio of Diversion plus Precipitation



Courtesy of W. Kramber and T. Morse, IDWR

ET from electrical power consumption vs. METRIC





(Morse et al., 2008)

Annual Costs to estimate net irrigation pumpage operationally for all of southern Idaho *(Morse et al., 2008)*

Method	Number of Wells	Total Cost	Cost per Well
Power Consumption Coefficients	3,830	$456,995	$119.
Landsat Evapotranspiration --equivalent area	3,830	$123,134	$ 32.
Landsat Evapotranspiration southern Idaho	5,948	$199,450	$ 34.

(Morse et al., 2008)

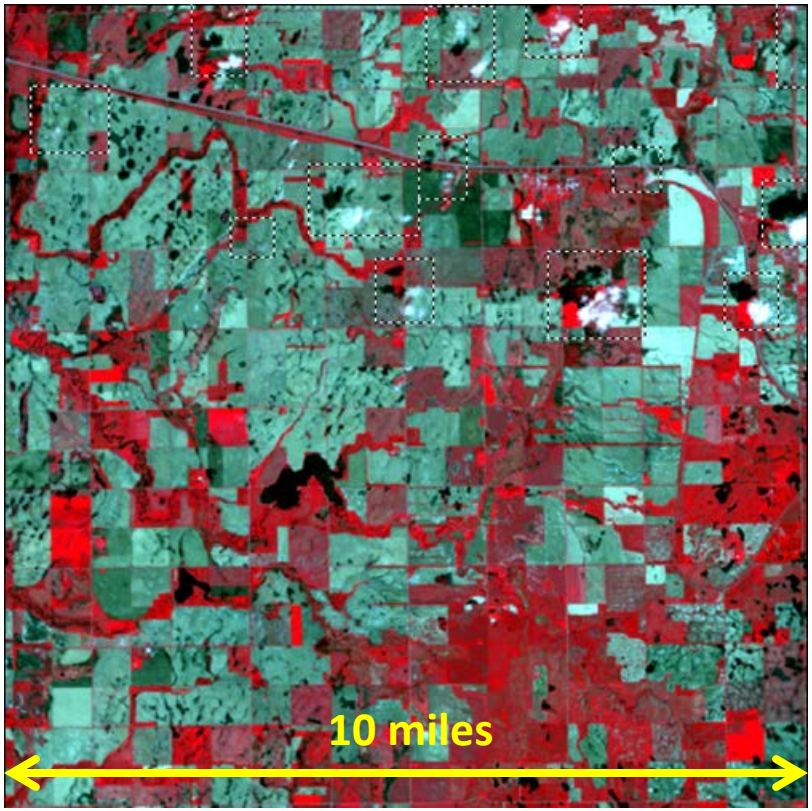
Cover crops

- Capture nutrients
- Improve soil structure
- Build organic matter
- Improve soil biology
- Improve soil water holding capacity

- …but what about the water use?

Estimating cover crop consumptive use

Estimate what the cover crop water consumptive use is compared to wheat stubble



False color Landsat 5 image of the study area 6/4 2011

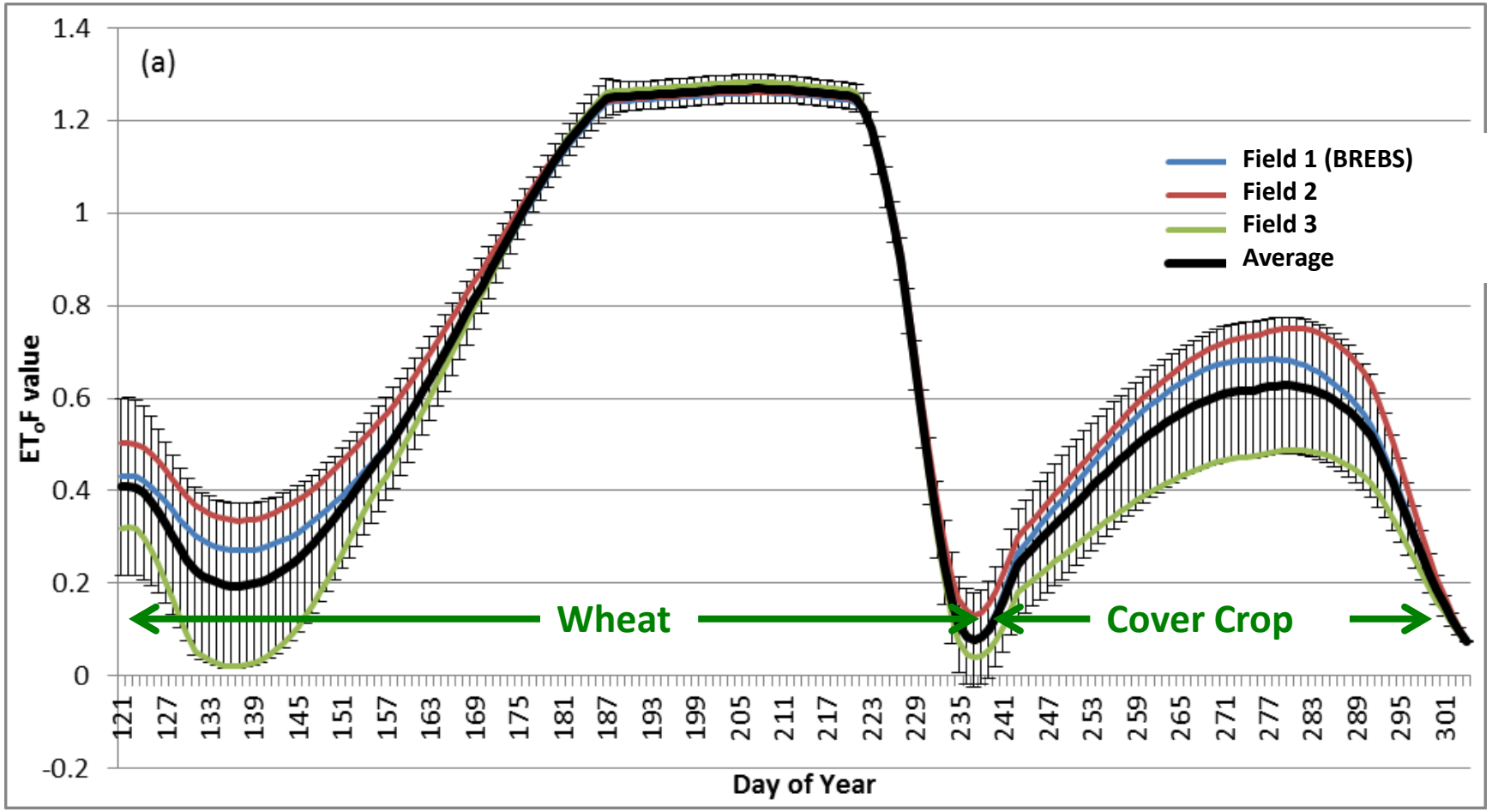
Field site

- Located in NE South Dakota
- Typical rotation: Corn, beans, wheat
- Typical cover crops: Ryegrass, field radish and field peas
- 2011 planting and harvest dates:

Activity	Approximate date
Wheat planted	April 29 2011
Wheat harvested	August 5 2011
Cover crop planted	August 12 2011
Killing frost	October 18 2011

Water use, cover crops

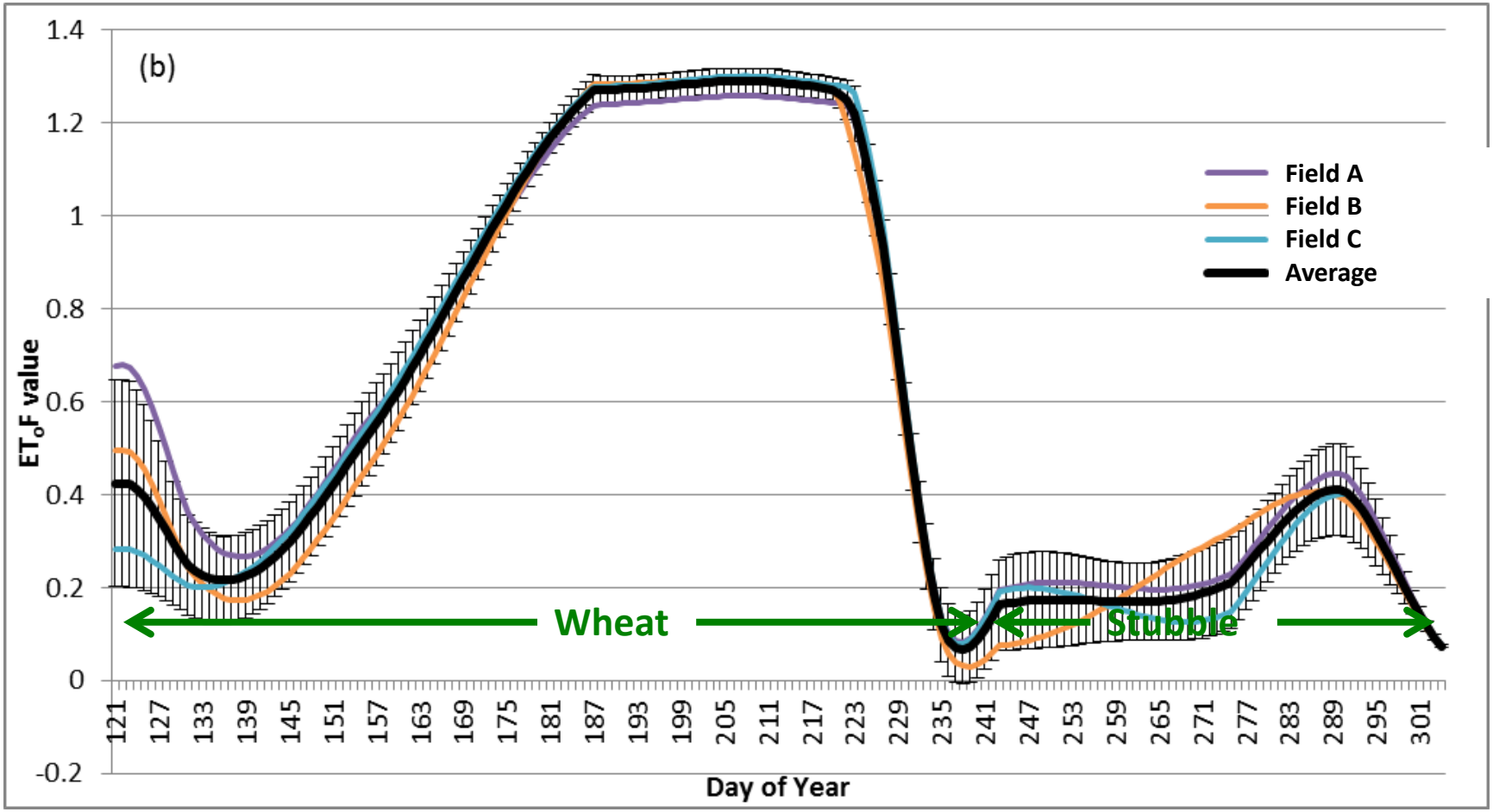
Error bars are one std. dev, n=1350



From Hankerson et al., 2012

Water use, no cover crops

Error bars are one std. dev, n=1959



From Hankerson et al., 2012

The cover crop used ~ 2 inches of water

Cumulative ET and precipitation from August 18 – October 18 2011

Measurement	Depth (mm)
ET_o	266
$ET_{\lambda E}$ (measured using BREBS)	136
ET_{cc} (METRIC, in BREBS field)	140
ET_{cc} (METRIC, 3 fields)	127
$ET_{no\ cc}$ (METRIC, 3 fields)	75
Precipitation	75

cc is cover crops
no cc is fields without cover crops

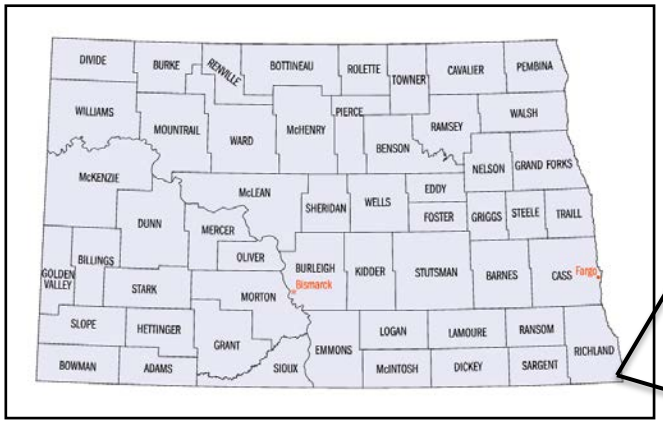
Crop water use with and without subsurface drainage

Location: 46.01 N, 96.6 W (Richland County)

Area: 44 ha (22 ha drained, 22 ha undrained)

Crop type : Corn (Planted: May 17; harvested: Nov. 18)

Study year: 2009



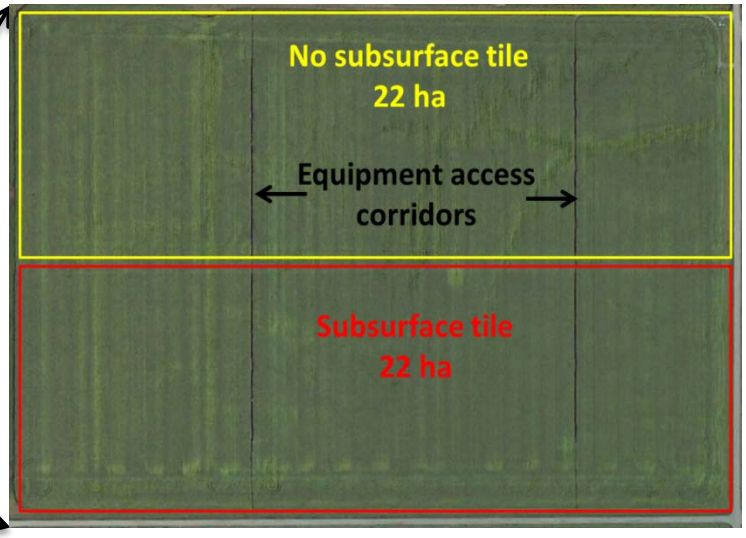
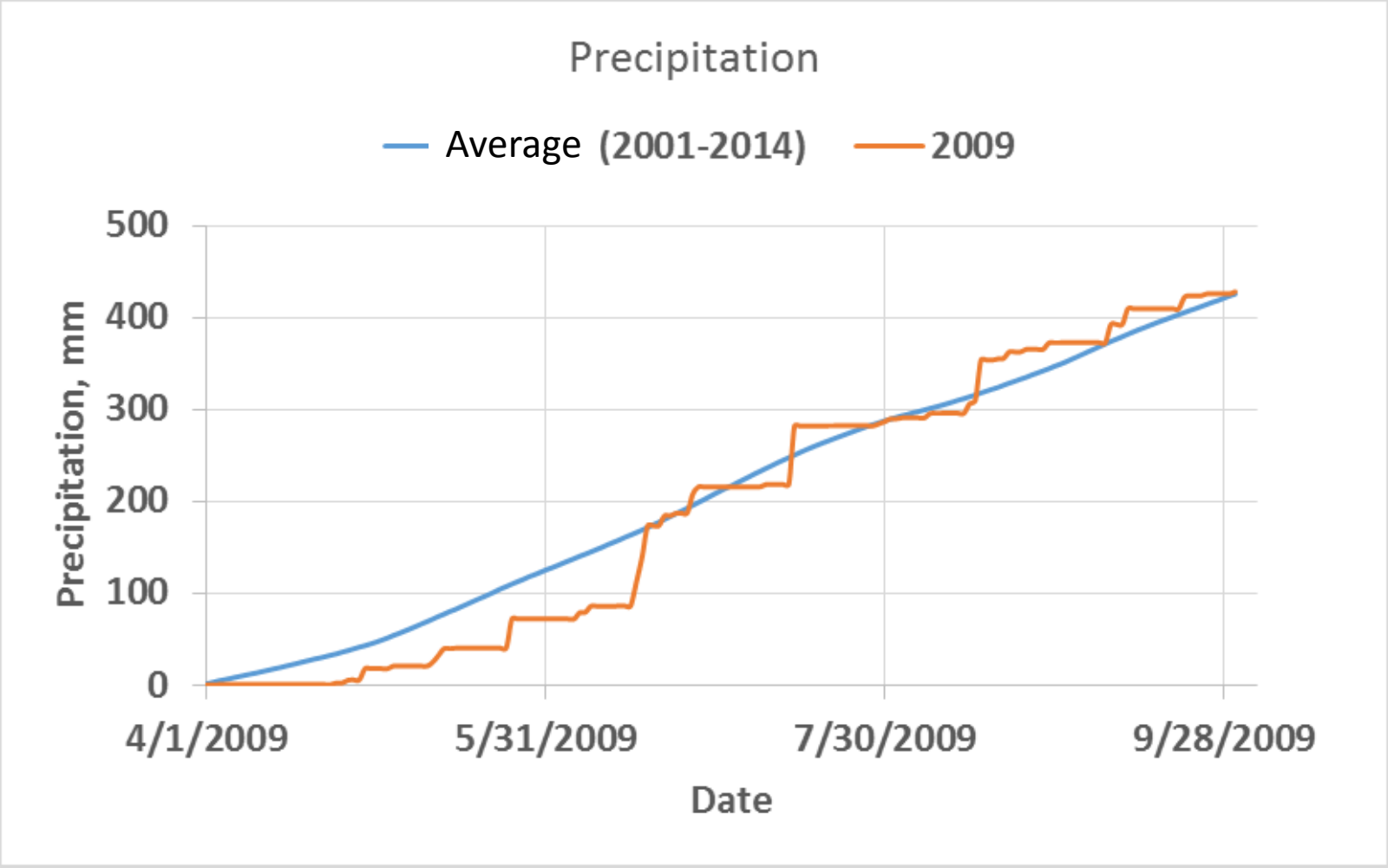
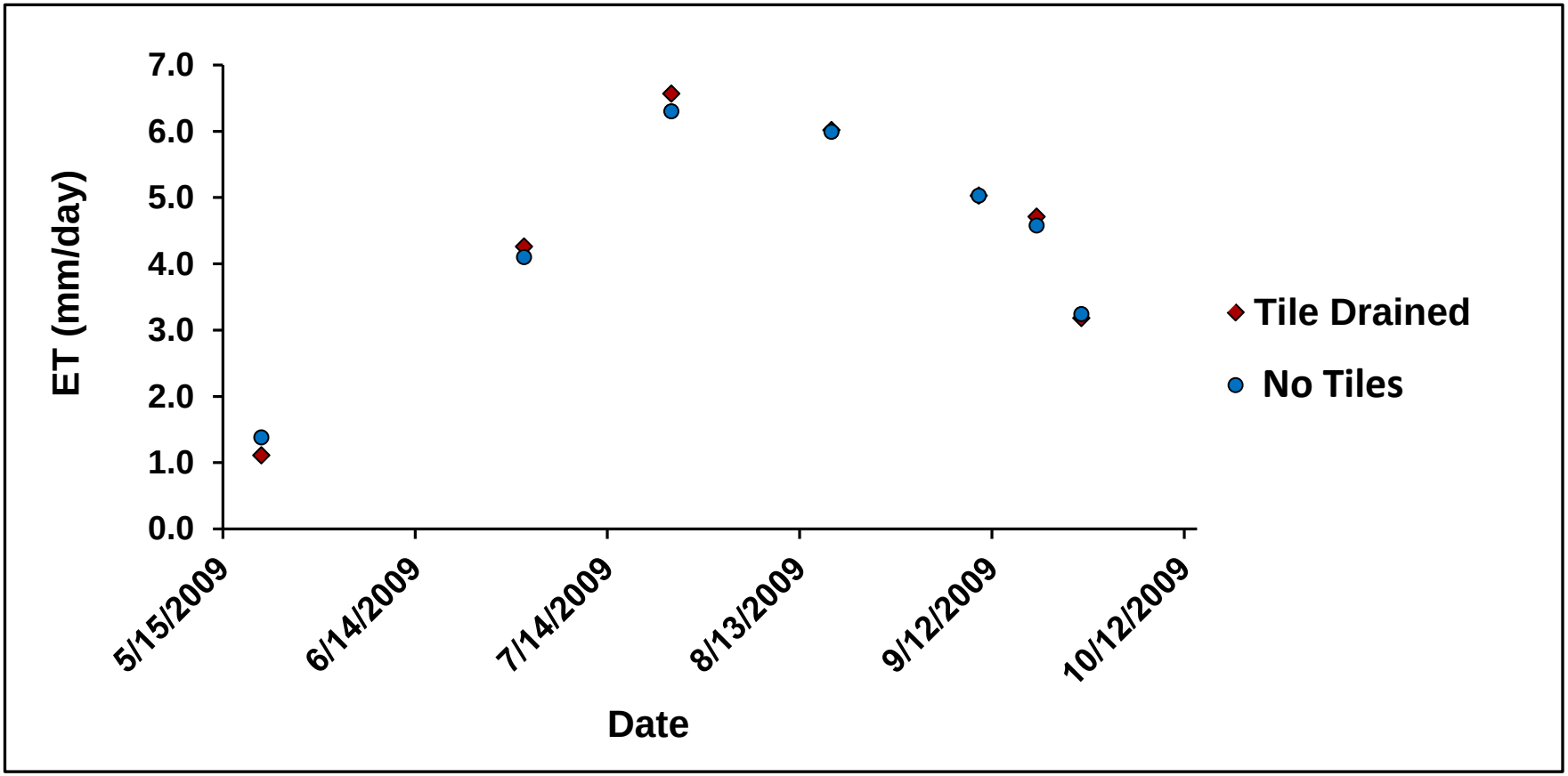


Figure not to scale
Source: Aerial photograph from USDA FSA (June 23, 2010)

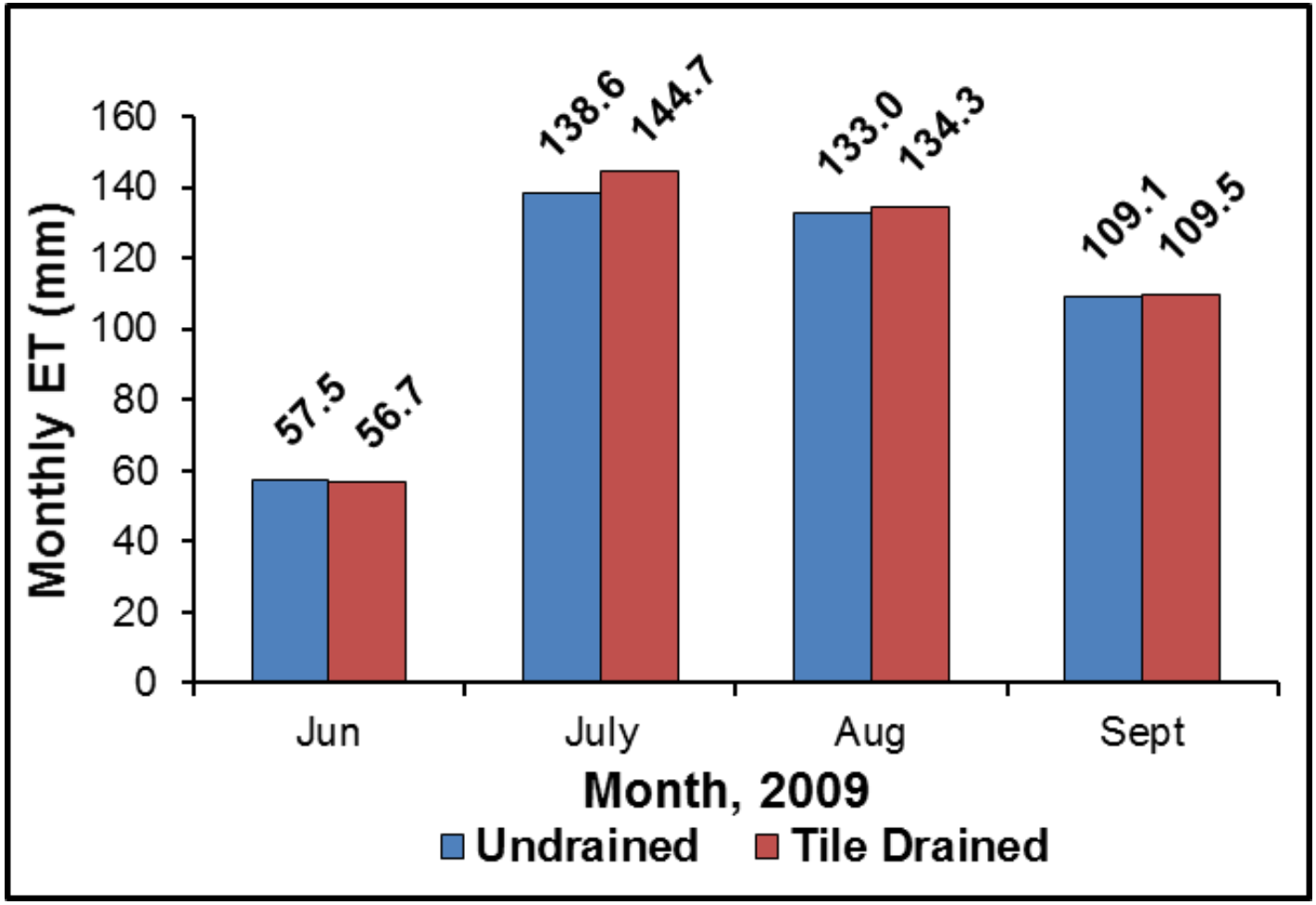
Precipitation was near normal



Small difference in crop water use



Small difference in ET



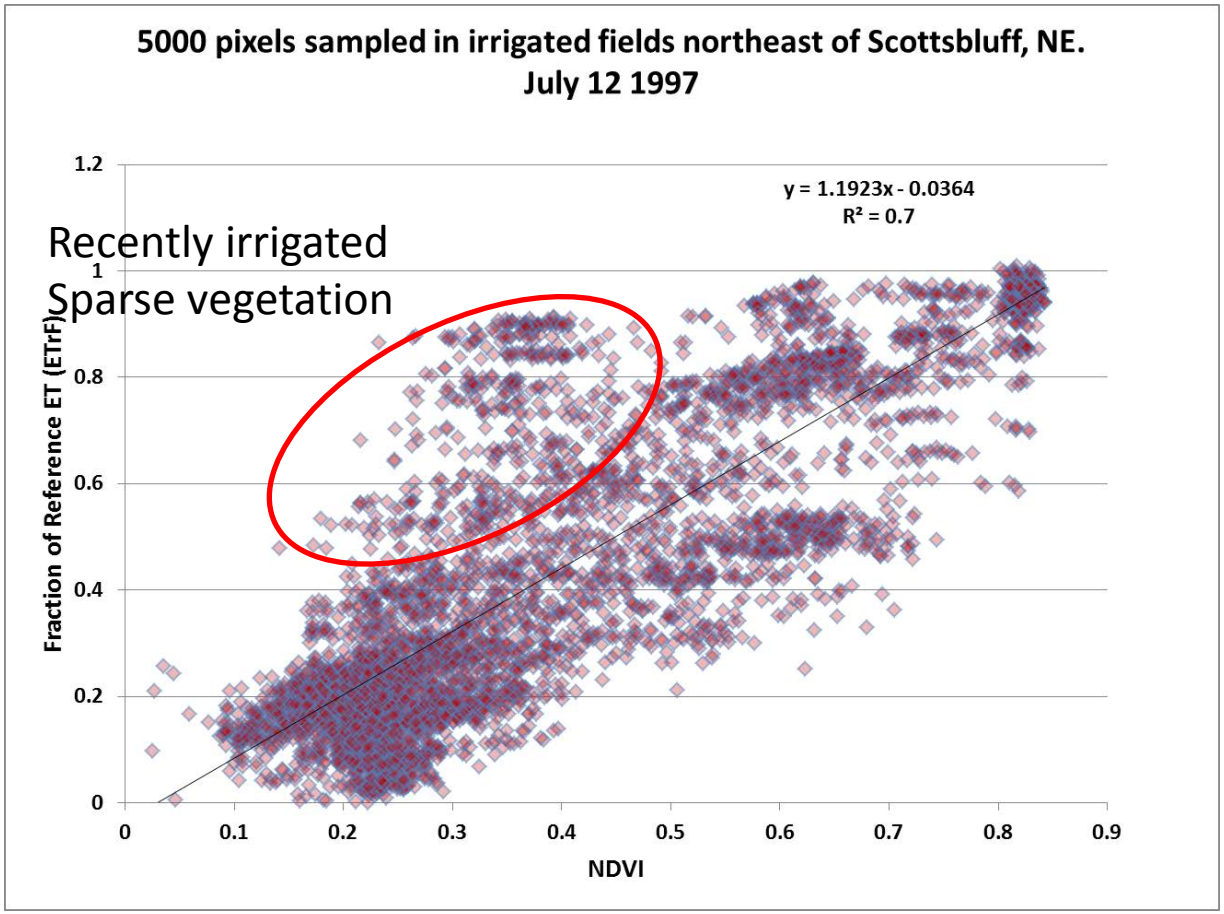
Relation between ET and NDVI

Is ET related to NDVI?

- Dense vegetation should equal high ET

For relatively simple, uniform cropping systems in a small area, NDVI and ET may be tightly related.

Most cropping systems are diverse and complicated (crop, irrigation, rain, difference in field management), and NDVI may be poorer related to ET.



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