# Evapotranspiration Estimation Incorporating FAO56 Methodology

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University of Idaho

# Discussion Points

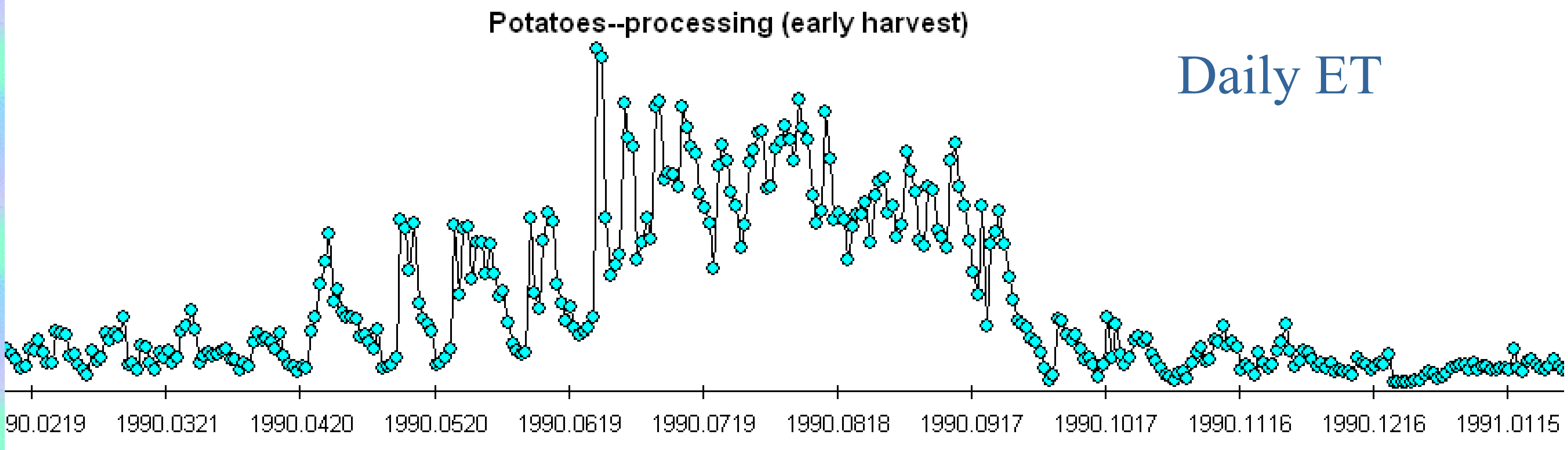
- Brief Review of the Crop Coefficient – Reference ET approach of FAO56
- Current Implementations
- Recent Applications

# Evapotranspiration (ET) varies widely with

- **Time of Year**
- **From Day to Day**

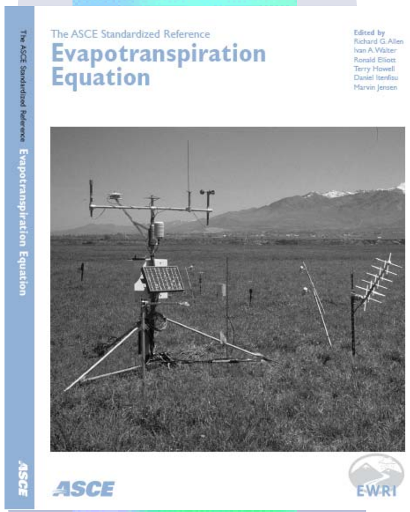
## Therefore, rigorous Equations and Models are needed

Ashton, Idaho, USA 1990 calendar year -- Potatoes



# Reference ET

# FAO56 Reference ET:
# A Living Evaporation Index





**full Penman-Monteith**

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

***50 s m$^{-1}$* (daytime hourly)**

***70 s m$^{-1}$* (24-hr) for grass**

**Standardized FAO56/ASCE Penman-Monteith**

$$ET_{ref} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

$C_n$ and $C_d$ are constants

f (Solar Radiation)

f (Temperature)

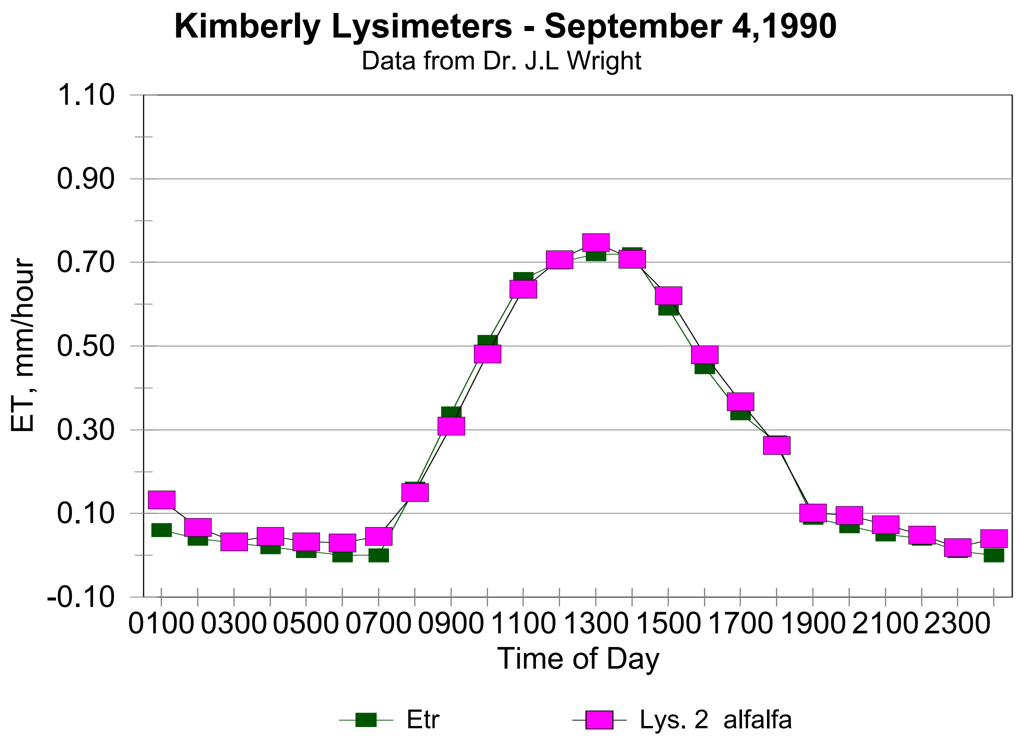
Wind Speed

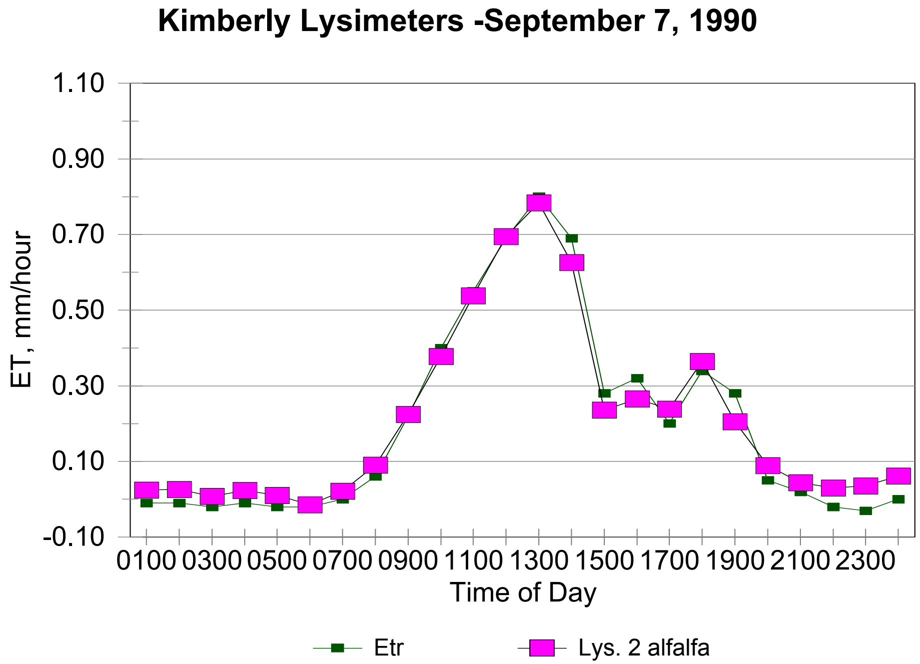
f (Humidity)

*ASCE PM can be applied to clipped grass and to 0.5 m tall alfalfa*

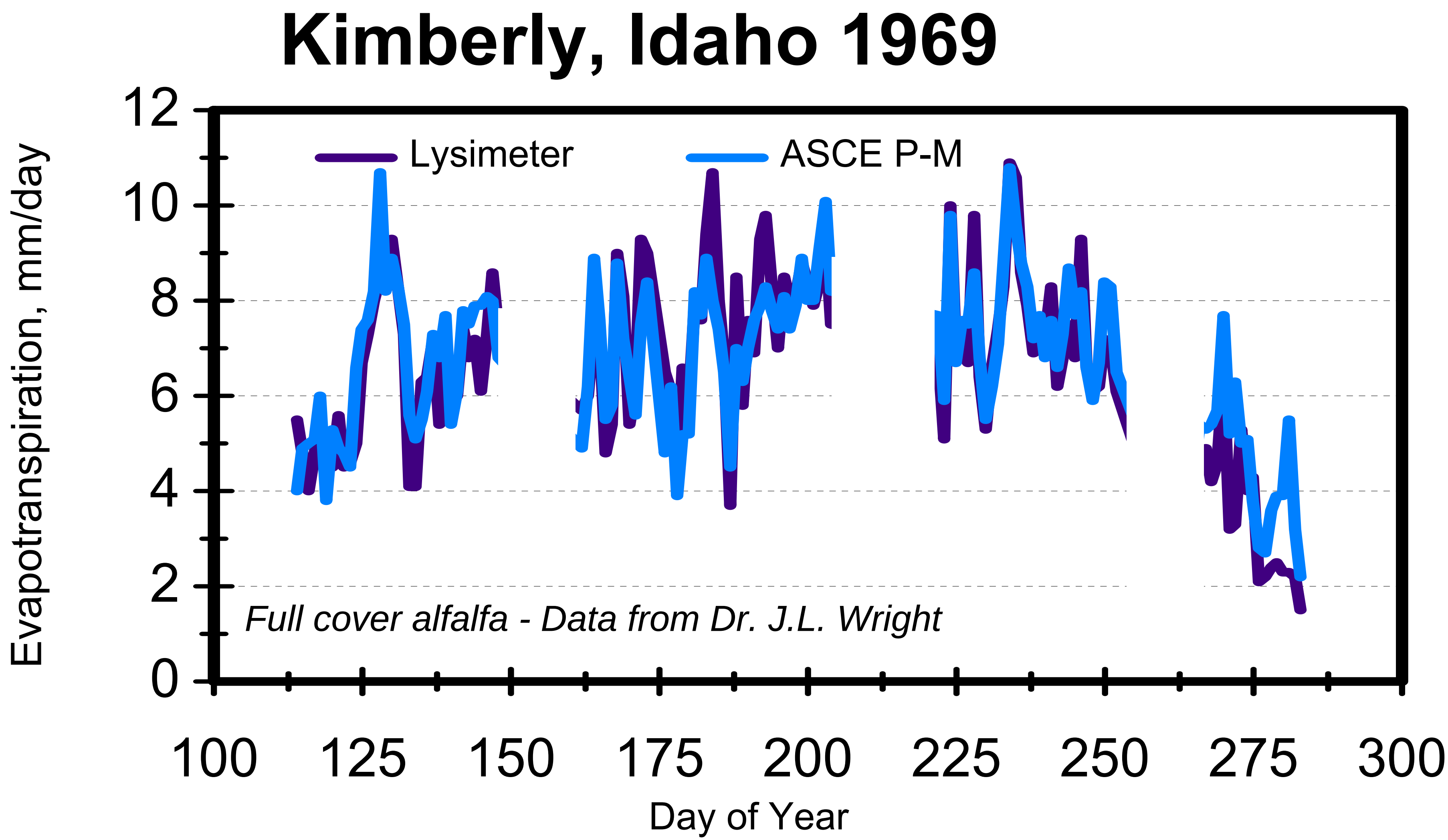

FAO and ASCE Penman-Monteith are traceable to the Davis, California and Kimberly, Idaho (USDA) Lysimeters

# ASCE Standardized Penman-Monteith (alfalfa reference) at Kimberly, Idaho - hourly time step



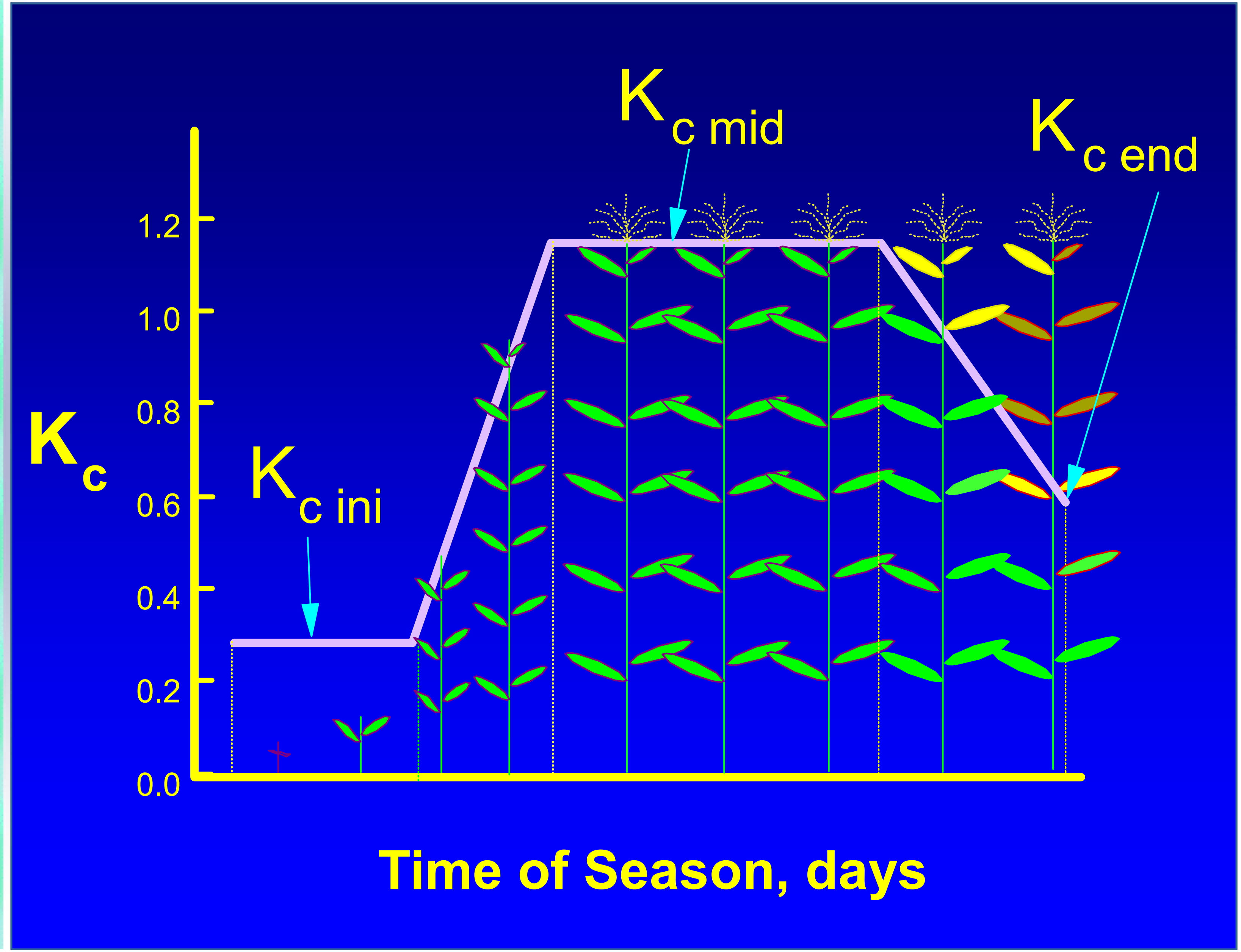
# Good day-to-day correspondance with lysimeter



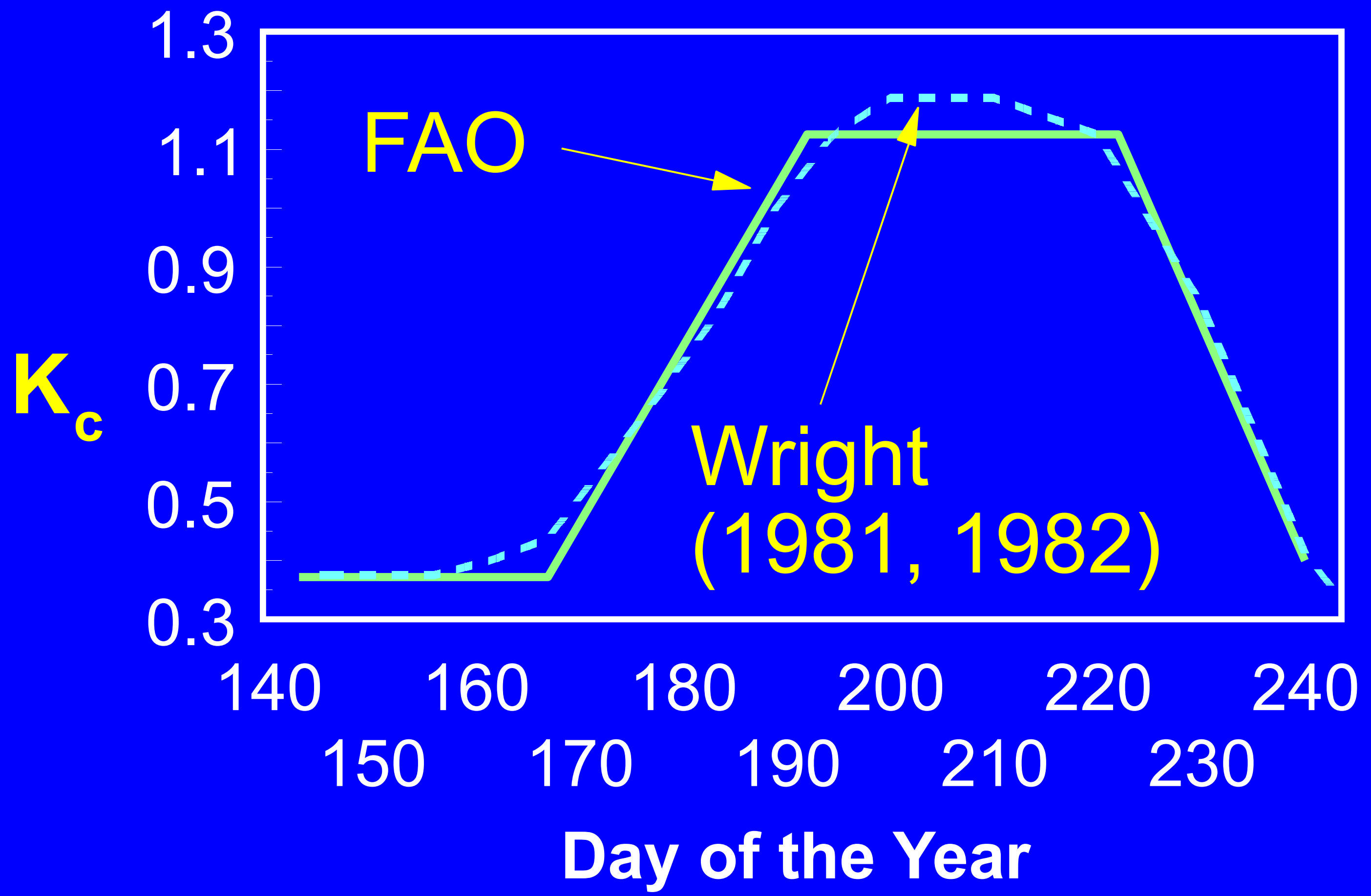

Daily Timestep

# Crop Coefficients

# Crop Coefficient = $ET/ET_{ref}$



# Crop Coefficient Curve Types



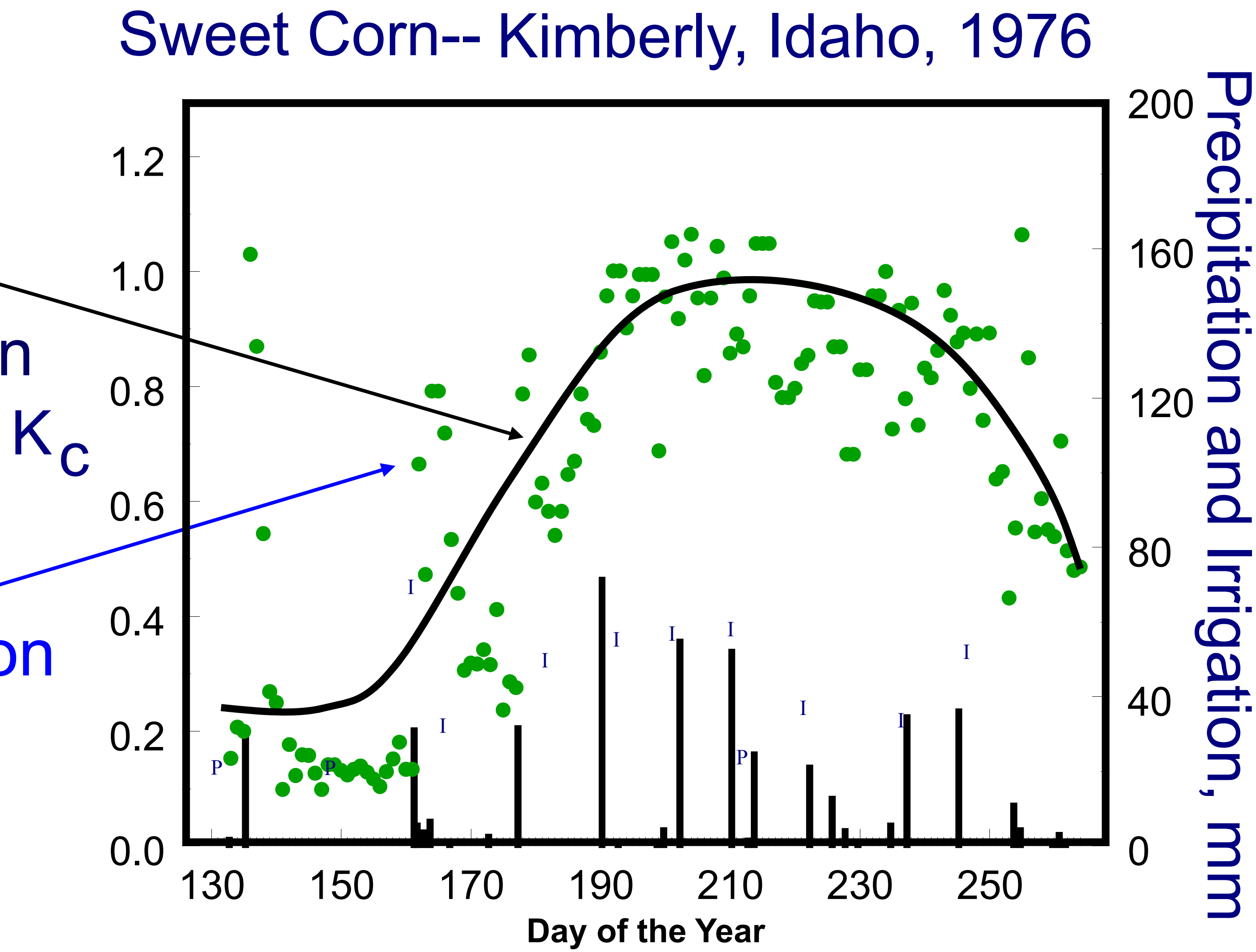
# Single or Dual $K_c$ ???

# $K_c$ measured by Lysimeter

*each dot is one day*

"Single" Curve averaging evaporation "Spikes"

Wet Soil Evaporation "Spikes" ($K_e$)




*data courtesy of Dr. J.L. Wright, USDA-ARS*

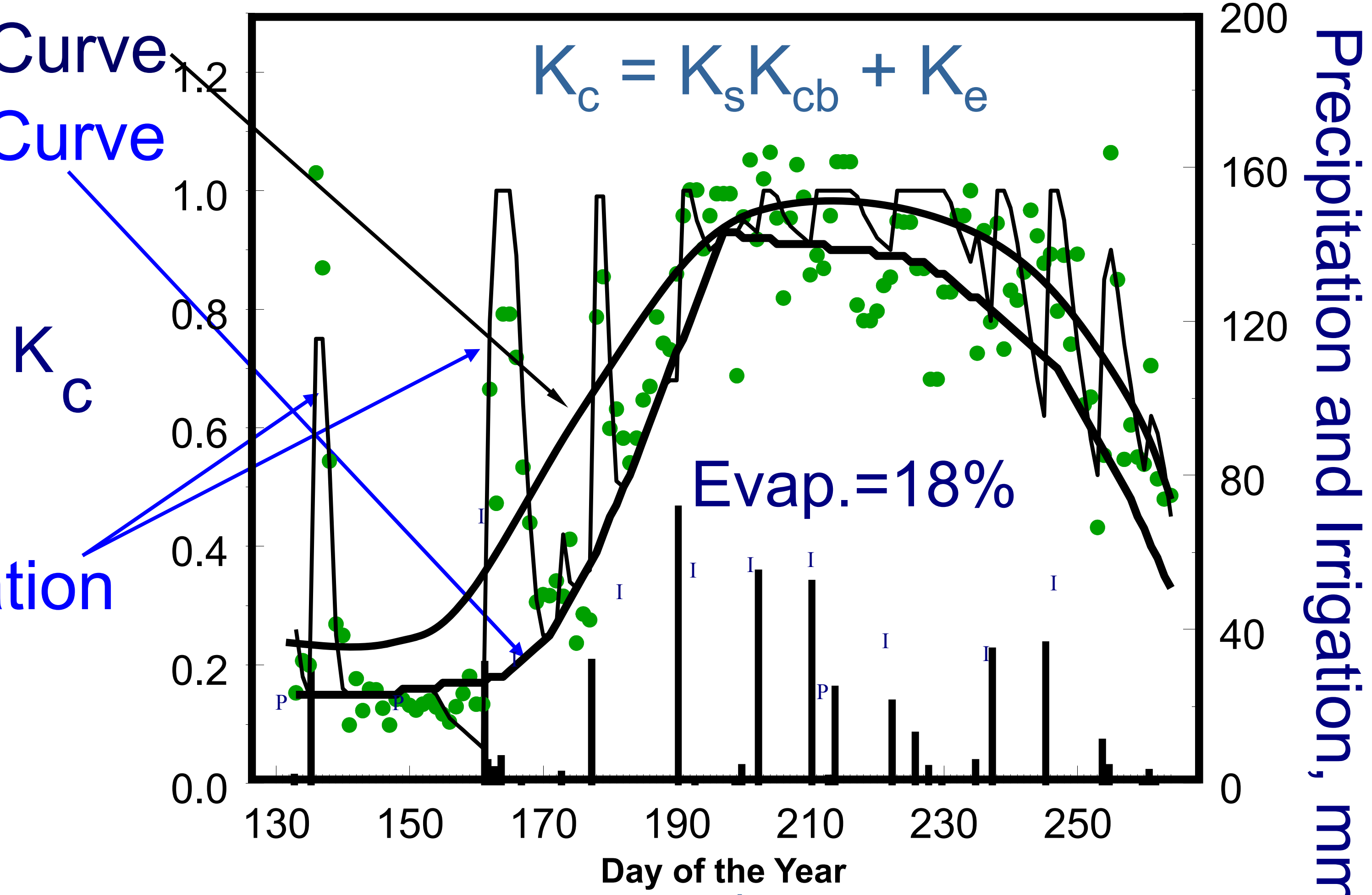
# The “Dual $K_c$” method Splits Soil Evaporation from Transpiration

Sweet Corn Kimberly, Idaho, 1976

“Mean” $K_c$ Curve

Basal $K_c$ Curve ($K_{cb}$)

Wet Soil Evaporation “Spikes” ($K_e$)




data courtesy of Dr. J.L. Wright, USDA-ARS

# 'Dual' $K_c$ Procedure

$$\frac{ET}{ET_{ref}} =$$

$$K_c = K_s K_{cb} + K_e$$

$K_s$ = water stress (0 - 1)

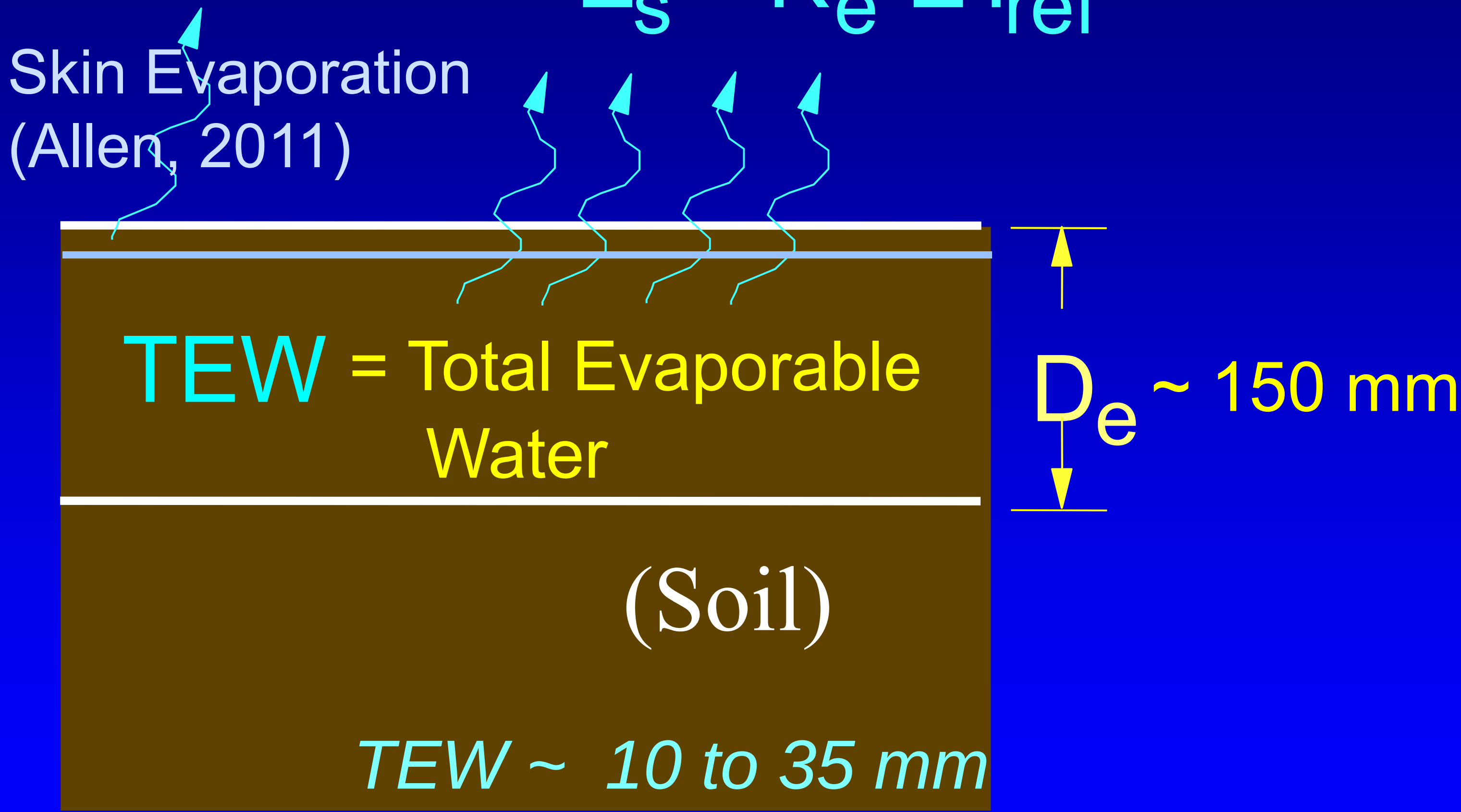
$K_{cb}$ = basal $K_c$ *(dry surface)*

$K_e$ = evaporation coefficient

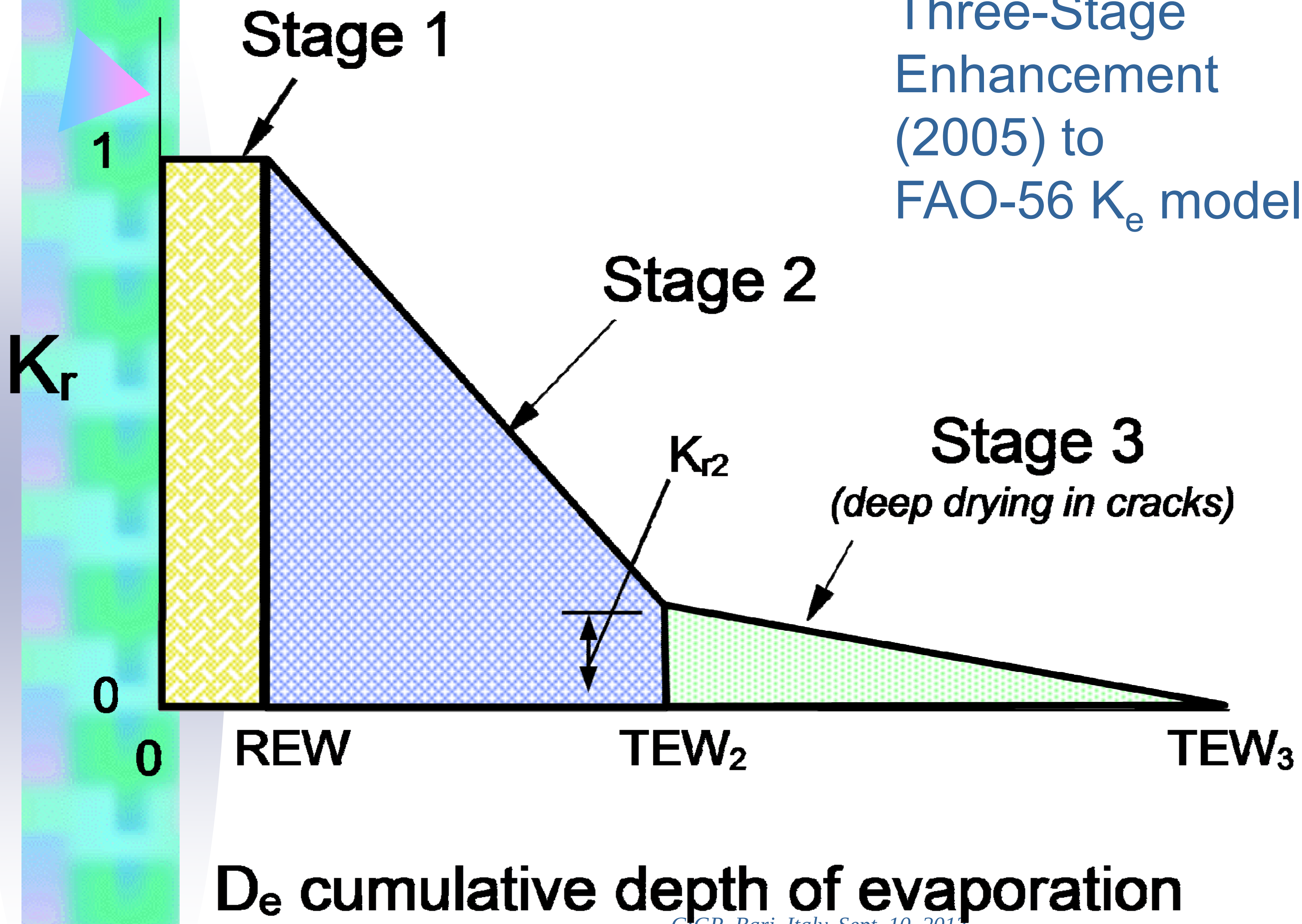
# Evaporation Coefficient - $K_e$

## FAO-56 Simple Drying Function

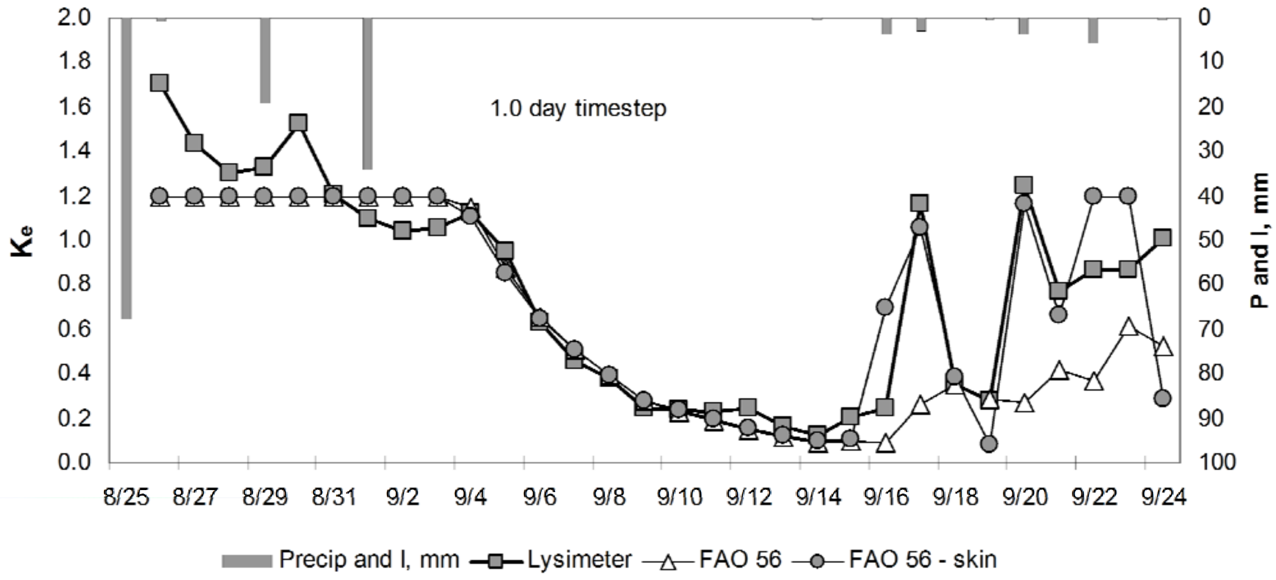
$$E_s = K_e \, ET_{ref}$$

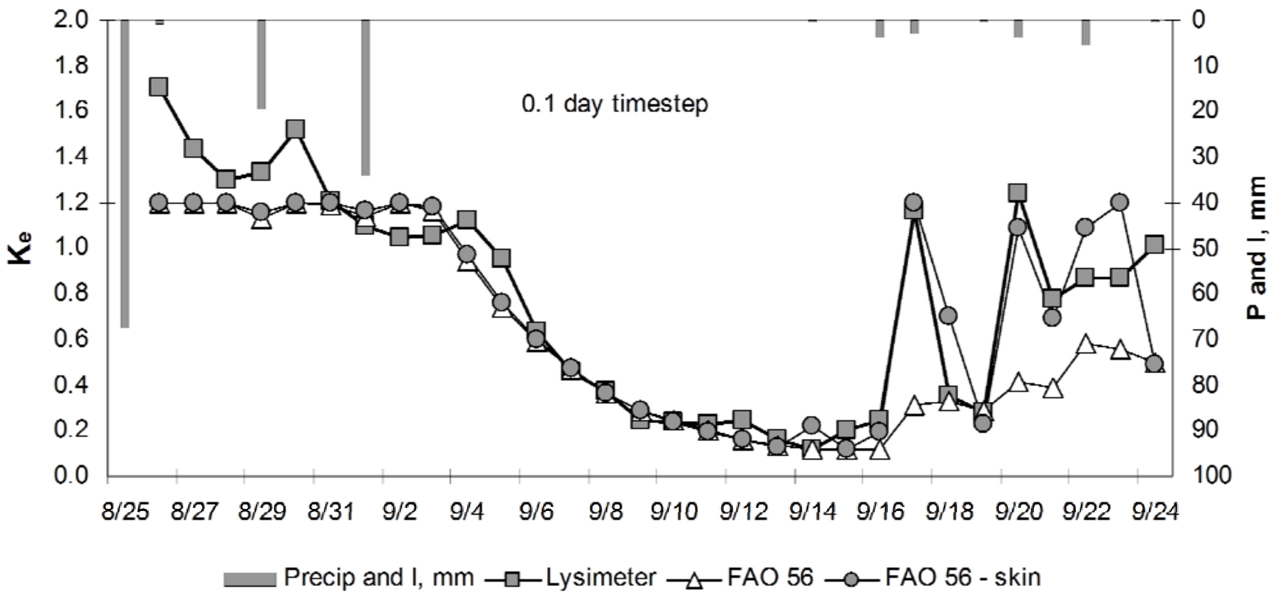


# Three-Stage Enhancement (2005) to FAO-56 $K_e$ model



# Skin Evaporation Enhancement (2011) to FAO-56 $K_e$ model




FAO-56 $K_e$ model vs. Kimberly Lysimeter

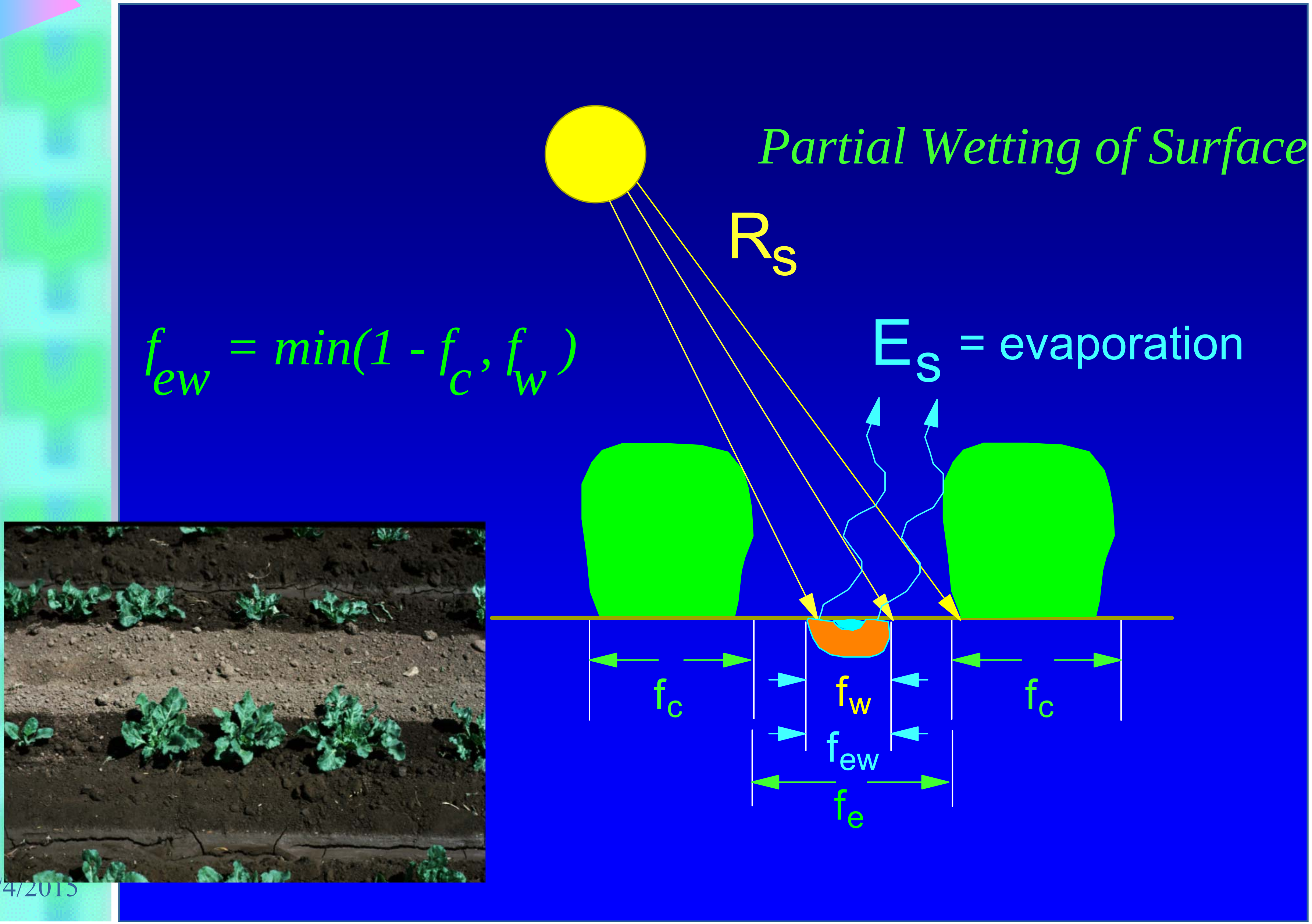
– Bare Soil

Conclusion: Skin Enhancement is Important for Precip. Events < 10 mm. Model can be applied on daily or hourly timestep

# Why Apply the Dual $K_c$ method for estimating water depletion?

- Advantages
  - $K_c$ value varies with wetting frequency
  - $K_c$ estimates can be made during wintertime when process is only evaporation from soil

# Partial Surface Wetting/Drying



# Some Example Applications of the FAO-56 Dual Kc Method in the United States

# Comparison of Aggregated Estimates against ET from Irrigation Scheme-wide Water Balance

# Imperial Irrigation District: Aggregated FAO-56 vs. ET by Water Balance ~ 200,000 irrigated ha

# Water Balance of the Imperial Project

**ET = Inflow - Surface Outflow**

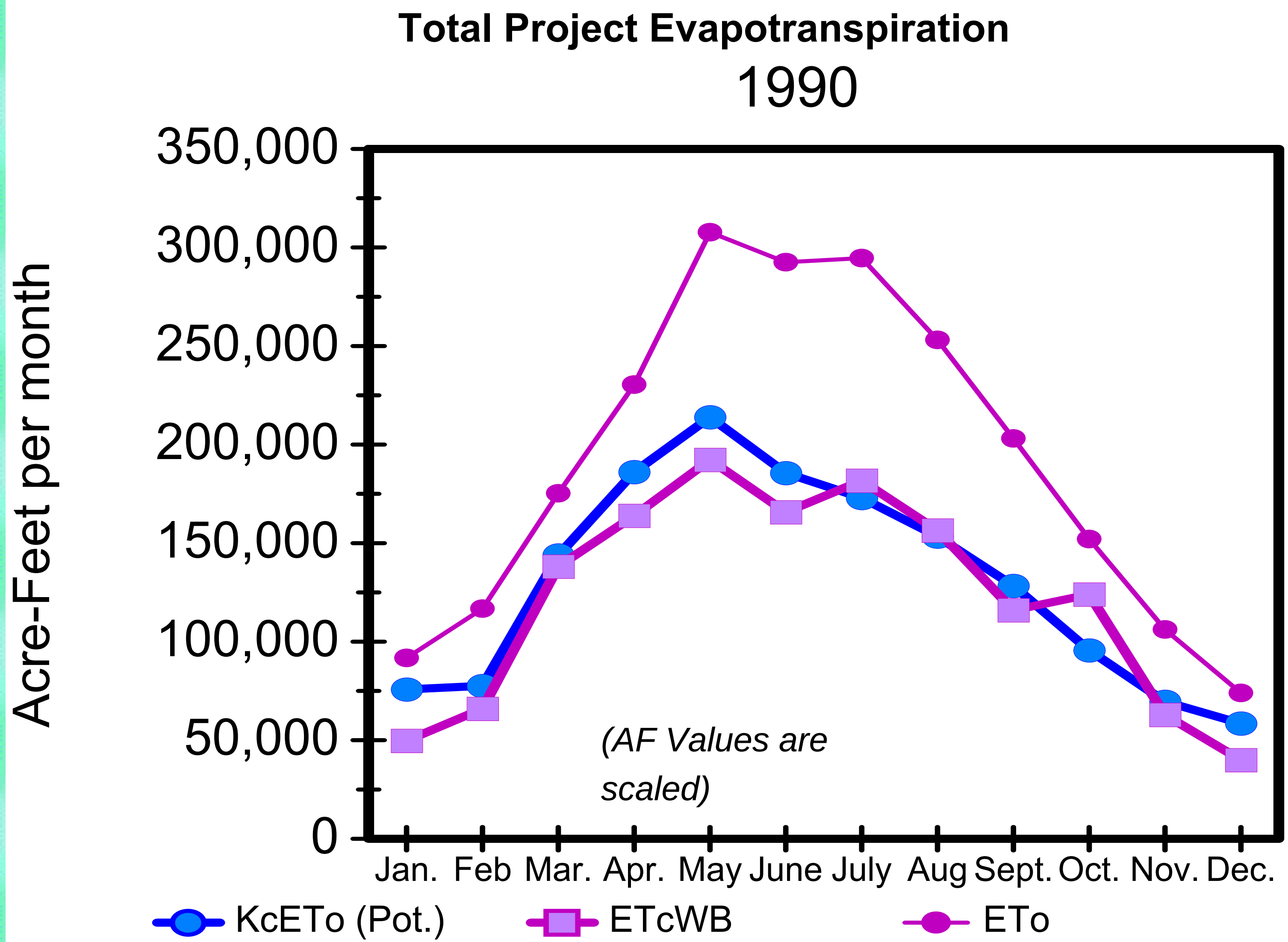
**+ Precipitation**

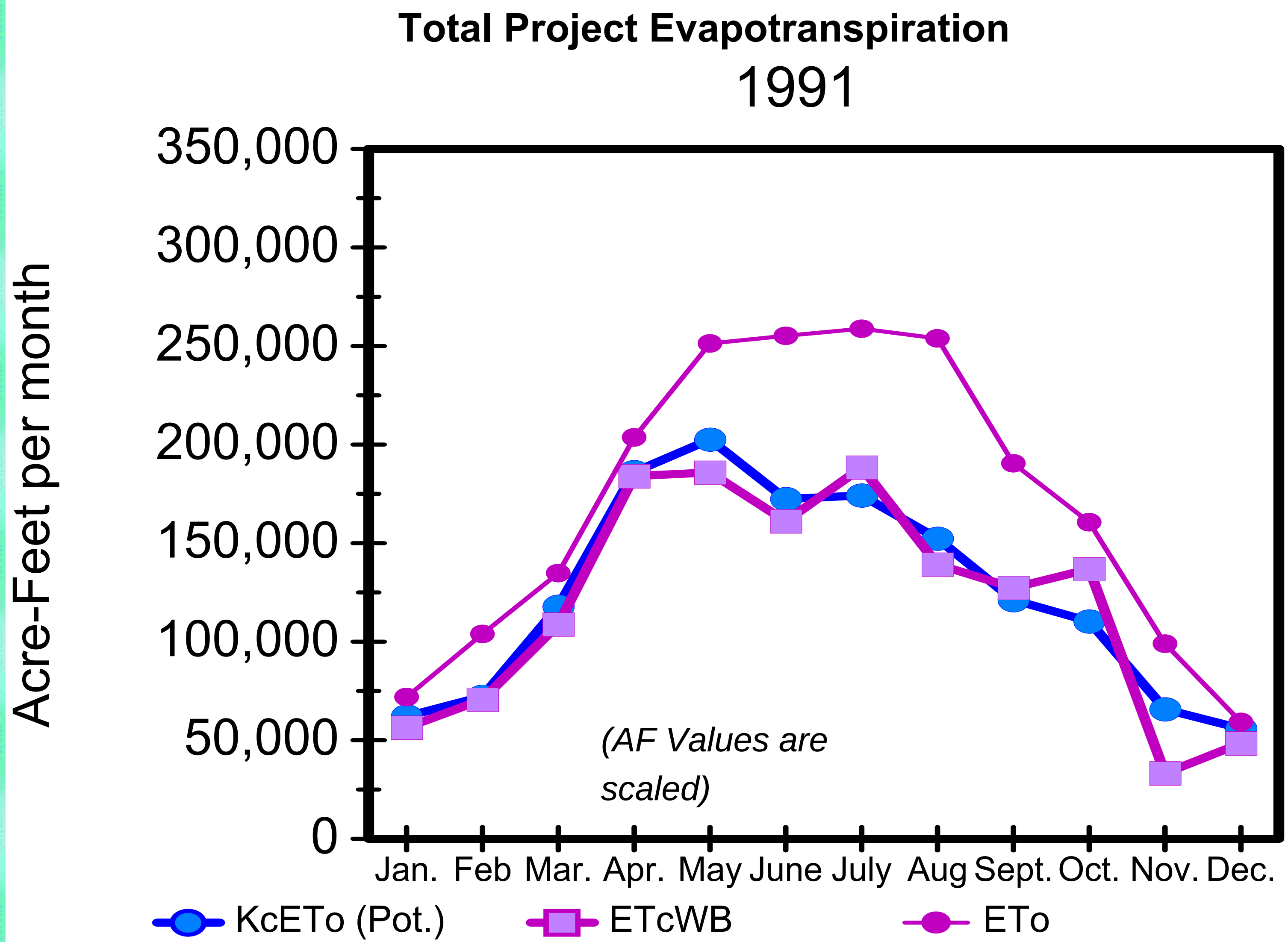
**- Δ Soil Water**

**- Deep Percolation**

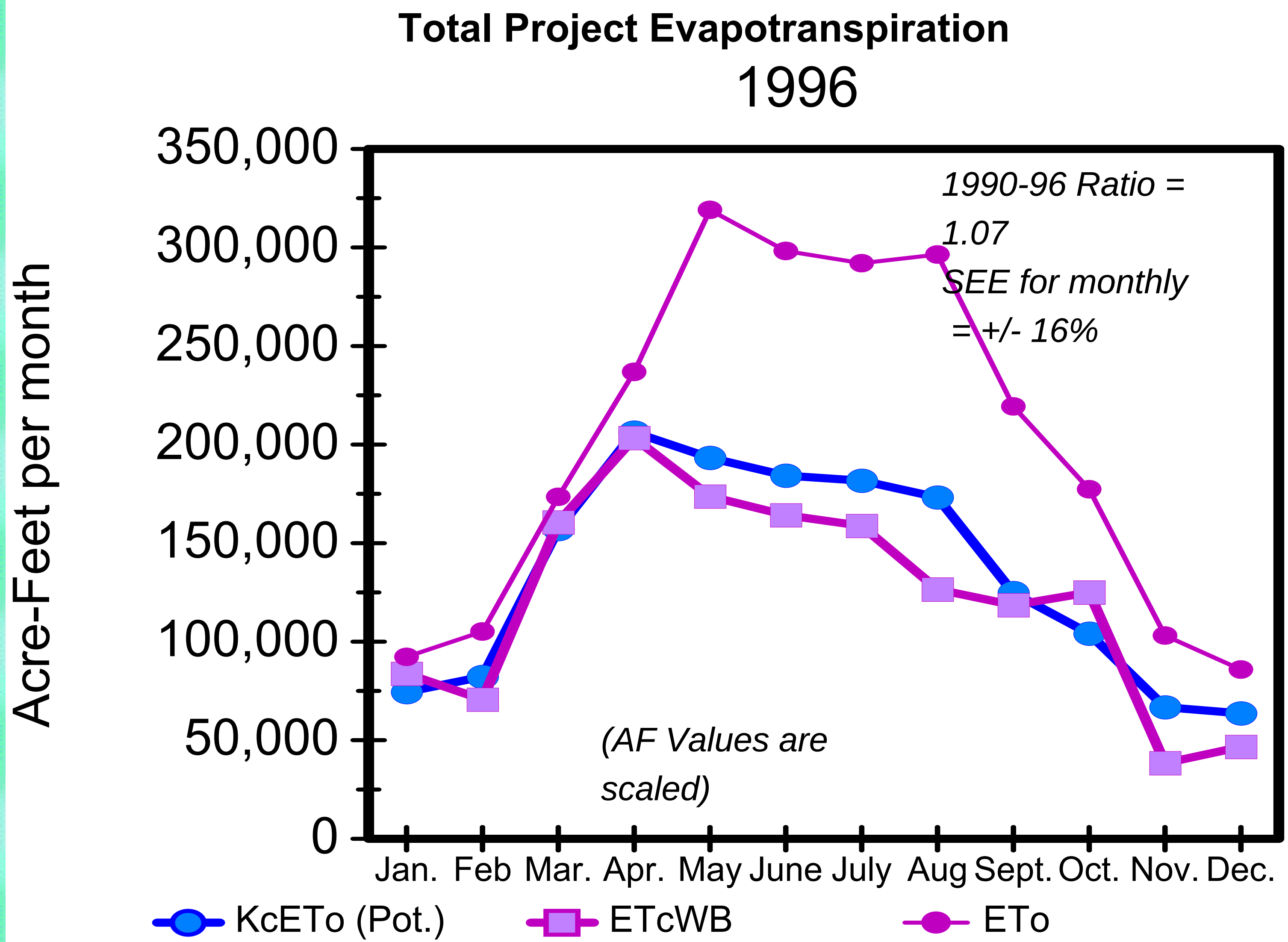
- **accuracy of annual ET from the Imperial Valley water balance is +/- 5% (95% C.I.)**

-- Used FAO-56 Grass Reference ETo and Linear $K_{cb}$ + $K_e$





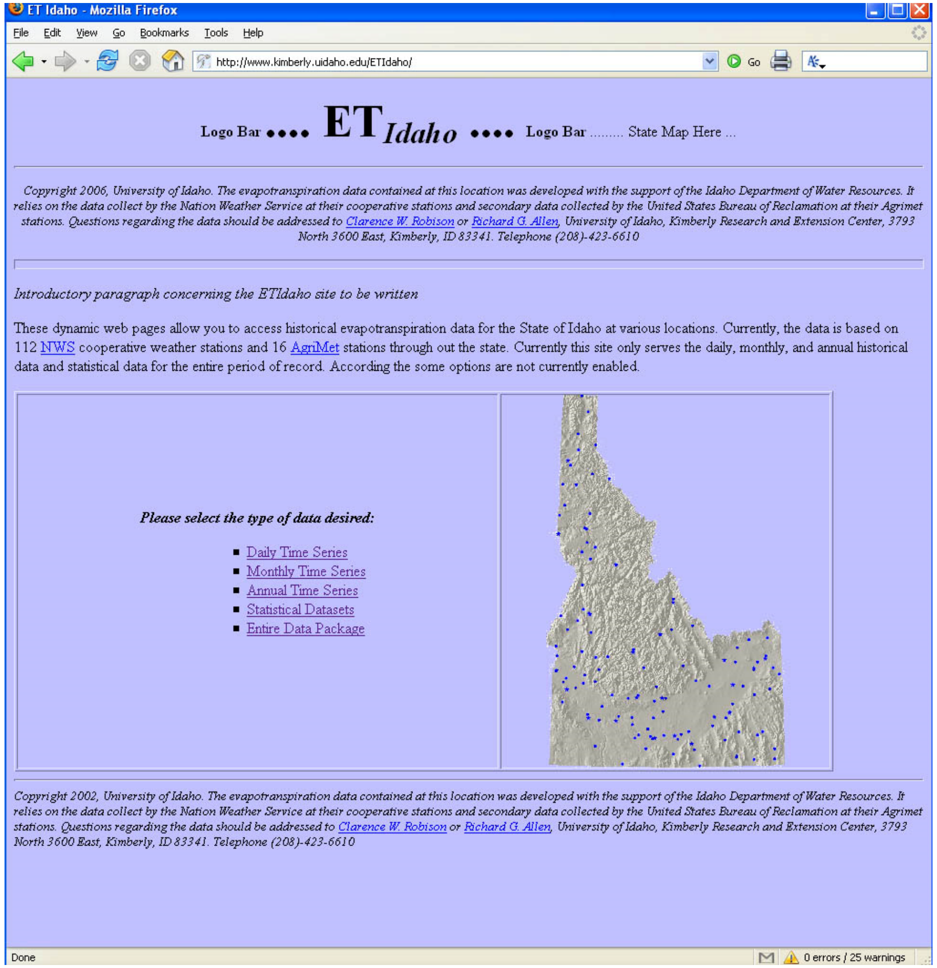
Total Project Evapotranspiration
1991
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
(AF Values are scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo


Total Project Evapotranspiration
1996
Acre-Feet per month
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
1990-96 Ratio =
1.07
SEE for monthly
= +/- 16%
(AF Values are
scaled)
Jan.
Feb
Mar.
Apr.
May
June
July
Aug
Sept.
Oct.
Nov.
Dec.
KcETo (Pot.)
ETcWB
ETo

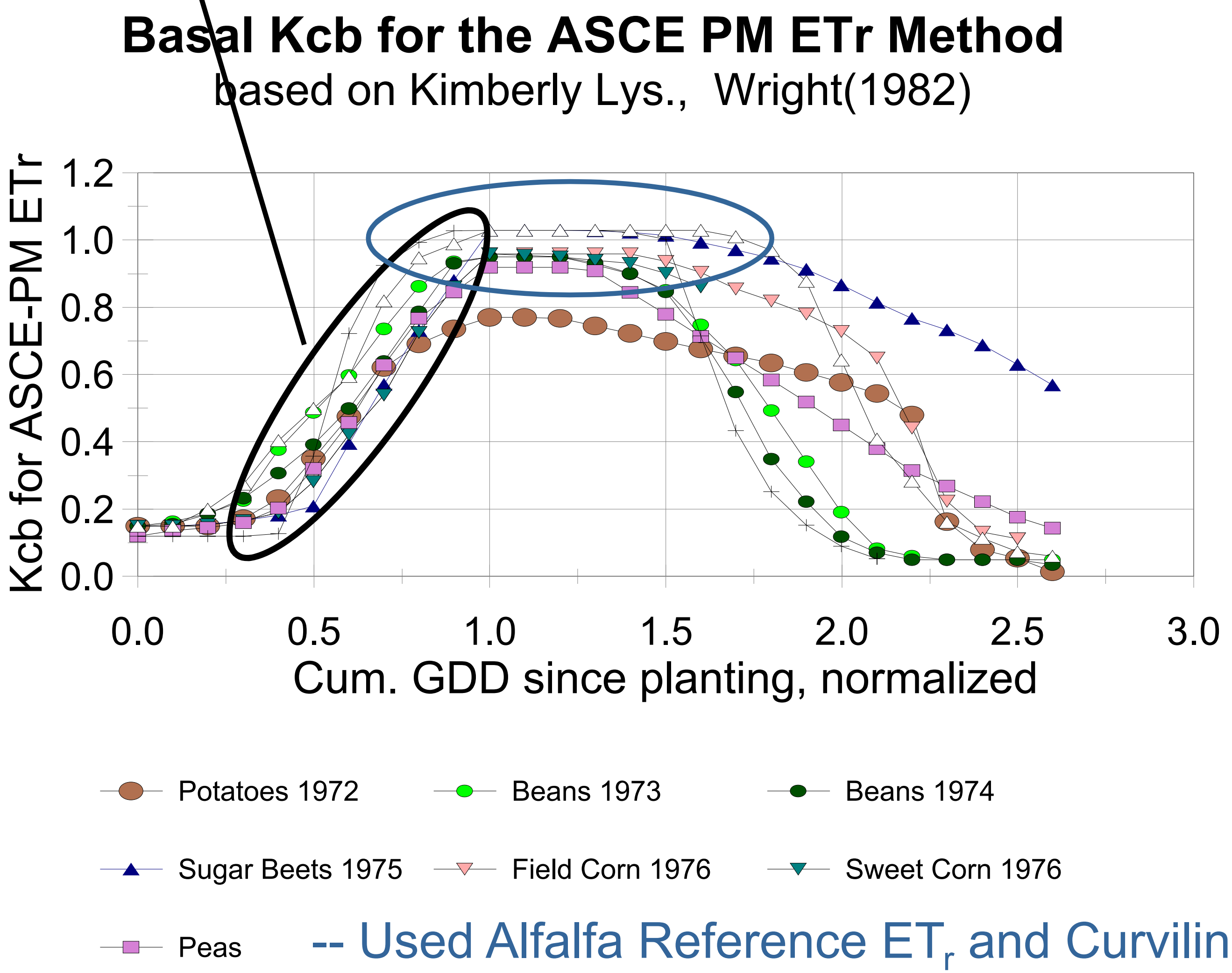
# ET-Idaho – ET and Irrigation Water Requirements for the State of Idaho -- FAO-56 Dual $K_c$ Basis

Operated 365 days/year

120 locations

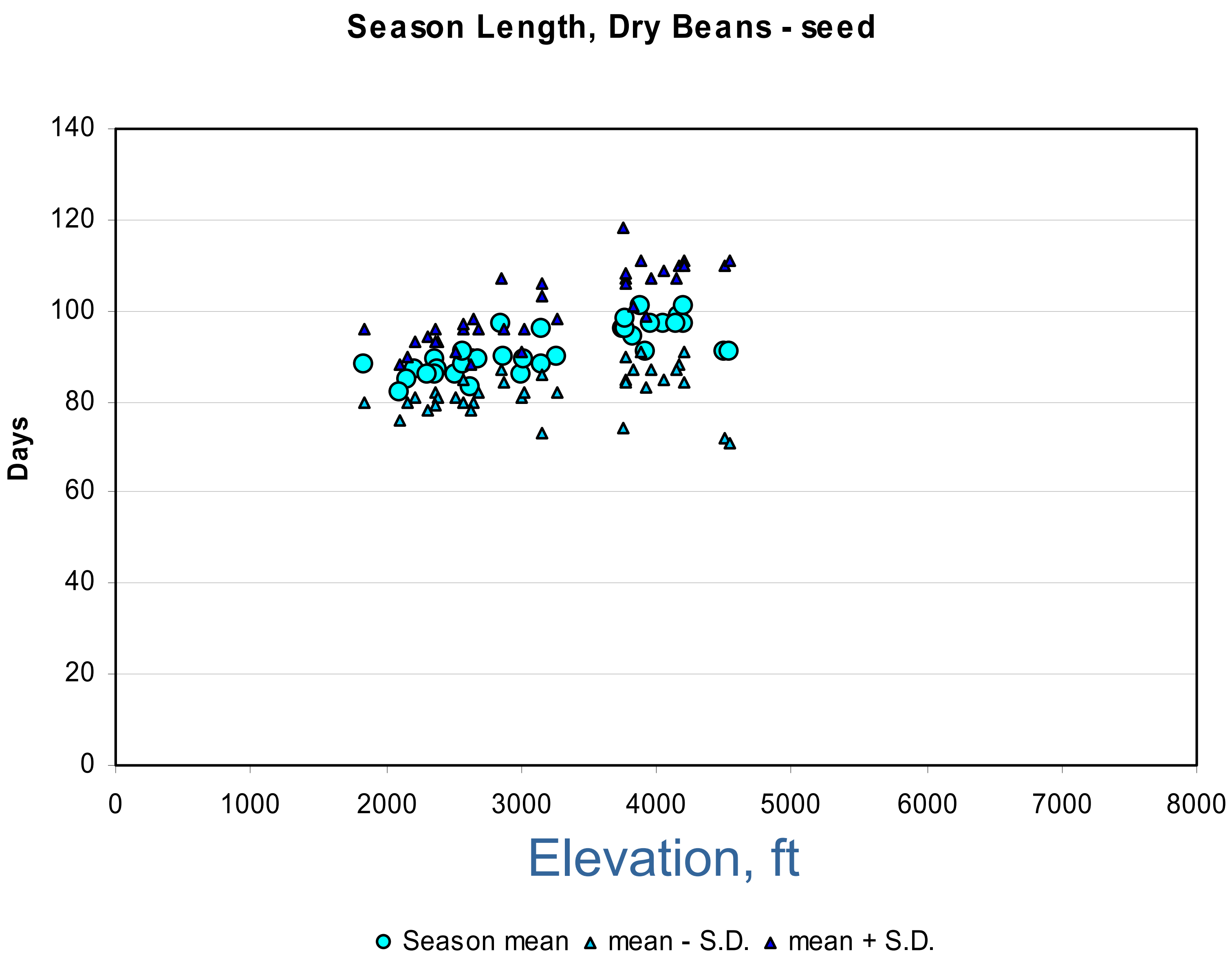


# Cumulative Growing Degree Days used to Estimate Kc Development. Using CGDD creates some similarity in the $K_{cb}$ shape

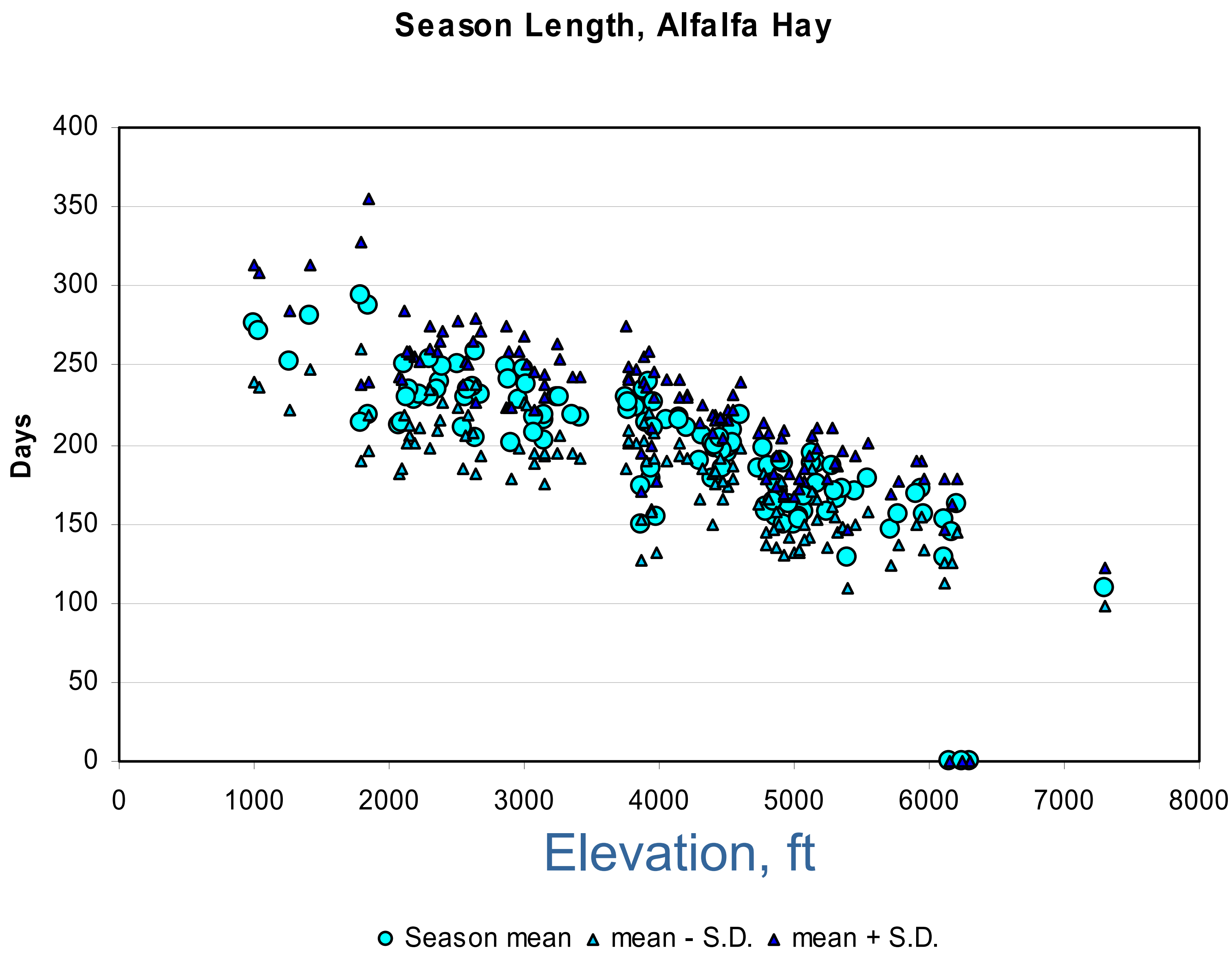



-- Used Alfalfa Reference $ET_r$ and Curvilinear $K_{cb} + K_e$

# Defined **Dry Bean** Season Lengths vs. Elevation Thermal-estimated Start and Thermal-estimated End

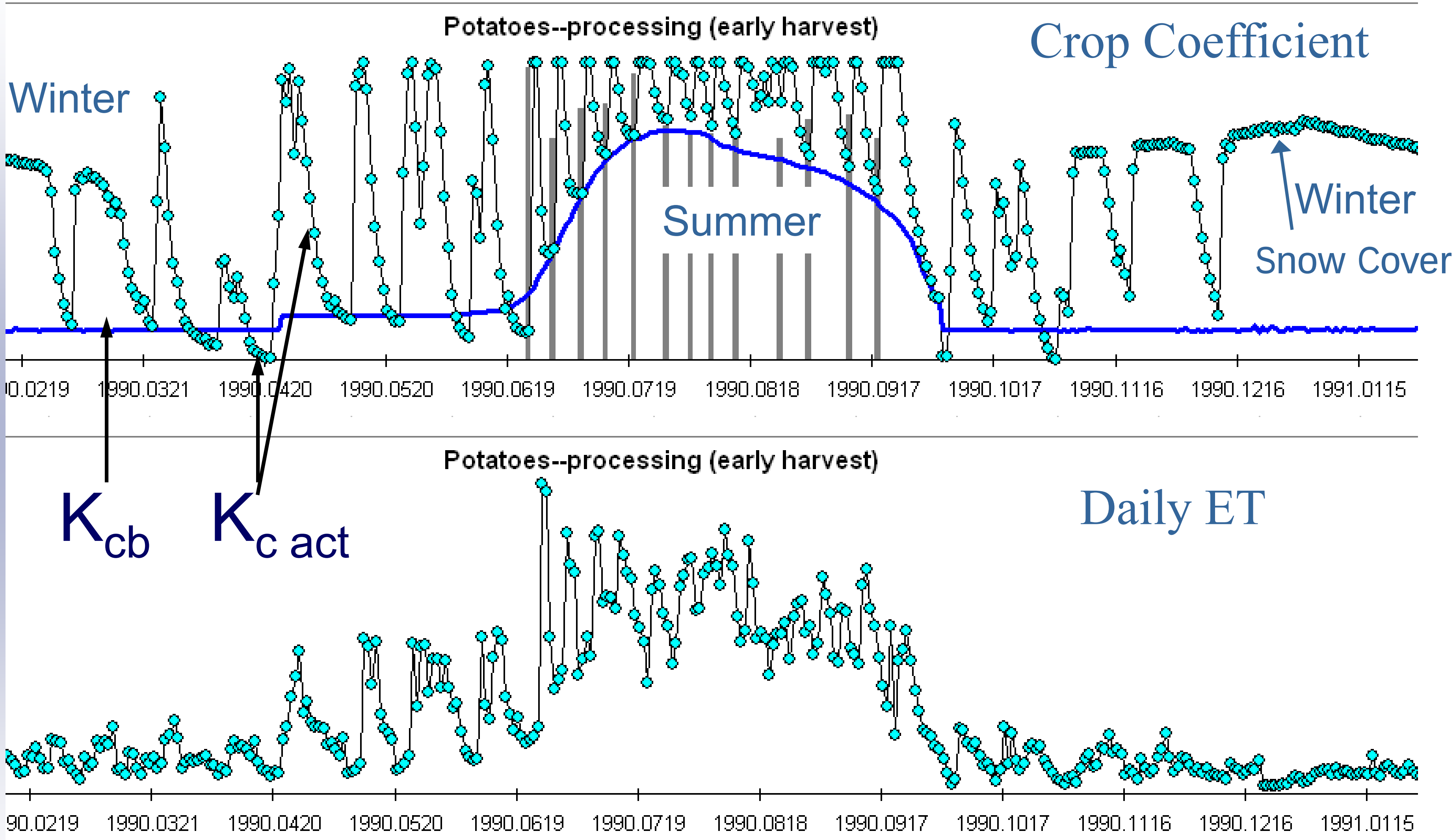


# **Alfalfa** Season Lengths vs. Elevation across Idaho Thermal-estimated Start and Frost Ended



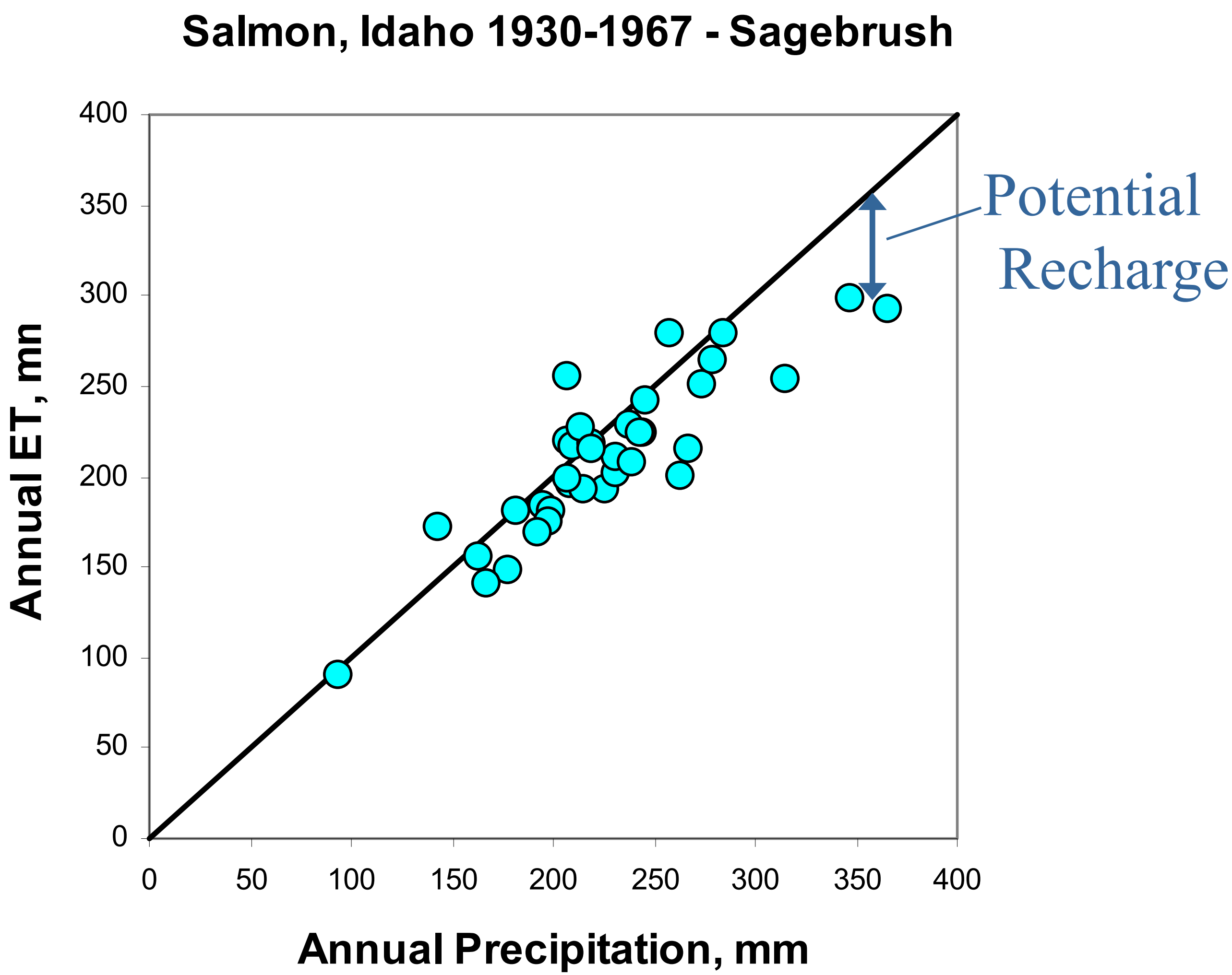
# Operated 365 days/year

## Ashton, 1990 calendar year -- Potatoes



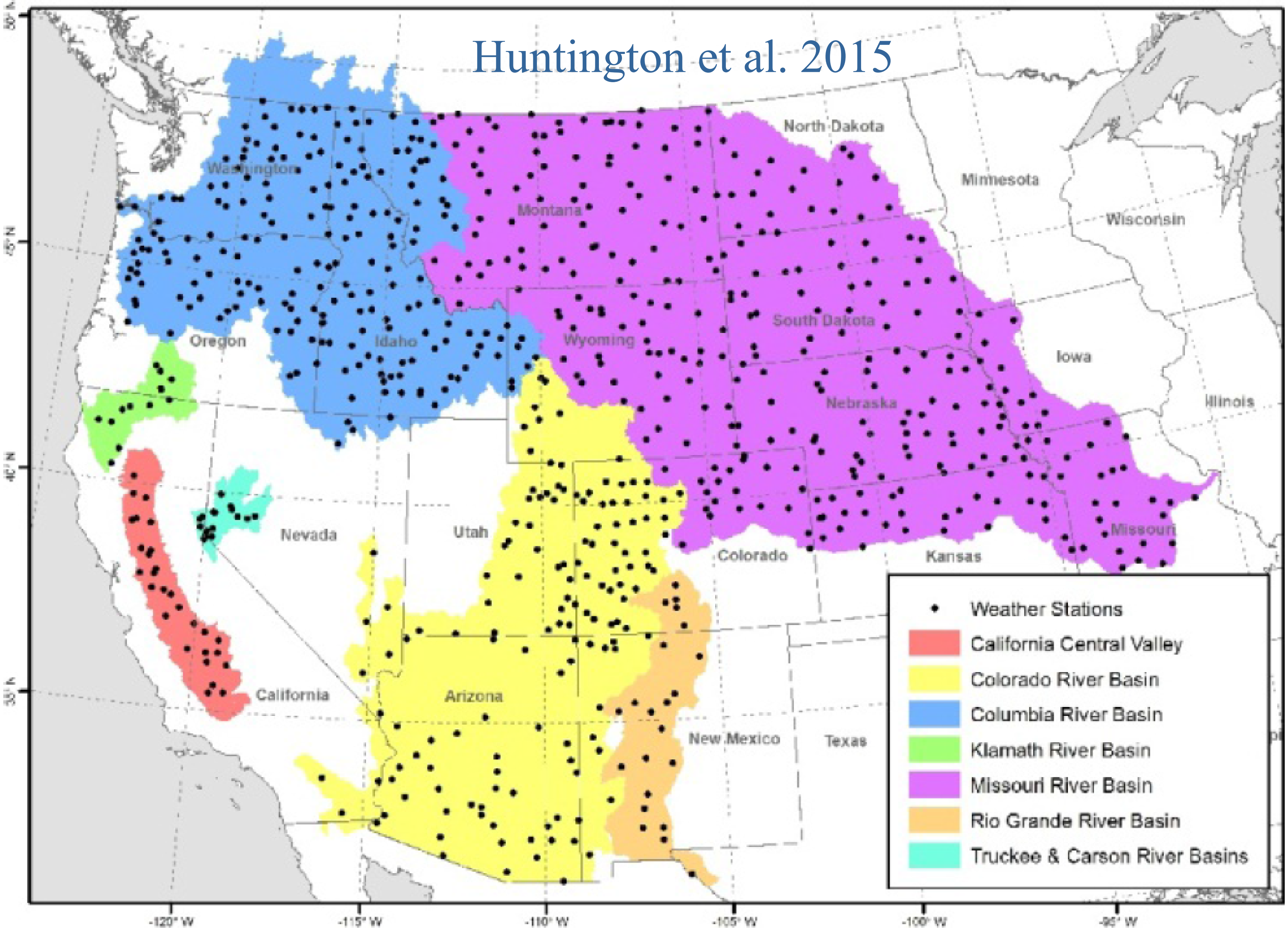

$$K_{c\ act} = \left(K_s\ K_{cb} + K_e\right)\ \left(and\quad ET_{c\ act} = K_{c\ act}\quad ET_r\ \right)$$

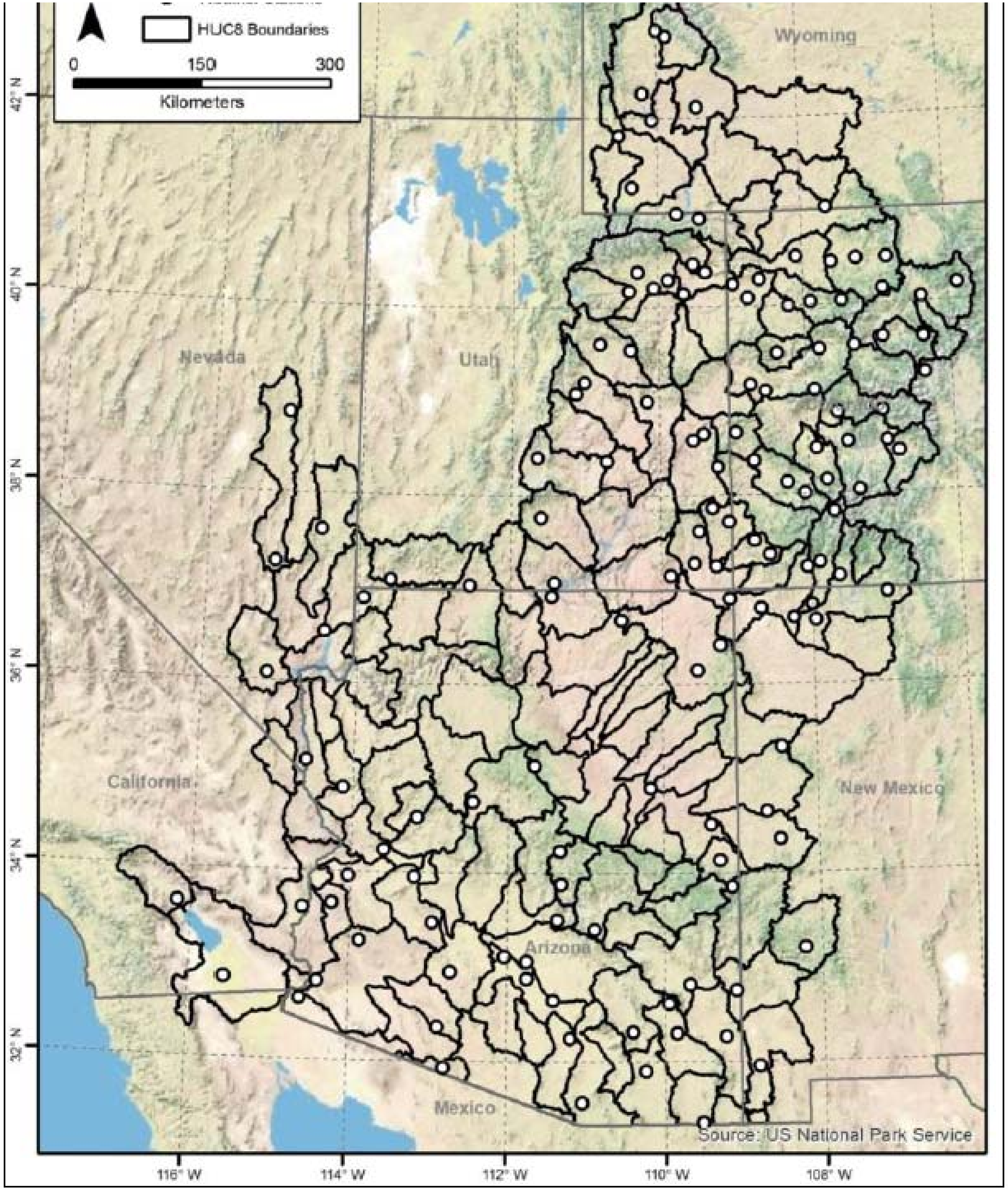
# Annual ET vs. Precipitation - Desert



# Projection of Impacts of Climate Change on ET and Net Irrigation Water Requirements

# West-Wide Climate Risk Assessment – Seven Major River Basins – US Bureau of Reclamation, DRI, UI



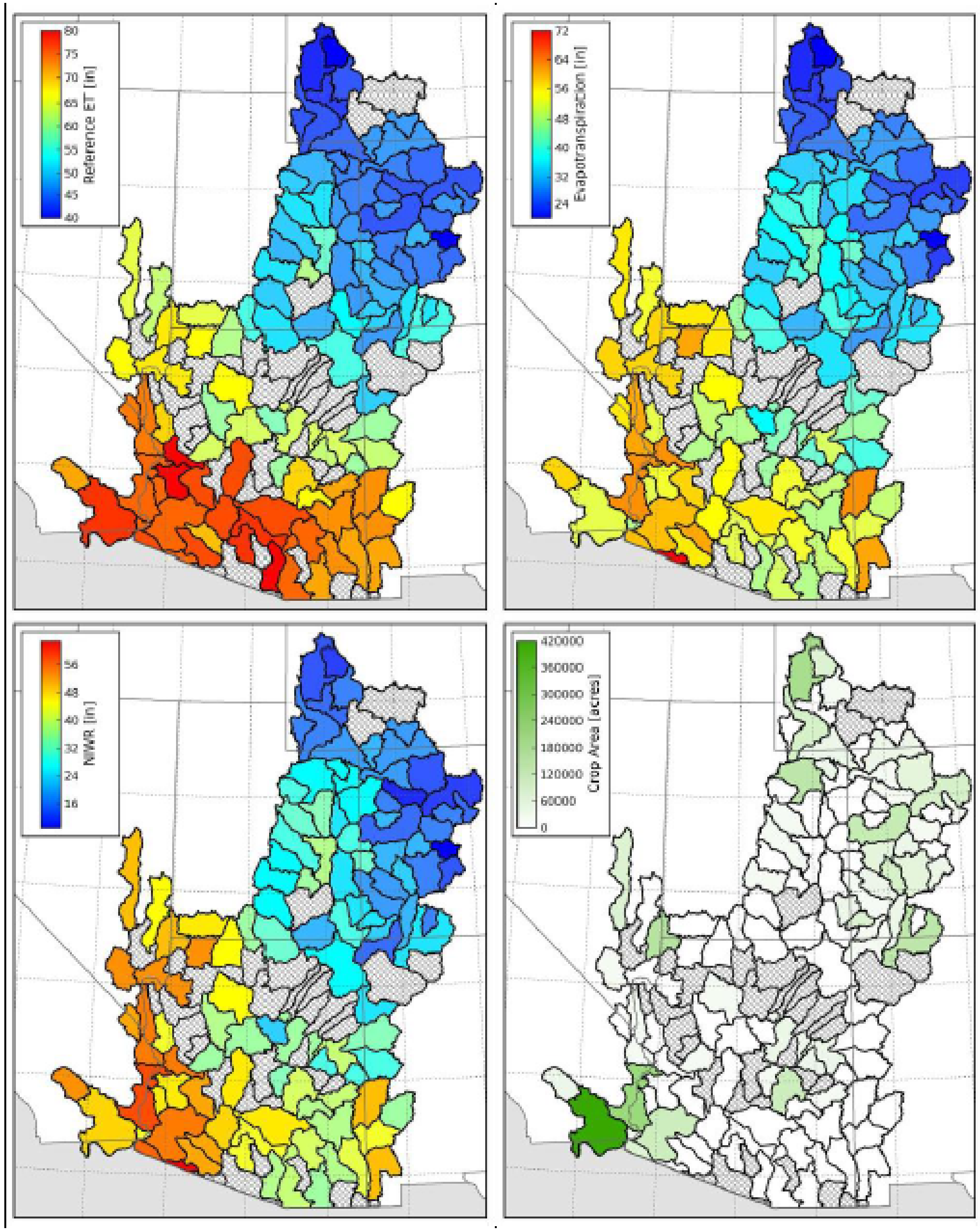



# Colorado River Basin

$ET_{ref}$

$ET_{crop}$

Baseline Values in the Basin




Net Irrigation Water Requirement (NIWR)

Distribution of Irrigation

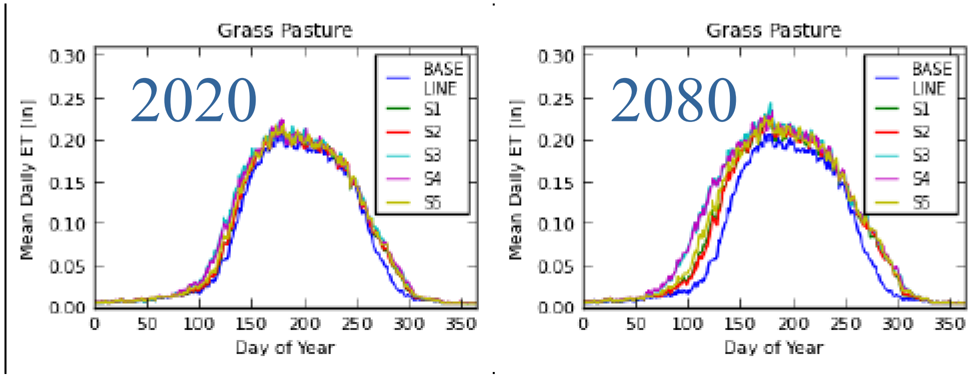



**Figure 20.—Colorado River Basin – COOP station WY6555 (Mountain View, WY). Baseline and projected mean daily grass pasture evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right).**

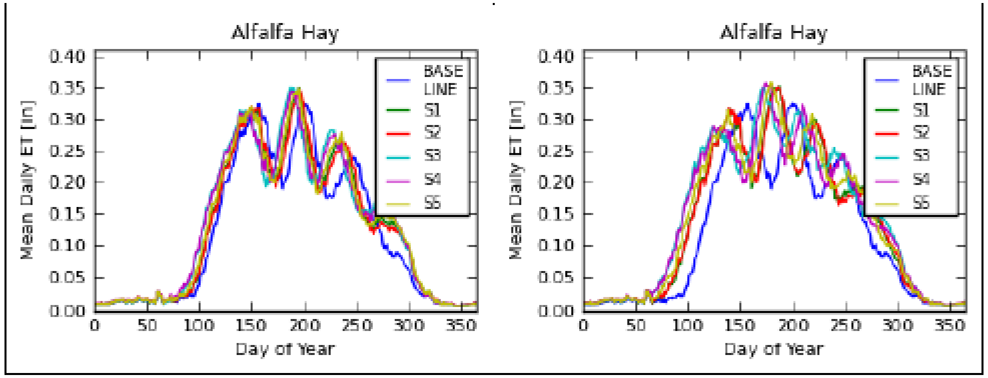
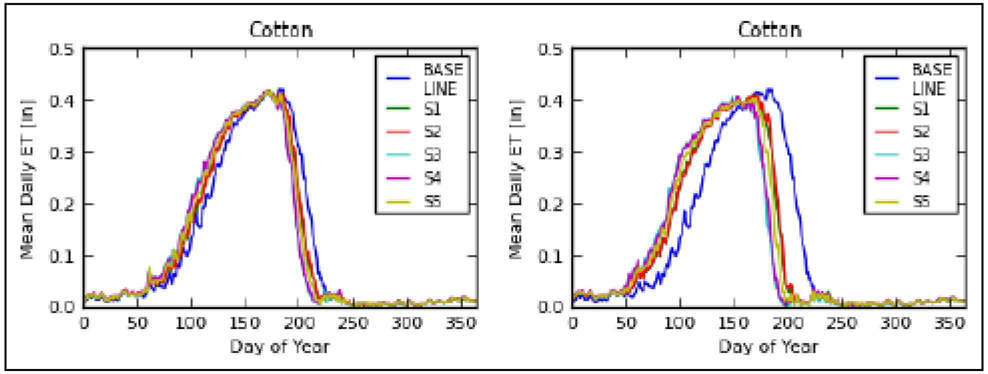


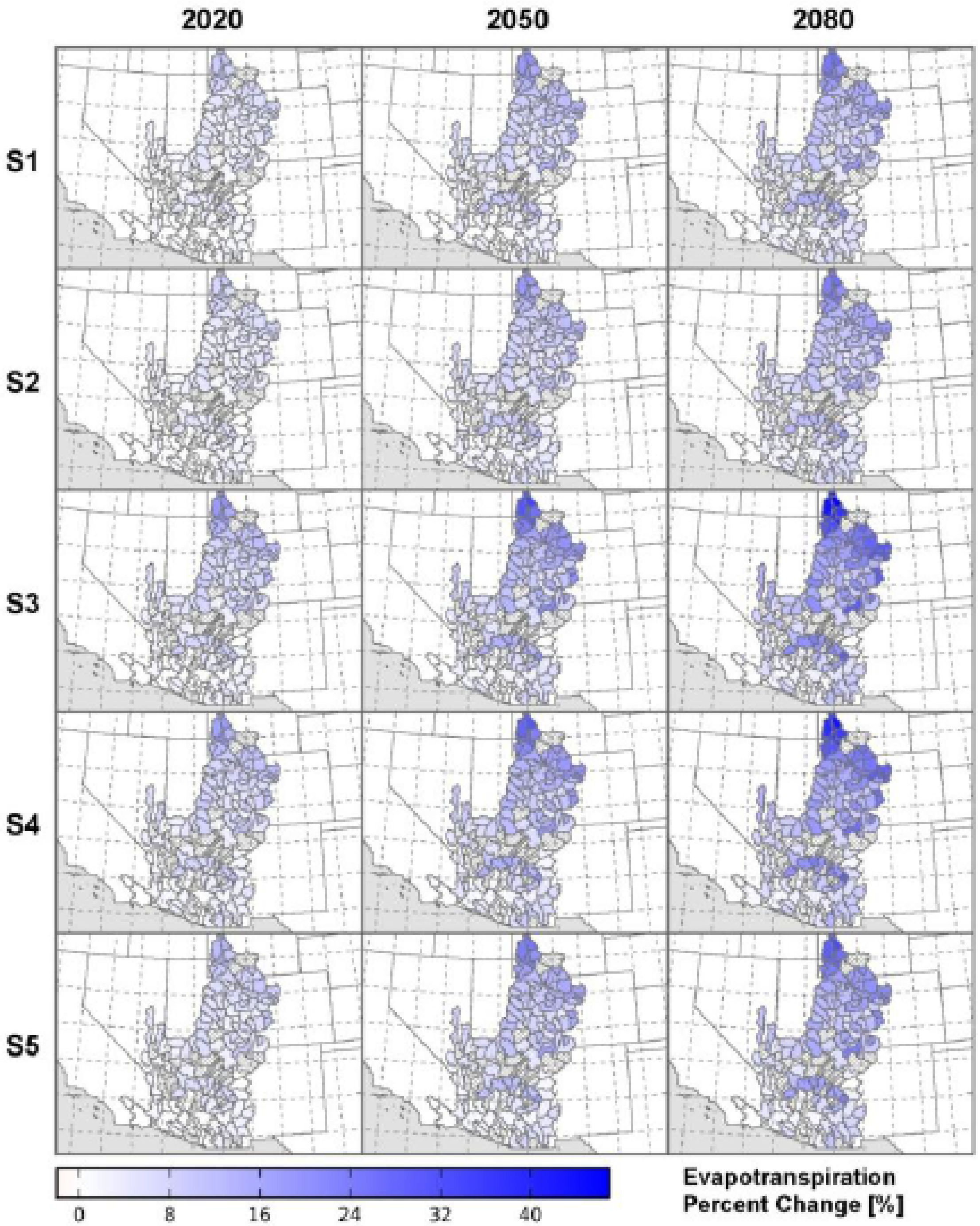

**Figure 21.—Colorado River Basin – COOP station UT5969 (Myton, UT). Baseline and projected mean daily alfalfa evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right).**




Shifts in ET

-- Kc curves were a function of thermal units

S1 – warmer, drier
S2 – warmer, wetter
S3 – hotter, drier
S4 – hotter, wetter
S5 – central tendency

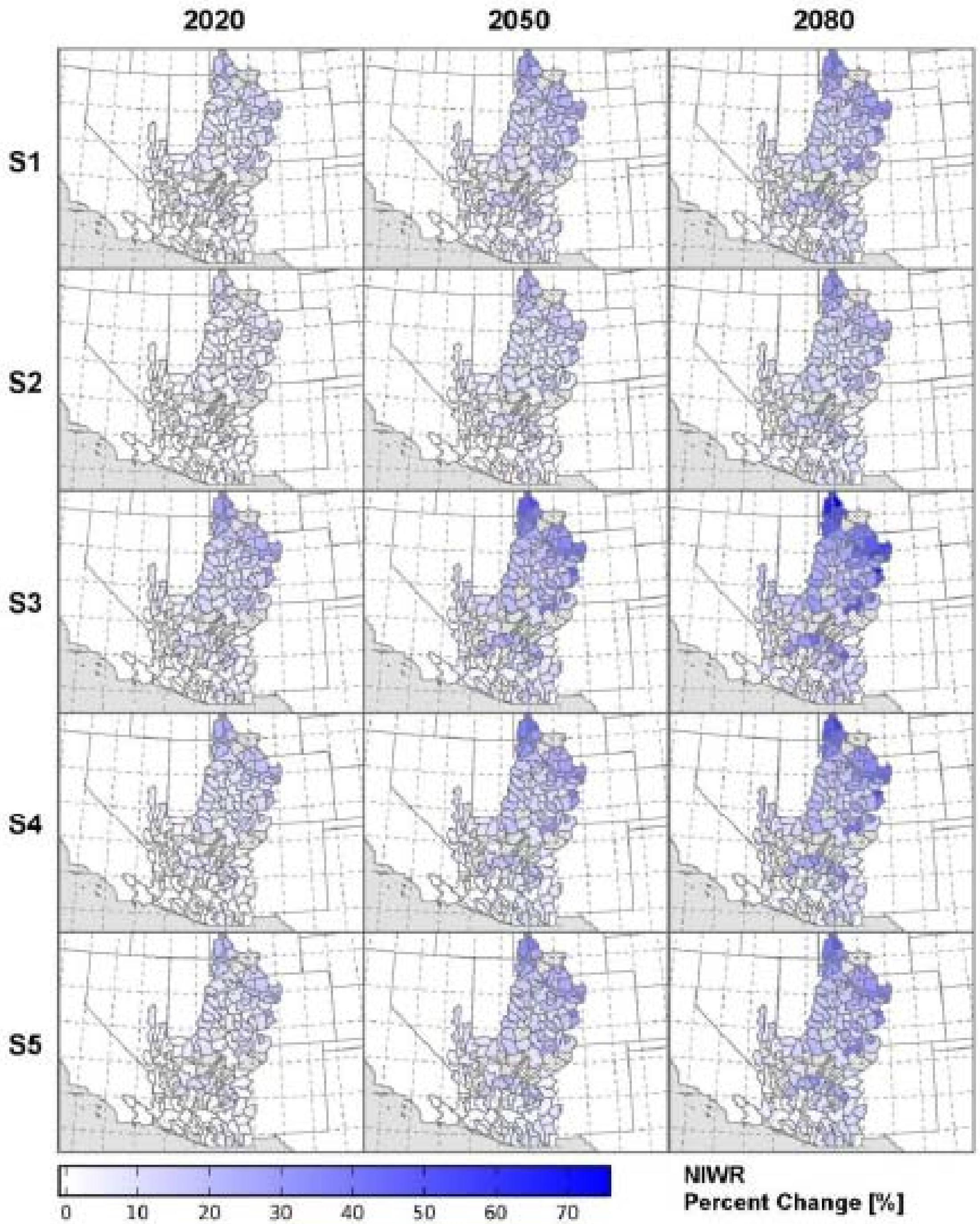



Percent Change in ET

--- using FAO-56 Dual Kc Method

S1 – warmer, drier
S2 – warmer, wetter
S3 – hotter, drier
S4 – hotter, wetter
S5 – central tendency

2015




Percent Change in Net Irrigation Water Requirement

--- using FAO-56 Dual Kc Method

S1 – warmer, drier
S2 – warmer, wetter
S3 – hotter, drier
S4 – hotter, wetter
S5 – central tendency

, 2015

# Mead, Nebraska –

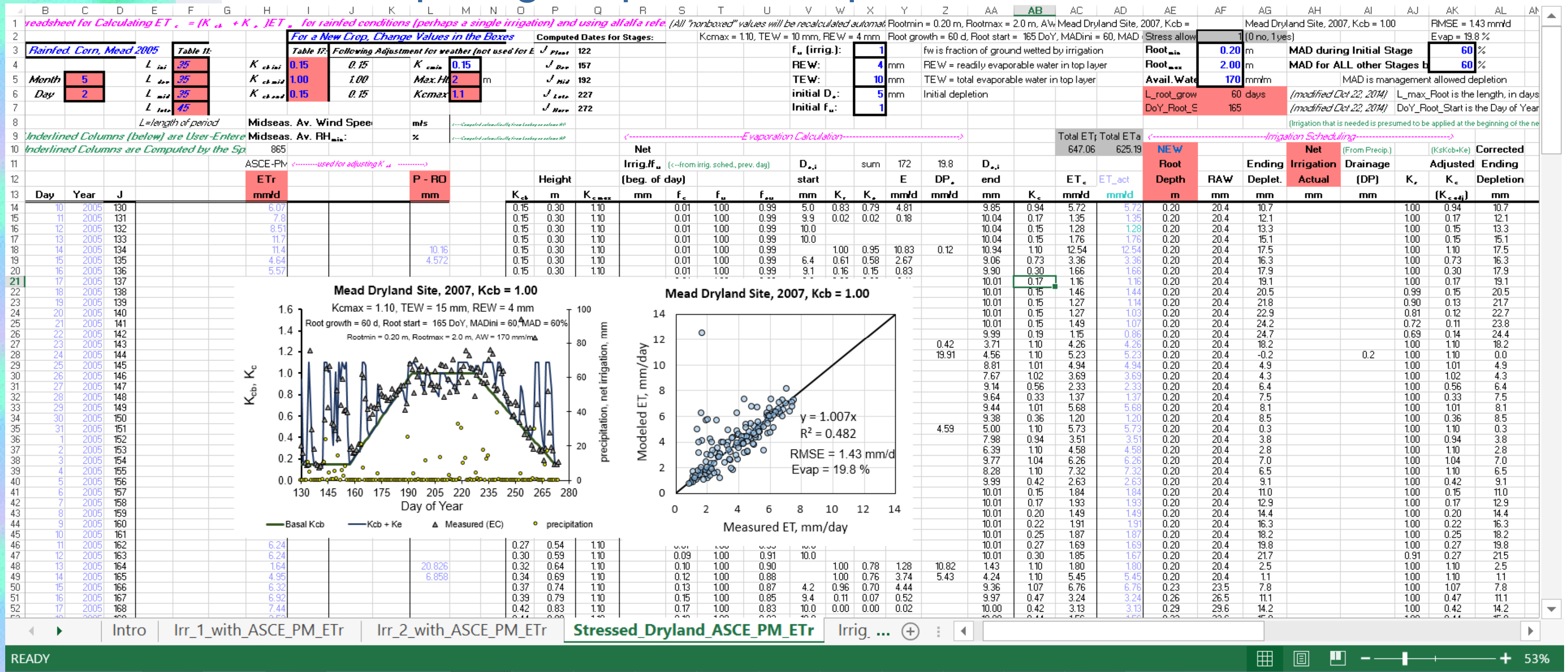
# Comparison with Eddy Covariance

# —Illustrate Low Sensitivity to $K_{cb\ mid}$

# FAO-56 Dual Kc Example Spreadsheet

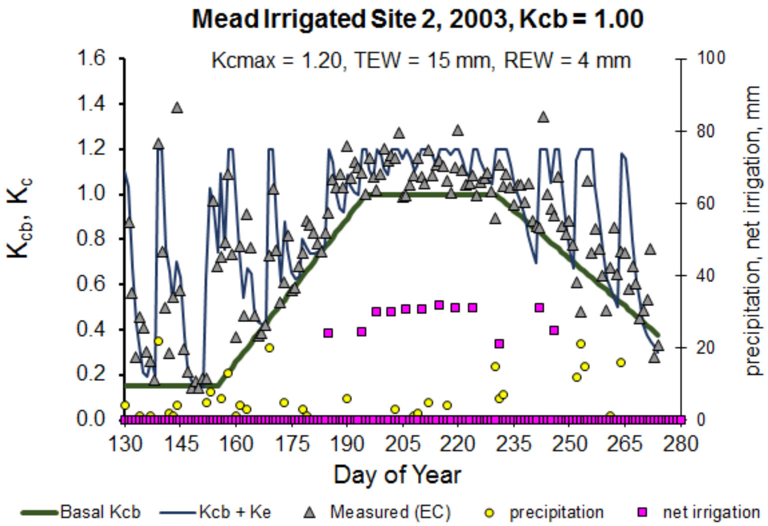
# -- Annex 8 of FAO-56 -- available at:

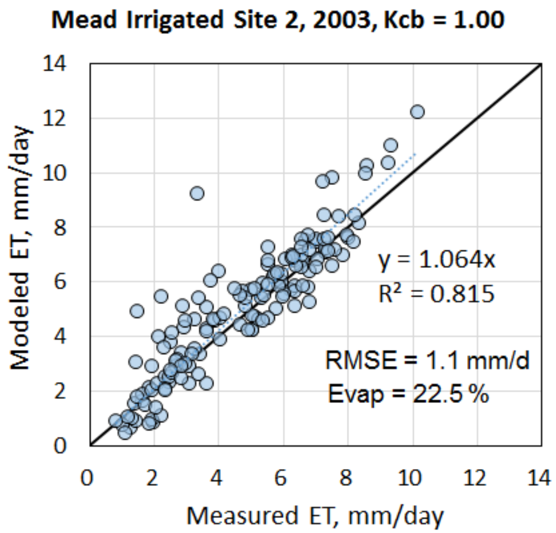
## http://extension.uidaho.edu/kimberly/2013/04/guidelines-for-computing-crop-water-requirements/



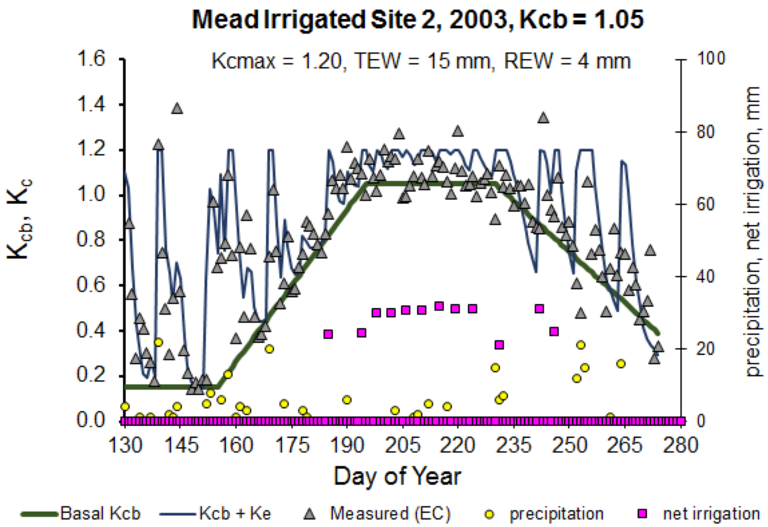

## Modified here to use <u>Alfalfa Reference</u>

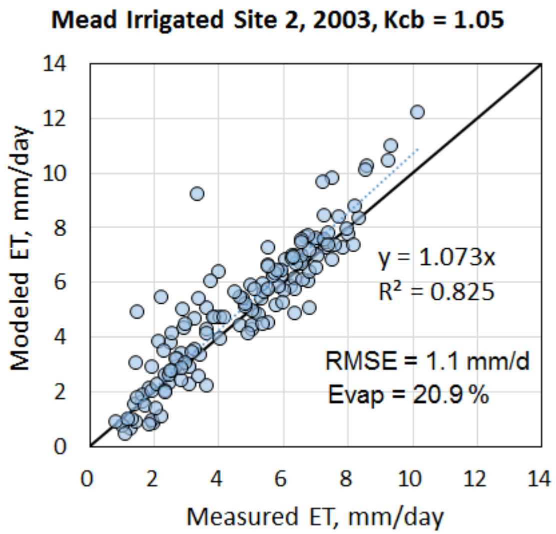
# Irrigated Field – Impact of $K_{c\ mid}$



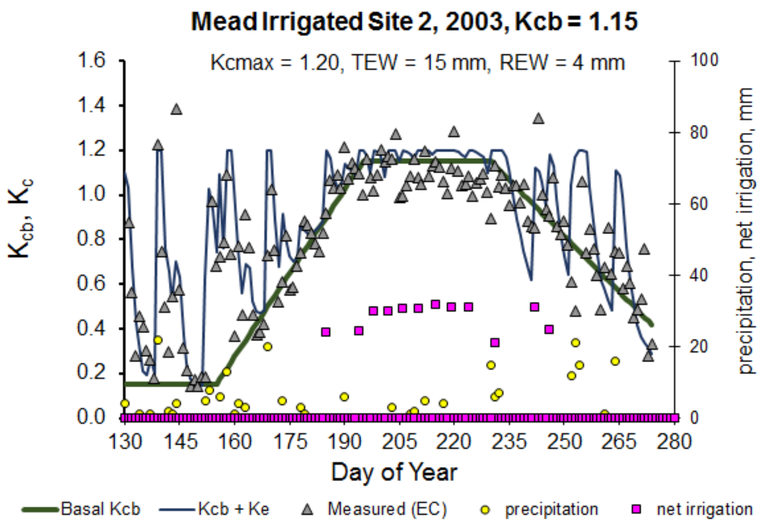

$K_{cb\ mid}$ = 1.00

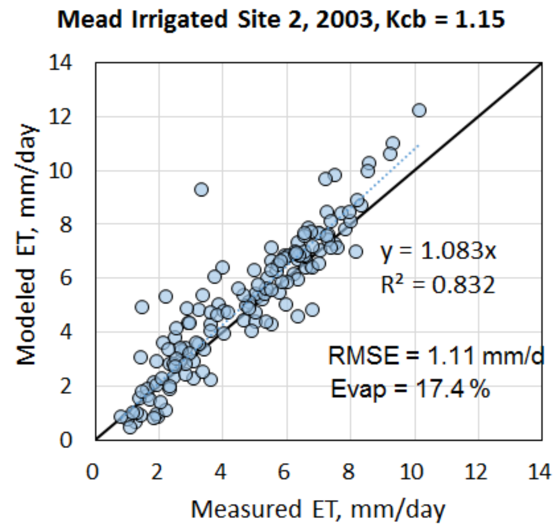


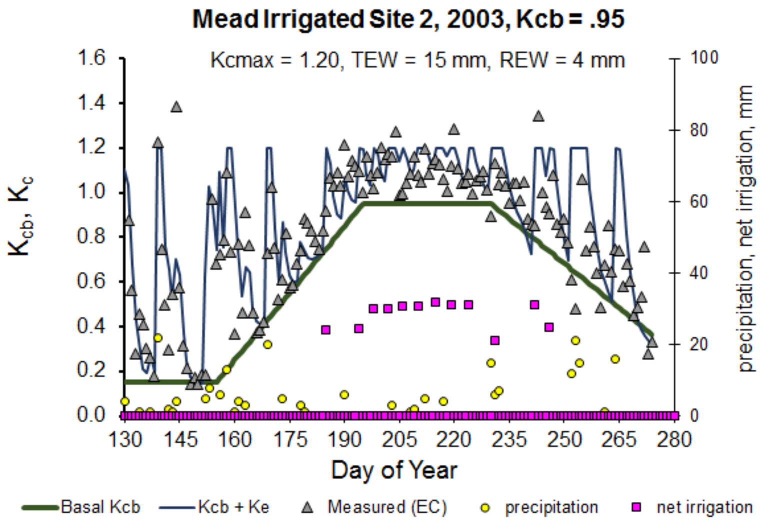

$K_{cb\ mid}$ = 1.05

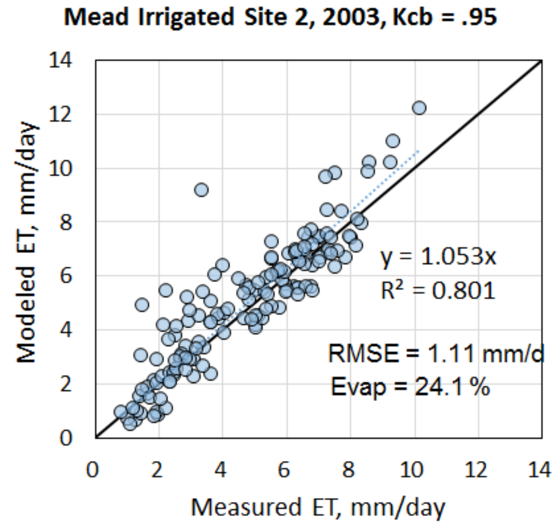
# Irrigated Field – Impact of $K_{c\ mid}$




$K_{cb\ mid}$ = 1.15

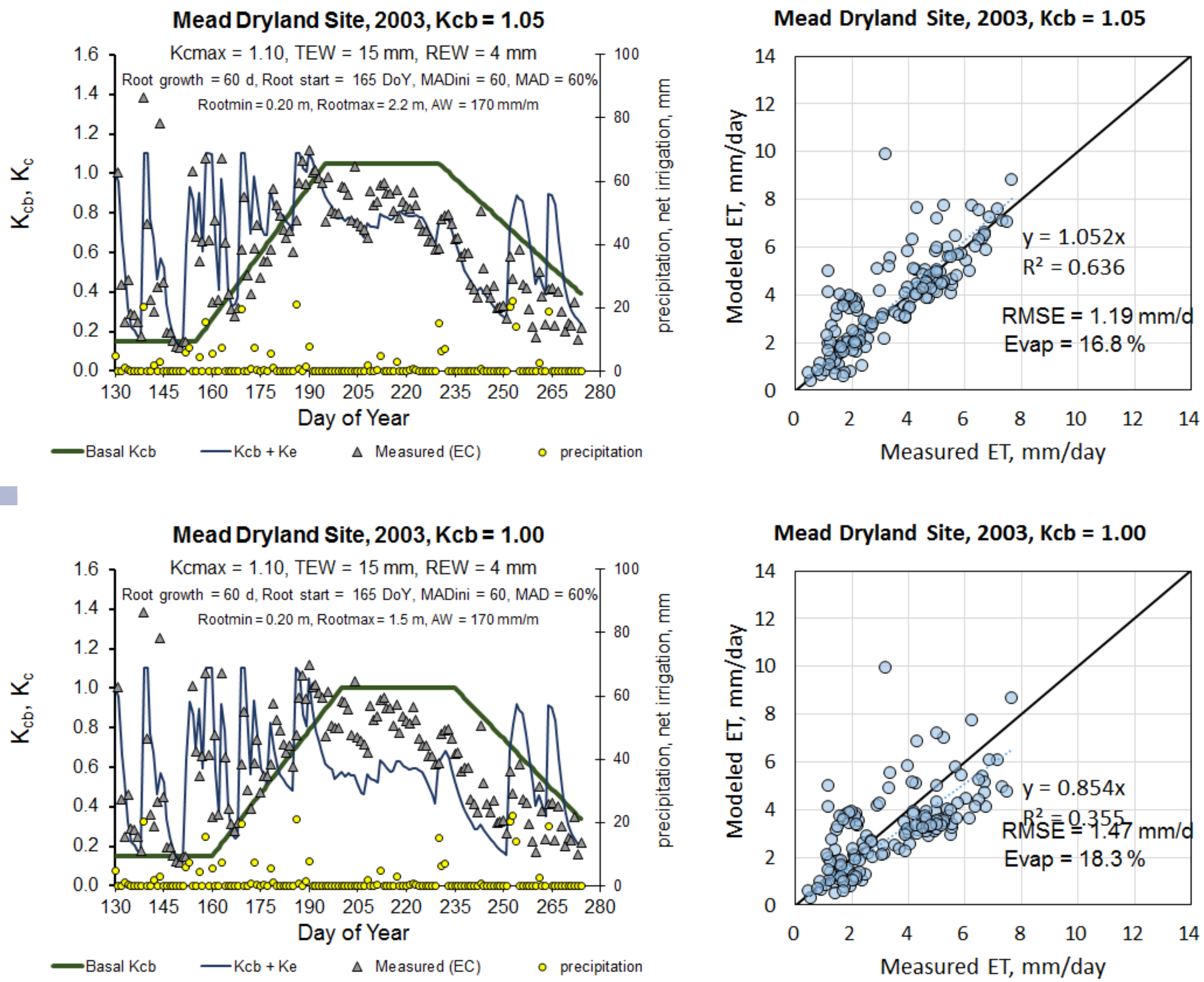



$K_{cb\ mid}$ = 0.95

Conclusion: It is difficult to determine correct separation in T and E and correct $K_{c\ mid}$ using measured ET only

# Rainfed Field – Impact of Rooting Depth




$K_{cb\ mid}$ = 1.05

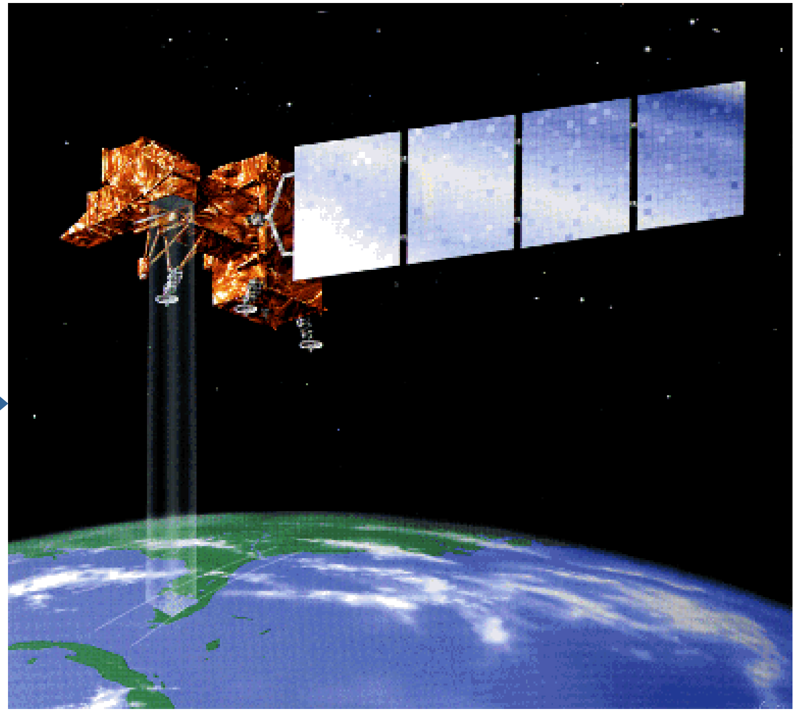
$Z_{root}$ = 2.2 m

$K_{cb\ mid}$ = 1.00

$Z_{root}$ = 1.5 m

Landsat 5 1984 – 2012

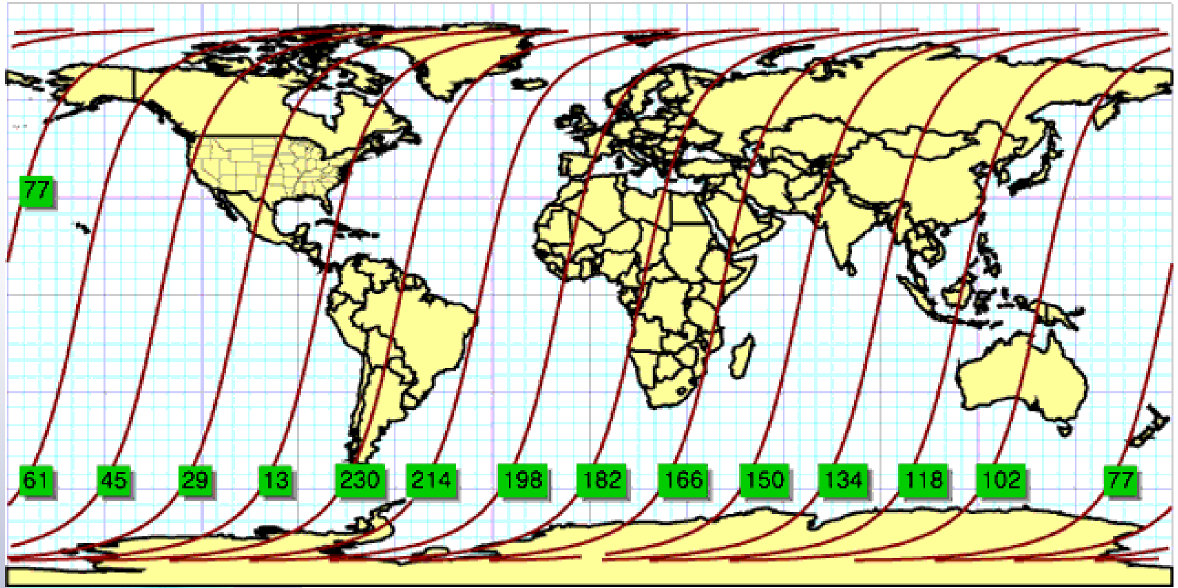
8-days apart

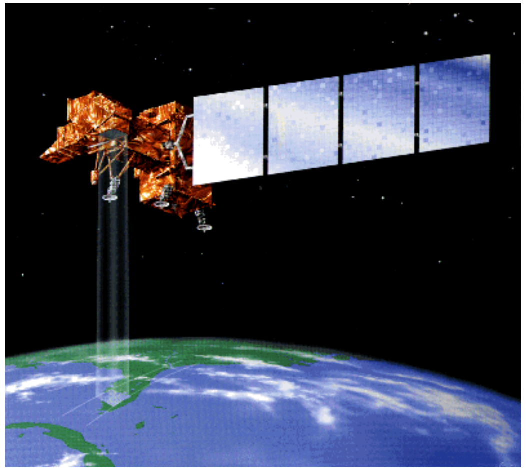


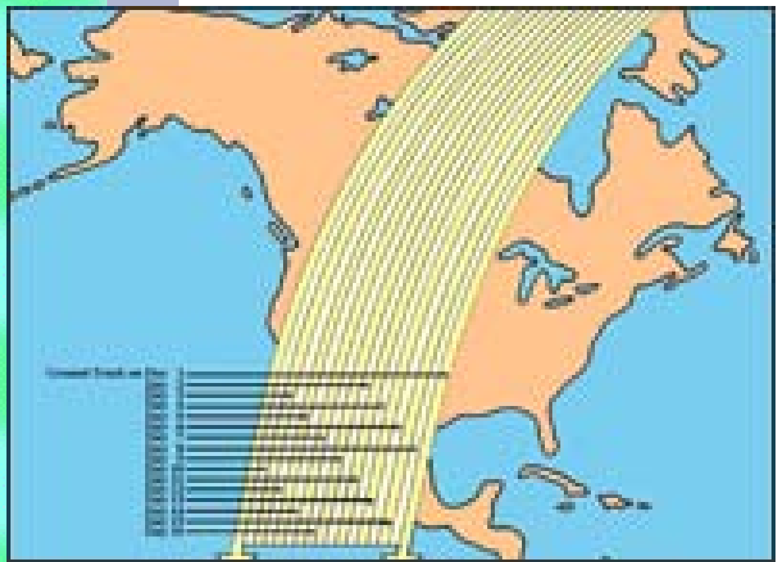
Landsat 7 1999 – 2017

Landsat 8 (LDCM)
Feb. 2013 – 20xx
*(replaced Landsat 5)*

# $K_c$'s from Space





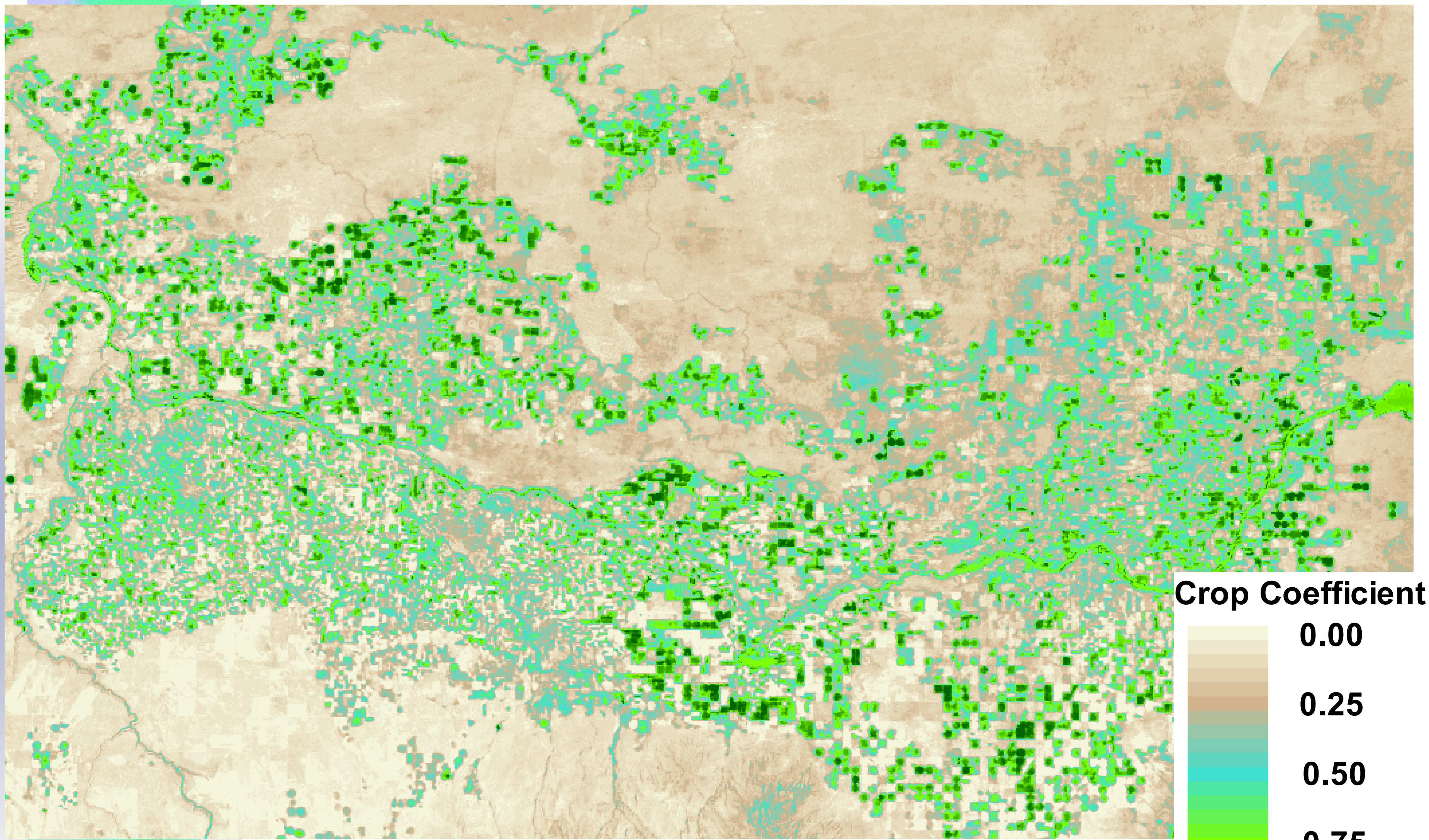
Landsat is a "polar orbiter"

orbiting Earth each 90 minutes

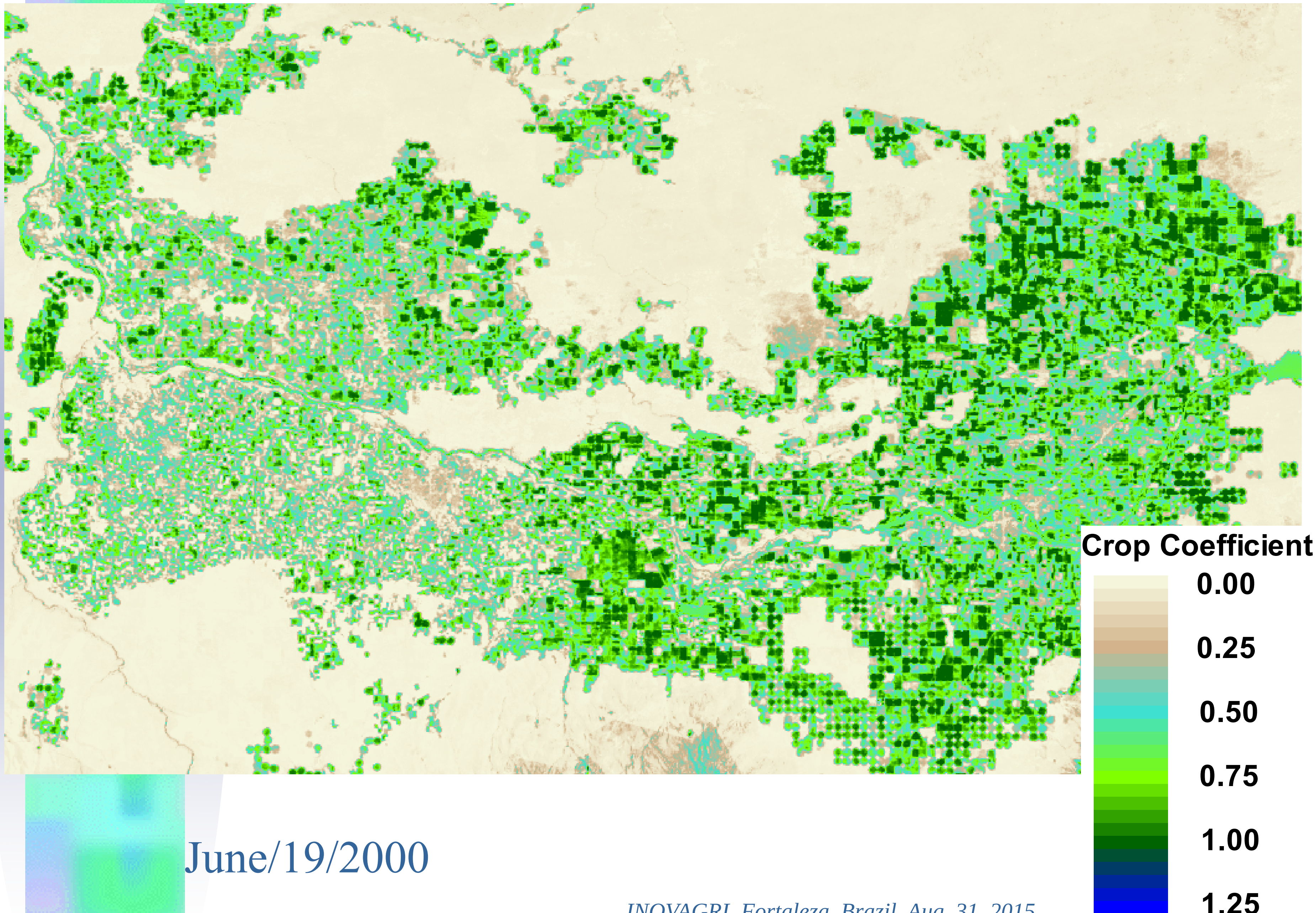
returning to the same location (path) each 16 days.

http://landsathandbook.gsfc.nasa.gov/orbit_coverage/prog_sect5_2.html

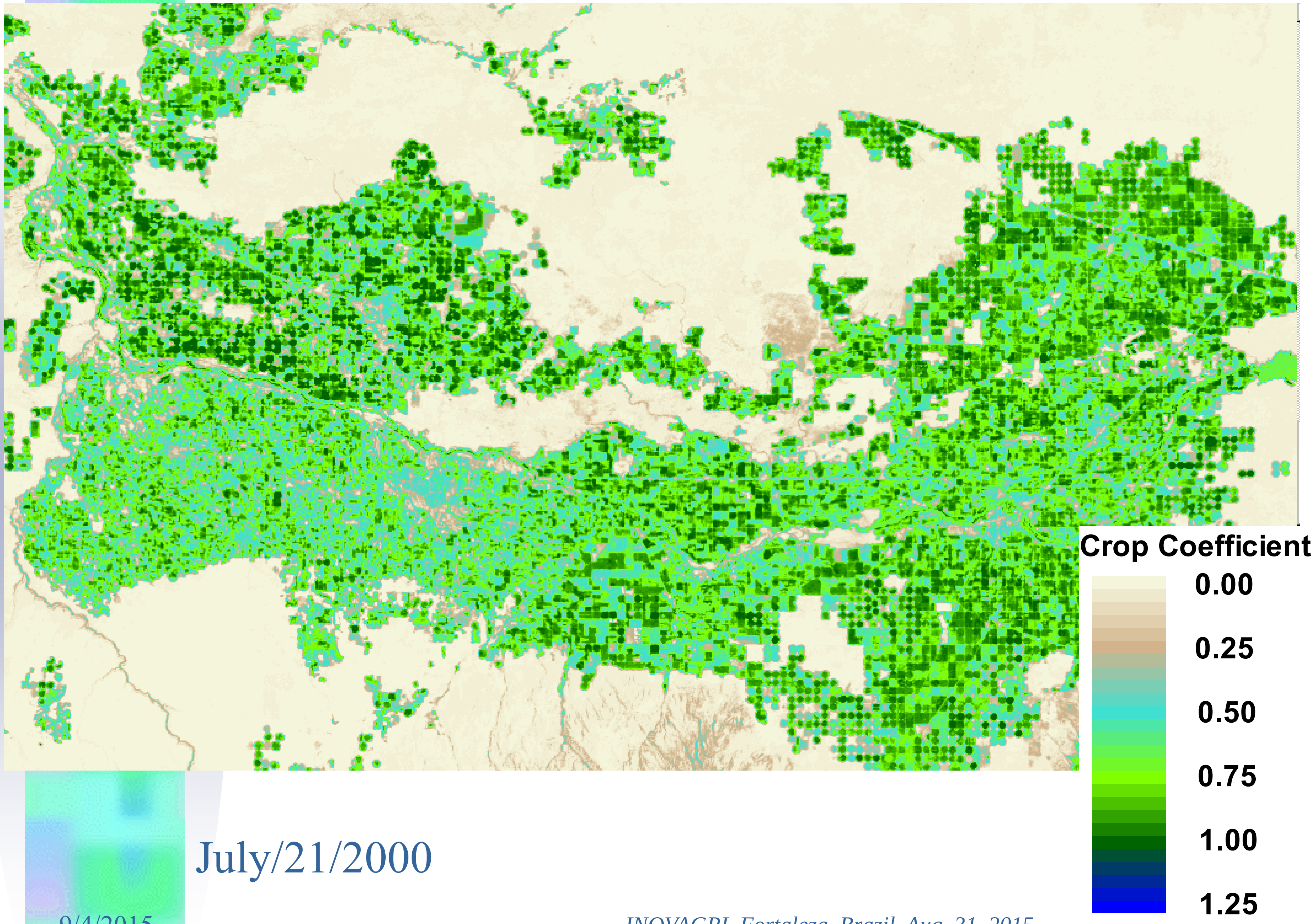
# 200,000 ha of Coverage – $K_c$ produced by METRIC



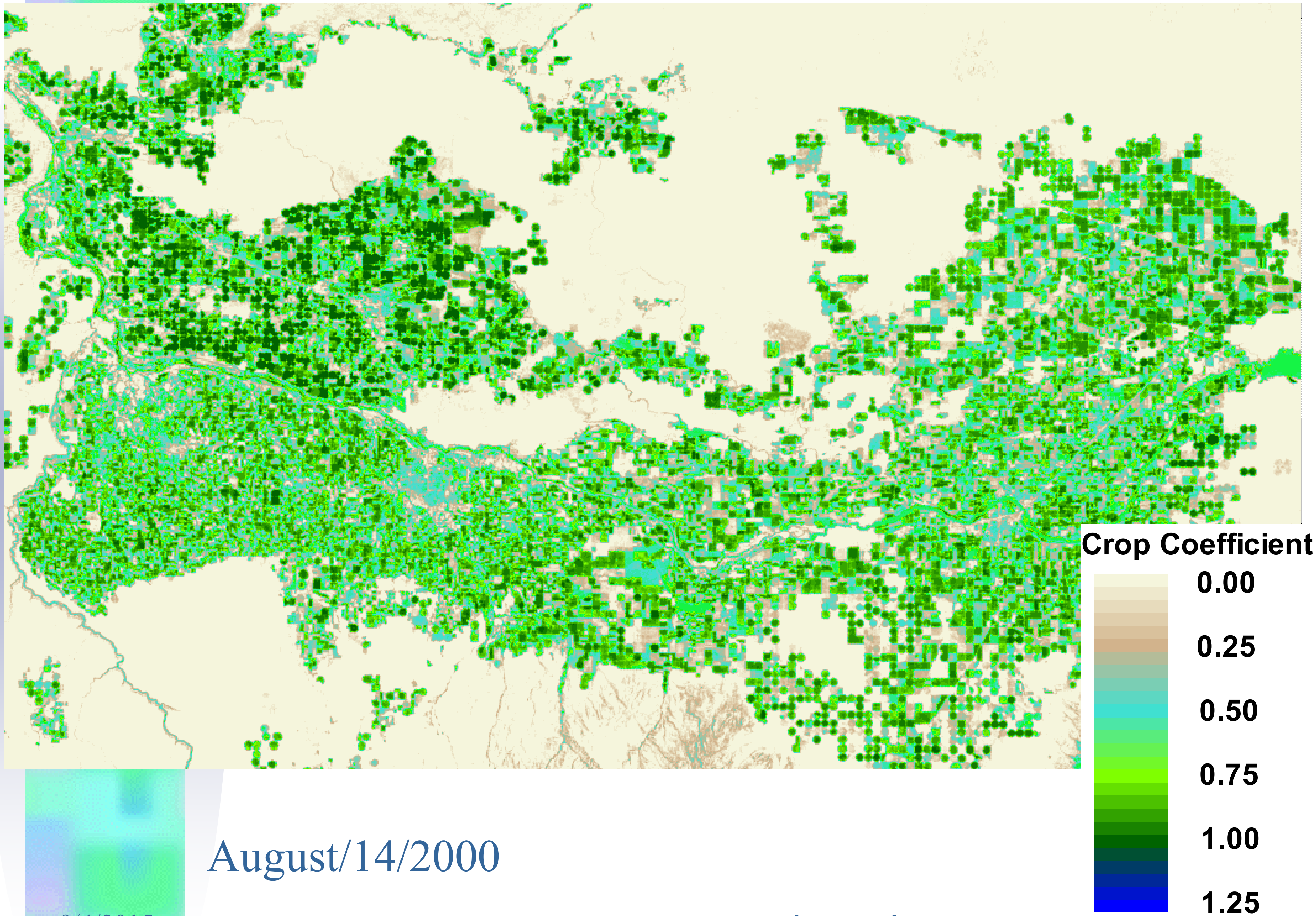

$K_c$ via METRIC-Landsat Energy Balance
May/2/2000 – SouthCentral Idaho, USA




June/19/2000

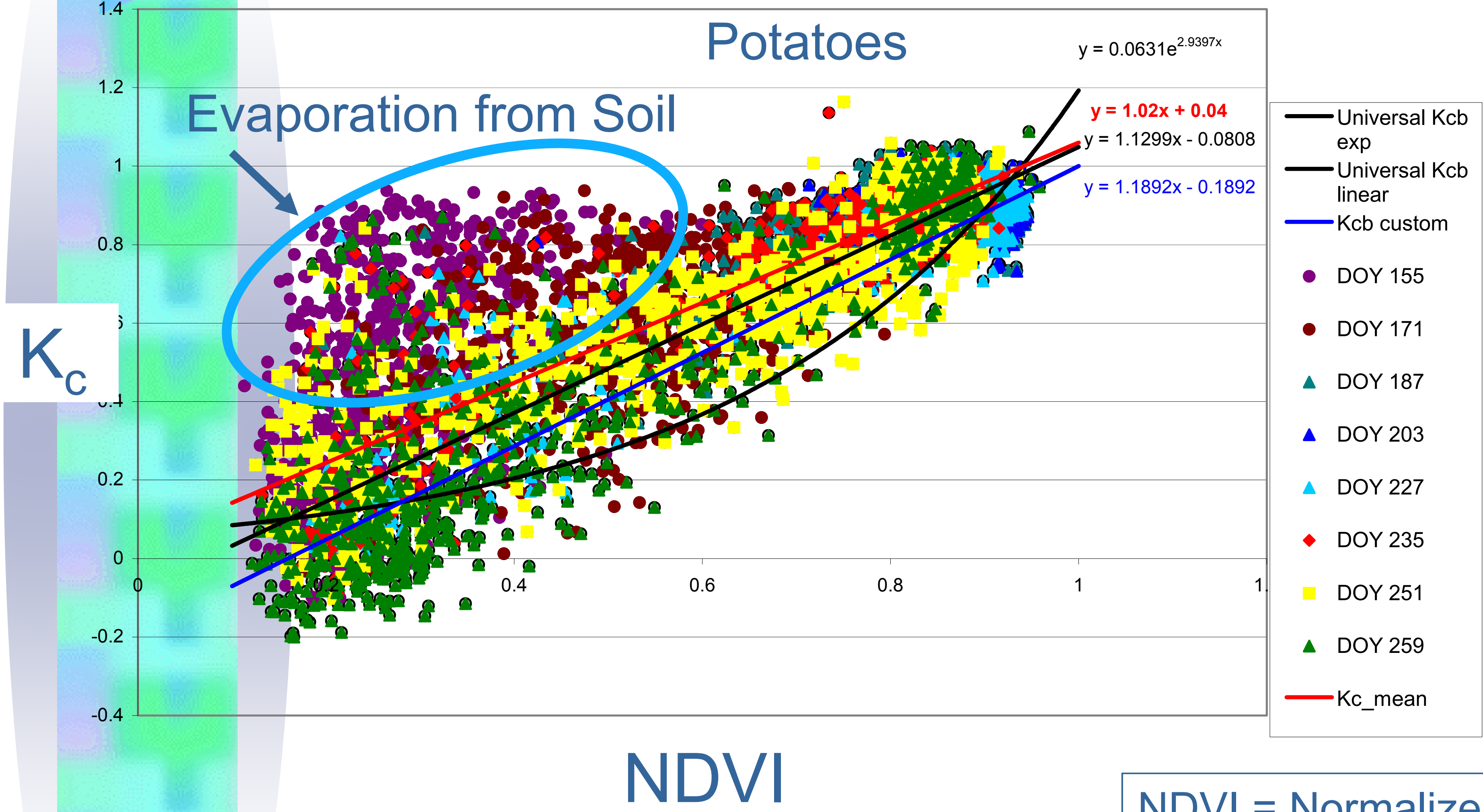



July/21/2000




August/14/2000

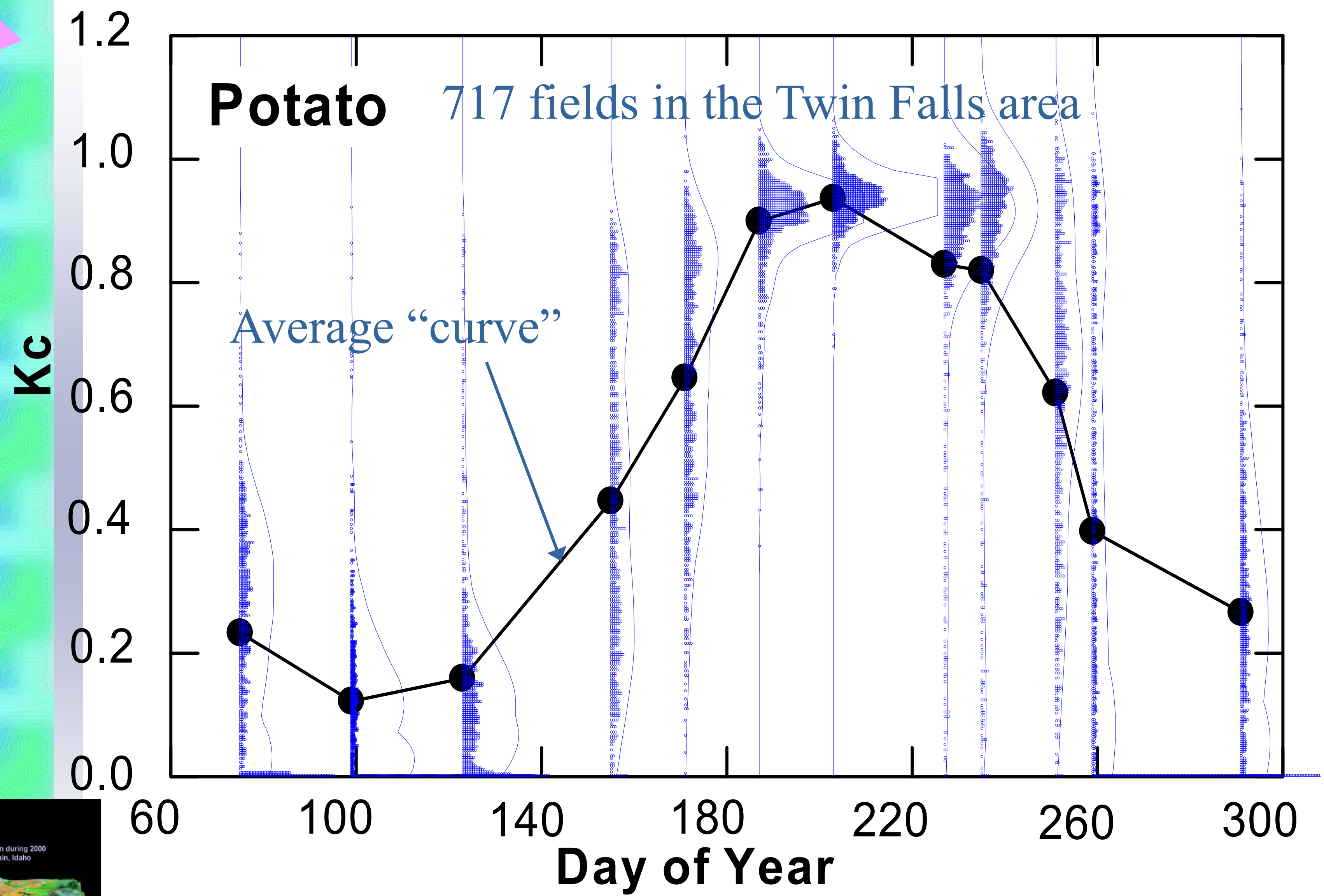
# We can also calibrate NDVI-based $K_c$ via Energy Balance

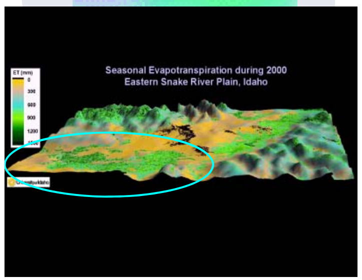



Each point is one agricultural field.
Each color is a Landsat date

NDVI = Normalized Difference Vegetation Index

## Use to Refine Local Information

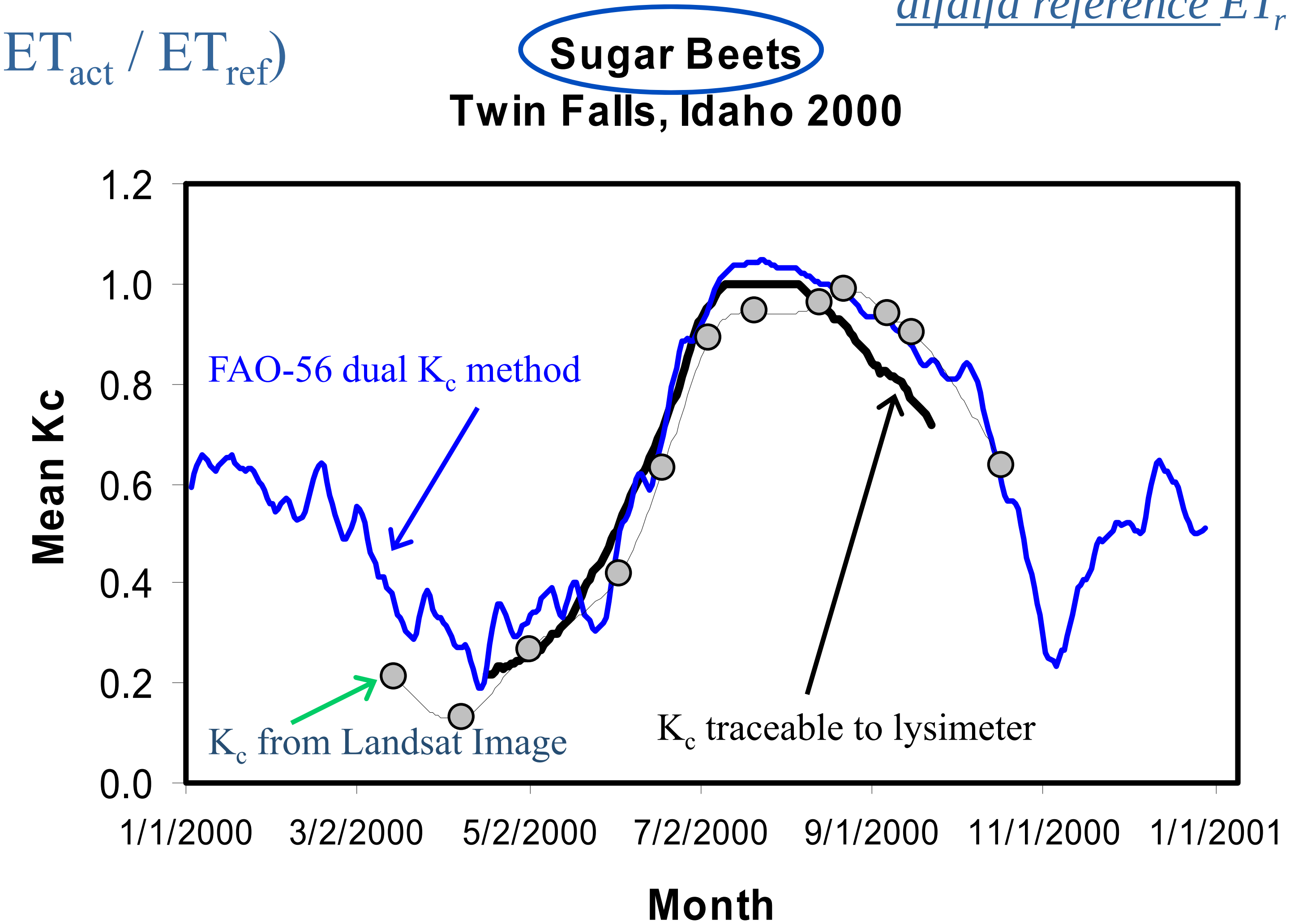


# Comparing METRIC vs. traditional $K_c$ $ET_{ref}$ methods

*alfalfa reference $ET_r$ basis*

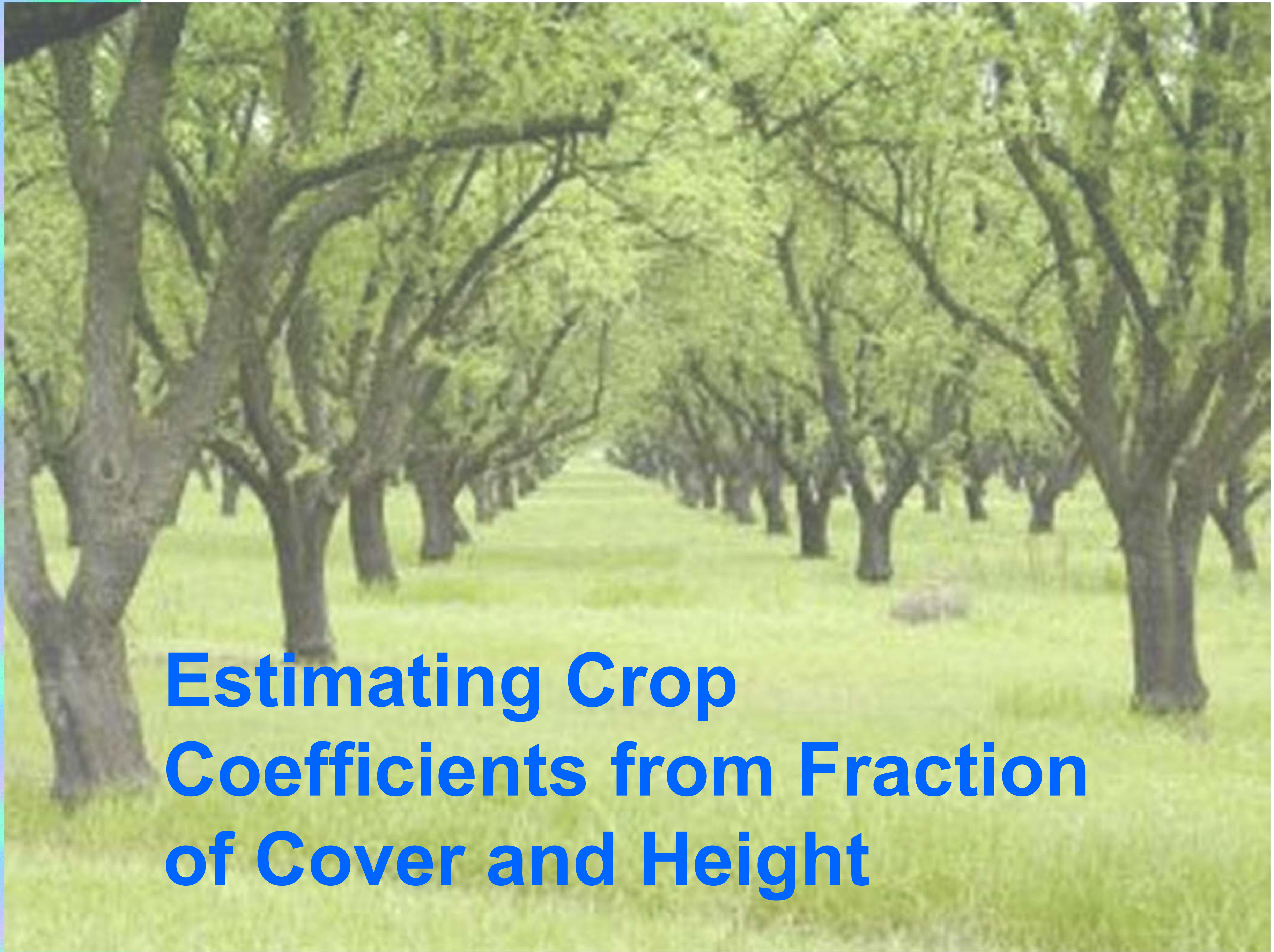
($K_c = ET_{act} / ET_{ref}$)




*(relatively good agreement among very independent approaches, including during the 'shoulder' periods when ground has partial cover)*

Agrimet for 2000 — Allen-Robison - 14 yr ave. — METRIC for 2000

$K_{cmean}$ $ET_{ref}$ — $(K_{cb} + K_e)$ $ET_{ref}$ — Energy Balance



# Estimating Crop Coefficients from Fraction of Cover and Height

# Why does $K_c$ change between two fields of the same crop?


*(these are both grapes. Why isn't the Kc the same?)*

*Allen and Pereira 2009, Irrigation Science, ASABE Mono.*

# --FAO-56 style approach

*(assuming bare soil between vegetation)*

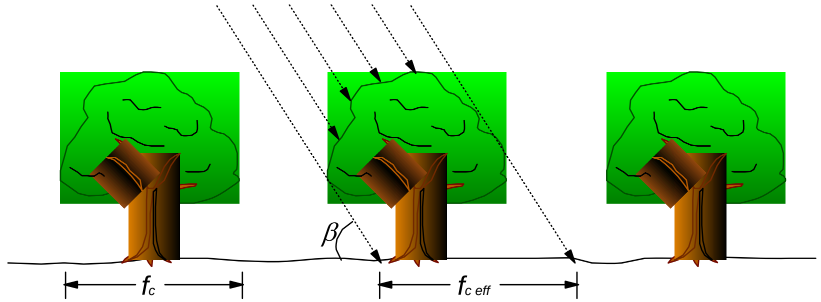
$$K_{cb} = K_{c\,min} + K_d \left( K_{cb\,full} - K_{c\,min} \right)$$

$K_{cmin}$ = minimum $K_{cb}$ for bare soil (~0.10-0.15)

$K_d$ = density coefficient (0-1)

$K_{cb\,full}$ = $K_{cb}$ for full ground covered by vegetation

# Density Coeff.




$$K_d = \min\left(1,\quad f_{c\,eff}^{\left(\frac{1}{1+h}\right)},\ M_L\, f_{c\,eff}\right)$$

$K_d$ = density coefficient (0-1)

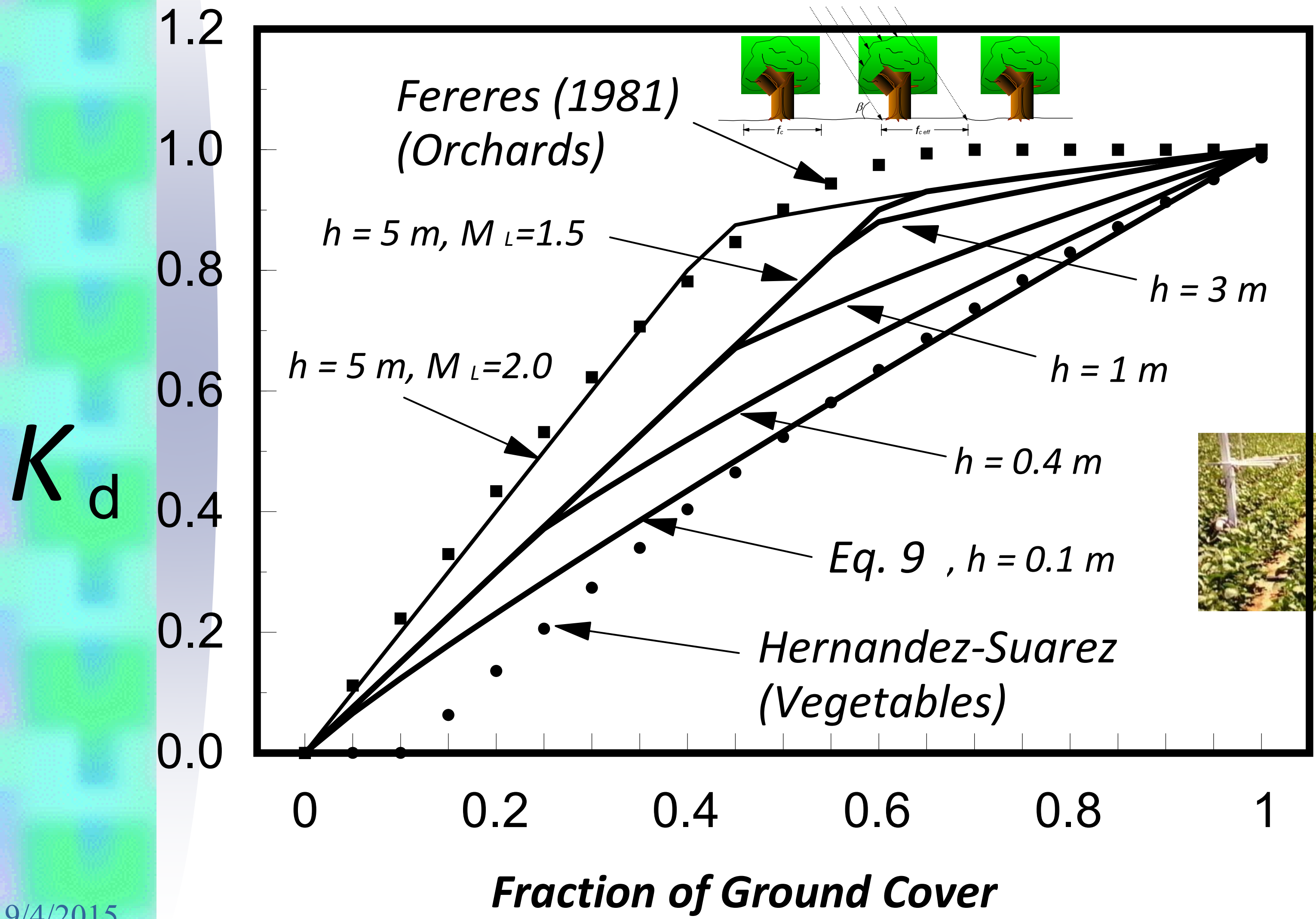
$M_L$ = multiplier on $f_{c\ eff}$ (~1.5-2)
*(to set upper flux limit per fraction of cover)*

$f_{c\ eff}$ = effective fraction of ground covere
(shaded) by vegetation (0-1)

$h$ = height, m *(for radiation + microadvection)*

# Density Coeff.

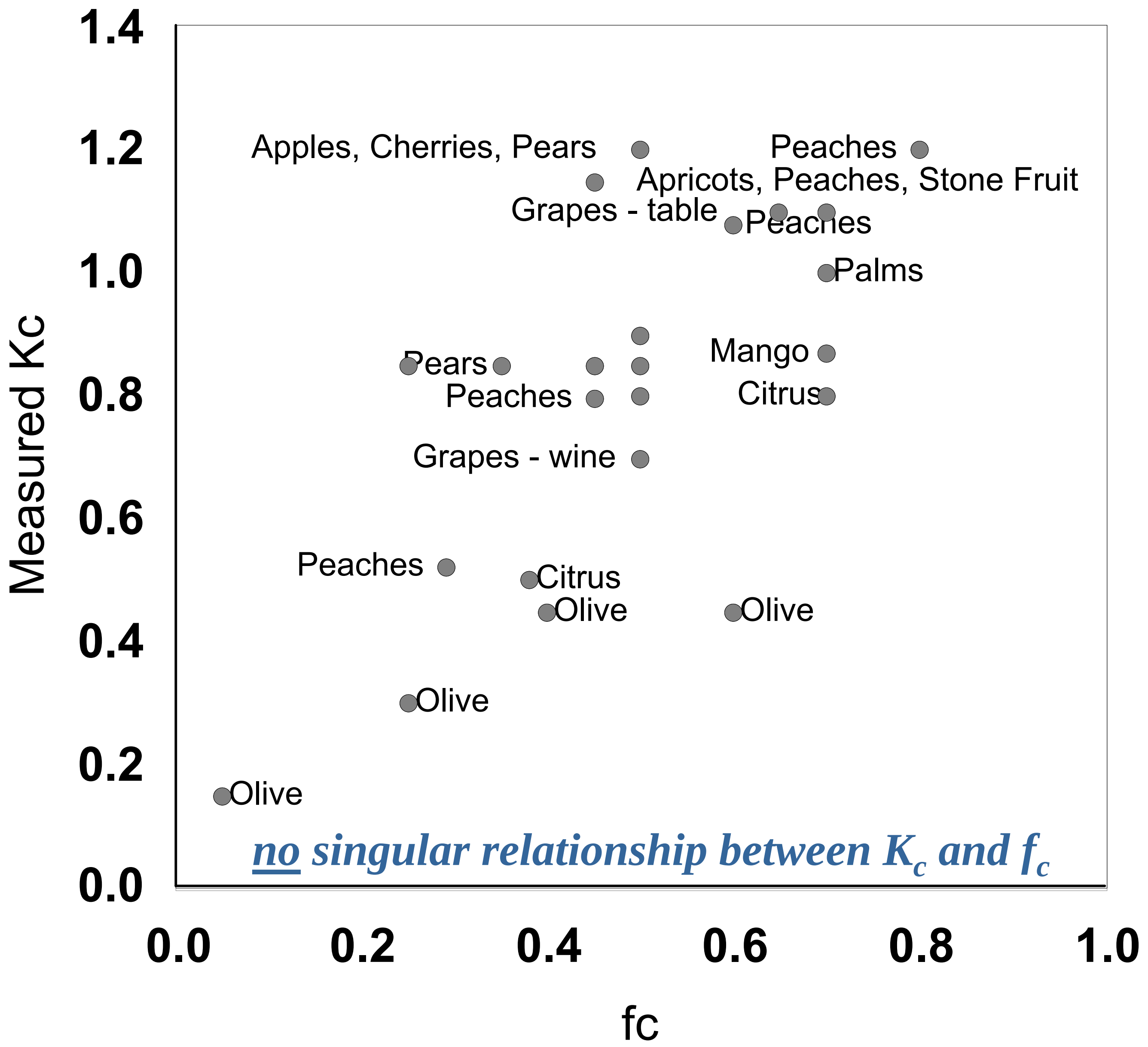
$$K_d = \min\left(1,\ f_{ceff}^{\left(\frac{1}{1+h}\right)},\ M_L\ f_{ceff}\right)$$



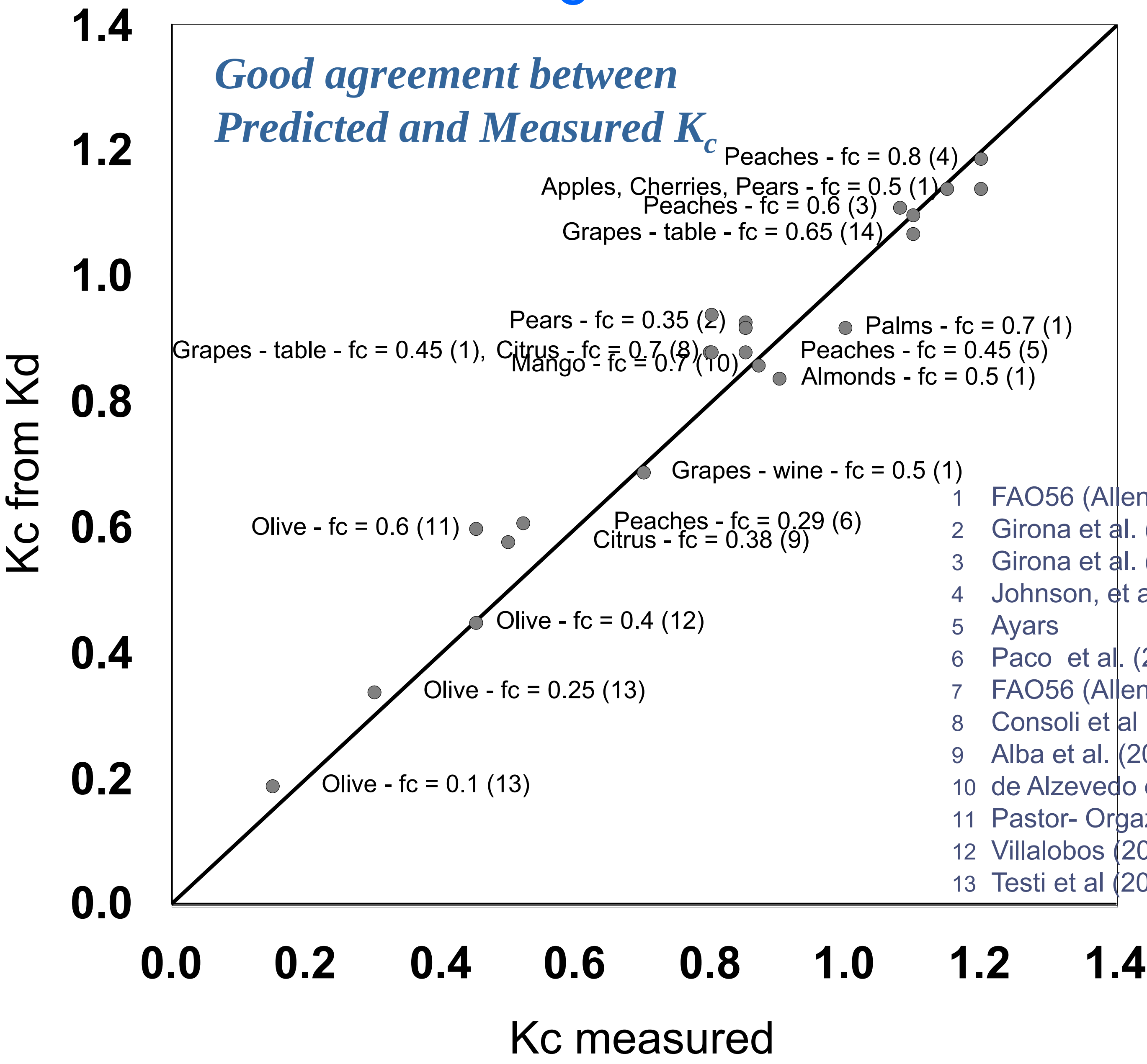

# Expanded $K_{co}$ tables for Orchards

| Crop | $K_{c\ ini}$ | $K_{c\ mid}$ | $K_{c\ end}$ | $K_{cb\ ini}$ | $K_{cbmid}$ | $K_{cb\ end}$ |
|---|---|---|---|---|---|---|
| Fruit Trees | | | | | | |
| **Almonds** | | | | | | |
| **- no ground cover - high density (fceff = 0.7)** | **0.40** | **1.00** | **0.70** | **0.20** | **0.95** | **0.65** |
| **- no ground cover - med. density (fceff = 0.5)** | **0.40** | **0.85** | **0.60** | **0.20** | **0.80** | **0.55** |
| **- no ground cover – low dens. / young (fceff = 0.25)** | **0.35** | **0.50** | **0.40** | **0.15** | **0.45** | **0.35** |
| **- active ground cover - high density (fceff = 0.7)** | **0.85** | **1.05** | **0.85** | **0.75** | **1.00** | **0.80** |
| **- active ground cover - med. density (fceff = 0.5)** | **0.85** | **1.00** | **0.85** | **0.75** | **0.95** | **0.80** |
| **- act. grnd cover – low dens. / young (fceff = 0.25)** | **0.85** | **0.95** | **0.85** | **0.75** | **0.90** | **0.80** |
| **Apples, Cherries, Pears** | | | | | | |
| **- no ground cover - high density (fceff = 0.7)** | **0.50** | **1.15** | **0.80** | **0.30** | **1.10** | **0.75** |
| **- no ground cover - med. density (fceff = 0.5)** | **0.50** | **1.05** | **0.75** | **0.30** | **1.004** | **0.70** |
| **- no ground cover - low dens./ young (fceff = 0.25)** | **0.40** | **0.70** | **0.55** | **0.25** | **0.65** | **0.50** |
| **- act. grnd cov., killing frost – h.dens. (fceff = 0.7)** | **0.50** | **1.20** | **0.85** | **0.40** | **1.15** | **0.80** |
| **- act. grnd cov., killing frost – m.dens. (fceff=0.5)** | **0.50** | **1.15** | **0.85** | **0.40** | **1.10** | **0.80** |
| **- act. grnd cov., killing frost – l.dens. (fceff = 0.25)** | **0.50** | **1.05** | **0.85** | **0.40** | **1.00** | **0.80** |
| **- act. grnd cov., no frosts – h. dens. (fceff = 0.7)** | **0.85** | **1.20** | **0.85** | **0.75** | **1.15** | **0.80** |
| **- act. grnd cov., no frosts – m. dens. (fceff = 0.5)3** | **0.85** | **1.15** | **0.85** | **0.75** | **1.10** | **0.80** |
| **- act. grnd cov., no frosts – l. dens. (fceff = 0.25)** | **0.85** | **1.05** | **0.85** | **0.75** | **1.00** | **0.80** |

# Orchard $K_c$'s from literature



# Orchard $K_c$'s from literature



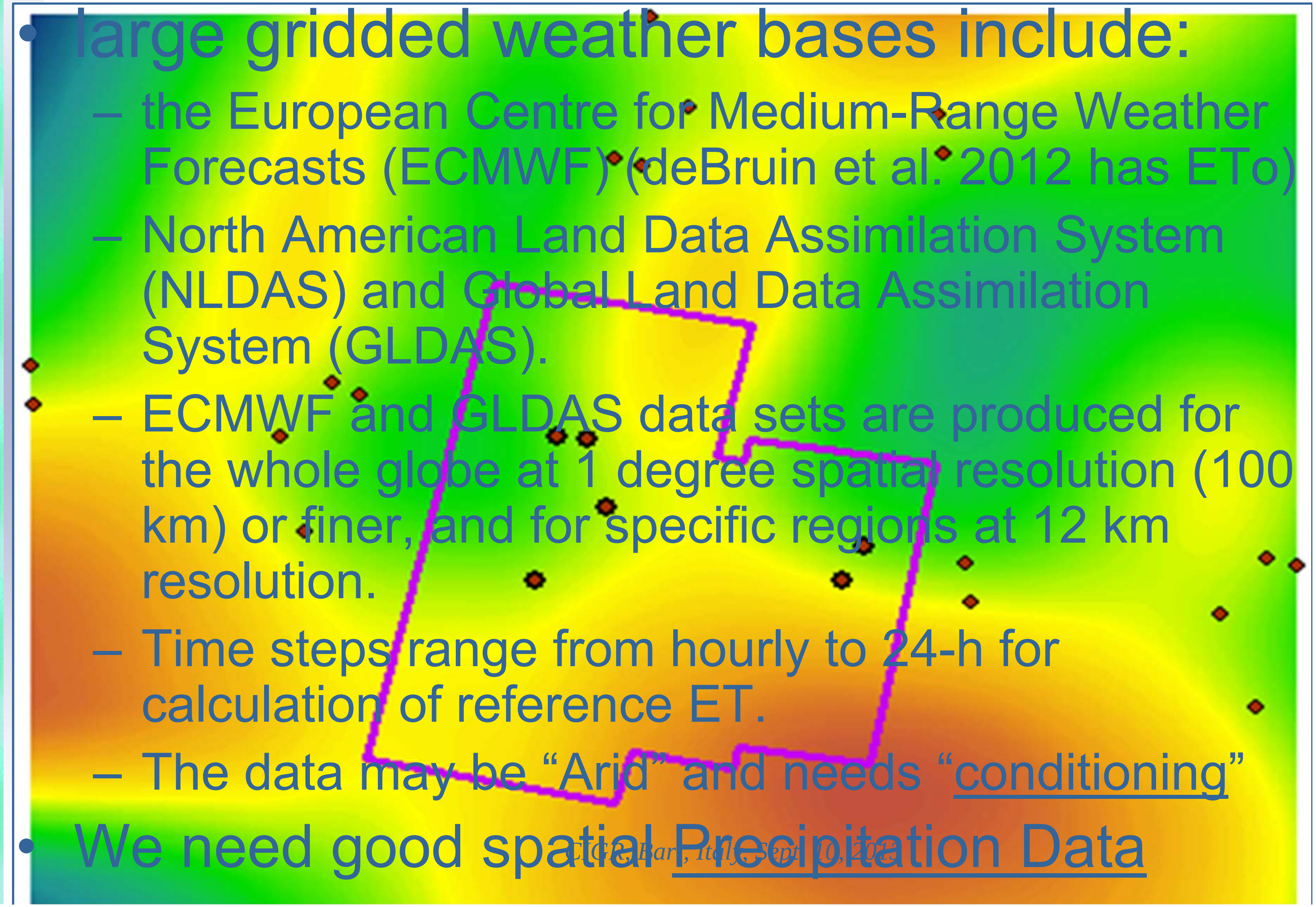

1 FAO56 (Allen et al., 1998)
2 Girona et al. (2003)
3 Girona et al. (2005)
4 Johnson, et al. (2006)-microspray,
5 Ayars
6 Paco et al. (2006)
7 FAO56 (Allen et al., 1998)
8 Consoli et al (2005)
9 Alba et al. (2006)
10 de Alzevedo et al. (2003)
11 Pastor- Orgaz (1994)
12 Villalobos (2000) (fc= .4)
13 Testi et al (2004)

# Conclusions on $K_c$

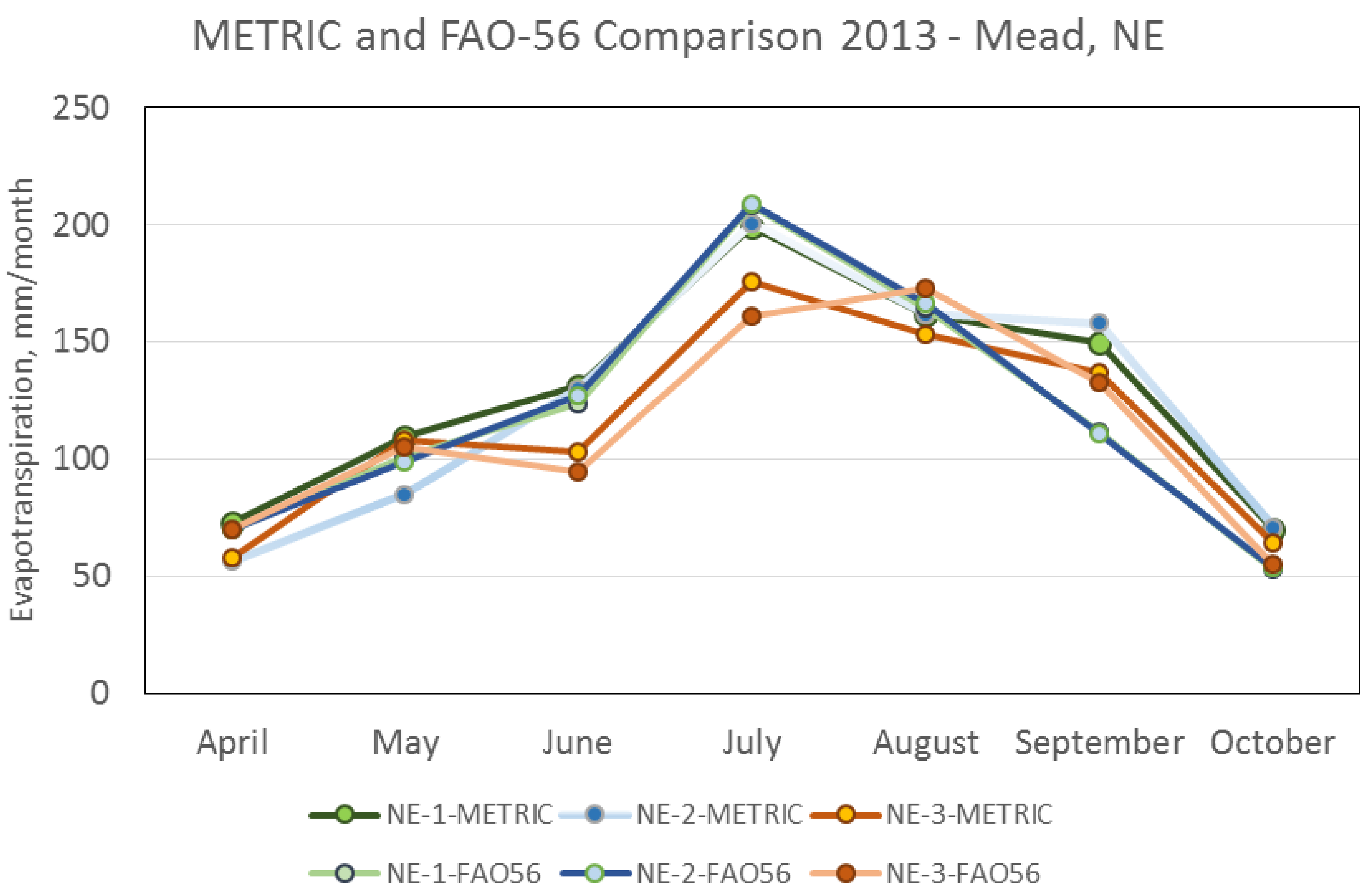
- The $K_c$ $ET_r$ method is robust and transferable
- The $K_c$ incorporates a number of factors affecting ET
- $K_c$ curves can be tailored based on
  - weather data
  - fraction of ground cover
- The dual $K_c$ provides good estimation of impacts of evaporation from soil

# Thank You

# Spatial $ET_{ref}$ from Gridded Weather Data Sets



- large gridded weather bases include:
  - the European Centre for Medium-Range Weather Forecasts (ECMWF) (deBruin et al. 2012 has ETo)
  - North American Land Data Assimilation System (NLDAS) and Global Land Data Assimilation System (GLDAS).
  - ECMWF and GLDAS data sets are produced for the whole globe at 1 degree spatial resolution (100 km) or finer, and for specific regions at 12 km resolution.
  - Time steps range from hourly to 24-h for calculation of reference ET.
  - The data may be "Arid" and needs "conditioning"
- We need good spatial Precipitation Data


METRIC and FAO-56 Comparison 2013 - Mead, NE
Evapotranspiration, mm/month
250
200
150
100
50
0
April
May
June
July
August
September
October
NE-1-METRIC
NE-2-METRIC
NE-3-METRIC
NE-1-FAO56
NE-2-FAO56
NE-3-FAO56