

# Evaporation, Transpiration, and Irrigation Scheduling from sound to satellites

Mark Roberson  
Formation Environmental

Kentucky Farm Bureau  
Water Management Working Group  
December 11, 2019

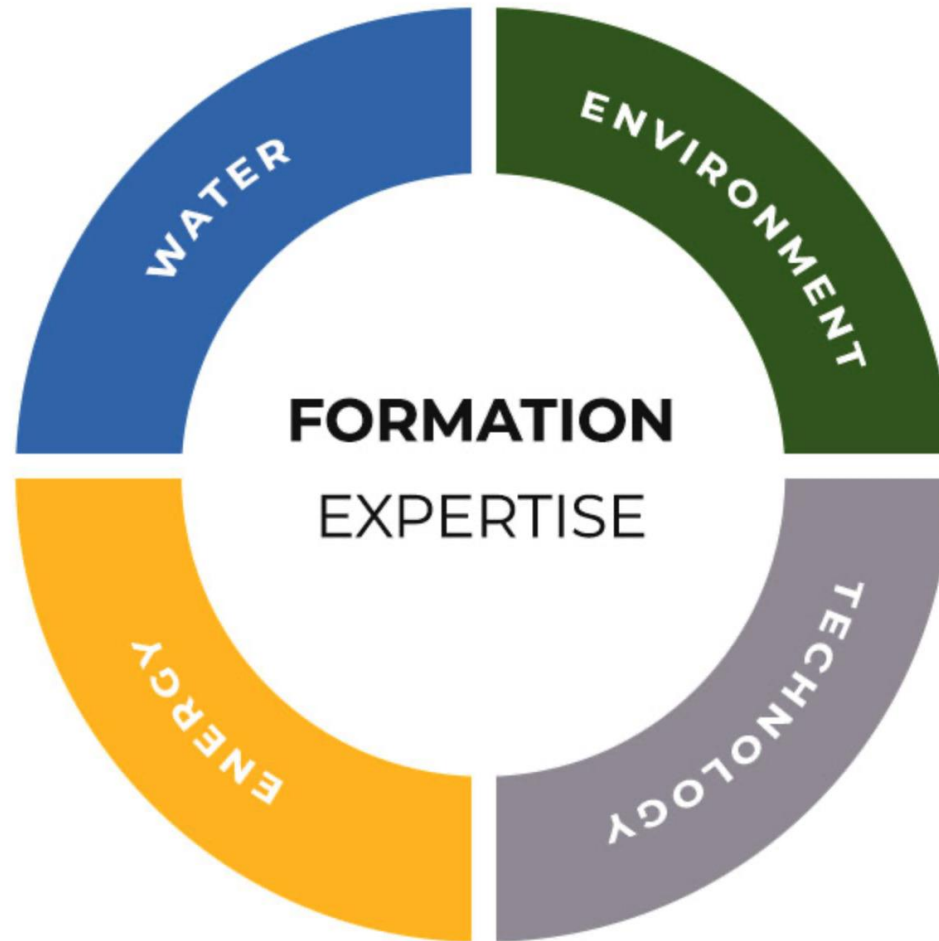
# Formation Environmental



Water Resources Engineers  
Soil Scientists  
Engineering Geologists  
Hydrogeologists  
Agricultural Engineers  
ETa Analysts  
Soil Technicians  
Agronomists  
Crop Scientists



Civil Engineers  
LiDAR Analysts  
Remote Sensing Analysts  
Certified Arborists  
Engineering Geologists  
Statisticians  
Meteorologists  
Geological Engineers



Environmental Scientists  
Environmental Engineers  
Geologists  
Chemists  
Botanists  
Risk Assessors  
Aquatic Biologists  
Ecotoxicologists  
Restoration Ecologists



UAS Pilots  
Aeronautical Engineers  
LiDAR Analysts  
GIS Analysts  
Applied Physicists  
IT Developers  
Database Analysts  
Data Scientists



# Formation Environmental Science Team

- George Paul, PhD – Agronomist/Agricultural engineer
- Chuan-Shin Chong – Electrical engineer
- Sushant Mehan, PhD – Agricultural engineer
- Ben Cheng, PhD – Remote sensing hydrologist
- Clint Kellar – GIS and web developer
- Macall Teague, Yuri Walsh, & Cameron Gurley – data support

## Scope of Today's Discussion

- Evapotranspiration – fundamental to irrigation scheduling
- Considerations for irrigation scheduling
- Fundamentals of irrigation scheduling
- Sensor based irrigation scheduling
- Irrigation scheduling in the age of computers and satellites



# My Irrigation Education



Peace Corps, Senegal



Irrigation Training and Research Center  
Cal Poly, SLO



Water Management Internship  
And Full Time Work!

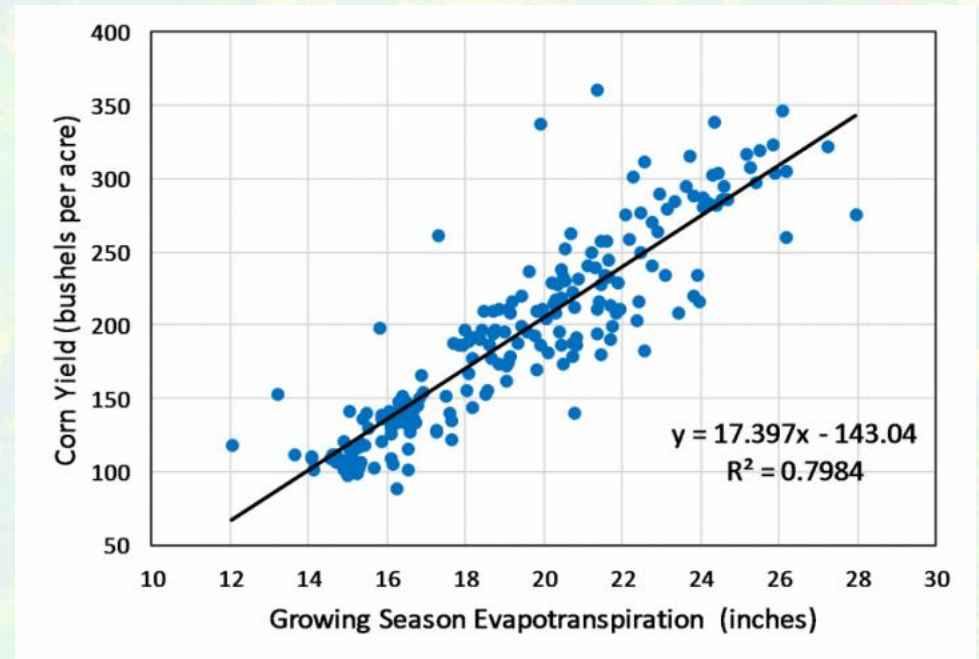
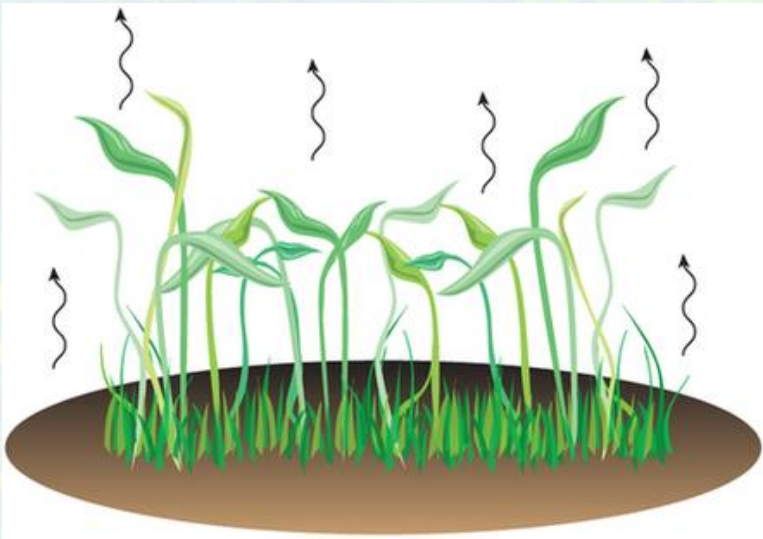


# Evaporation and Transpiration aka Evapotranspiration or ET

Evaporation – of water from soil and plant leaves to the atmosphere

Transpiration – water moving through a plant due to atmospheric demand

Combined – ET is what is required to keep a plant alive and productive!



# Evaporation and Transpiration

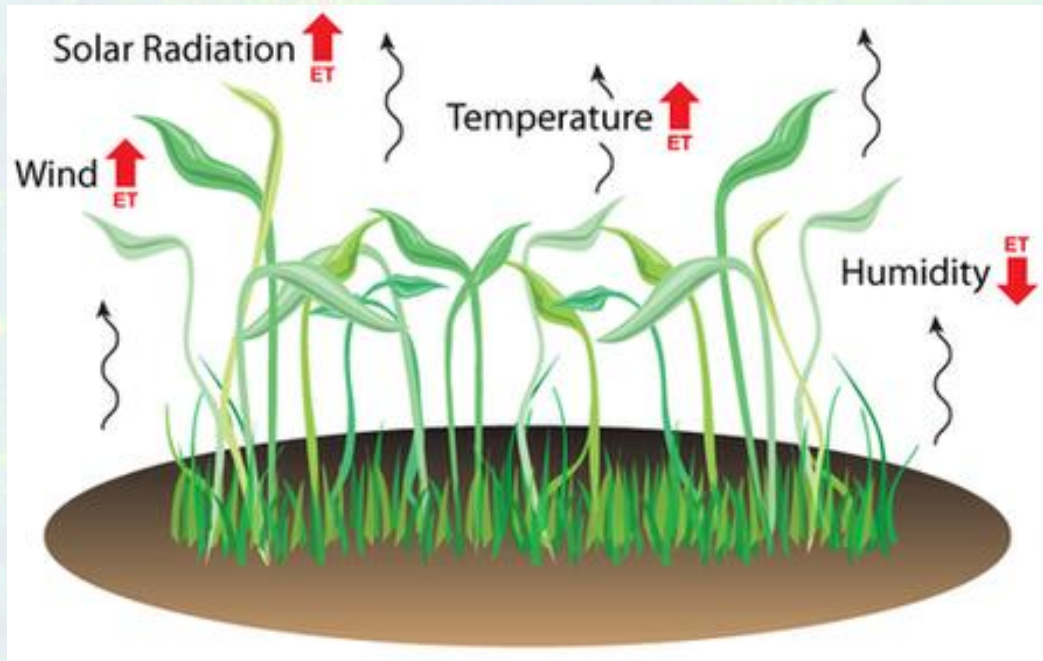
## Lots of definitions

- $ET_o$  – grass crop reference evapotranspiration
- $ET_c$  – crop evapotranspiration
- $ET_a$  – actual evapotranspiration
- $ET_p$  – potential crop evapotranspiration
- $ET_a$  – actual evapotranspiration

**Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56**




# Atmospheric Drivers of ET



- Sunlight – more sunlight, higher ET
- Temperature – higher temperature, higher ET
- Wind – higher wind, higher ET and
- Humidity – higher humidity, lower ET





## Constrainers of ET

- In adequate soil water
- Nutrient deficiency
- Salt toxicity
- Ion toxicity
- Pests and diseases



# Methods of Measuring ET

## Weighing lysimeter

### Research level

- Measures **mass** of water input and output
- Very low spatial and temporal resolution
- \*5% measurement error with trained expert
- Requires trained operator and analytical scientist
- Expensive





# Methods of Measuring ET

## Eddy Covariance

### Research level

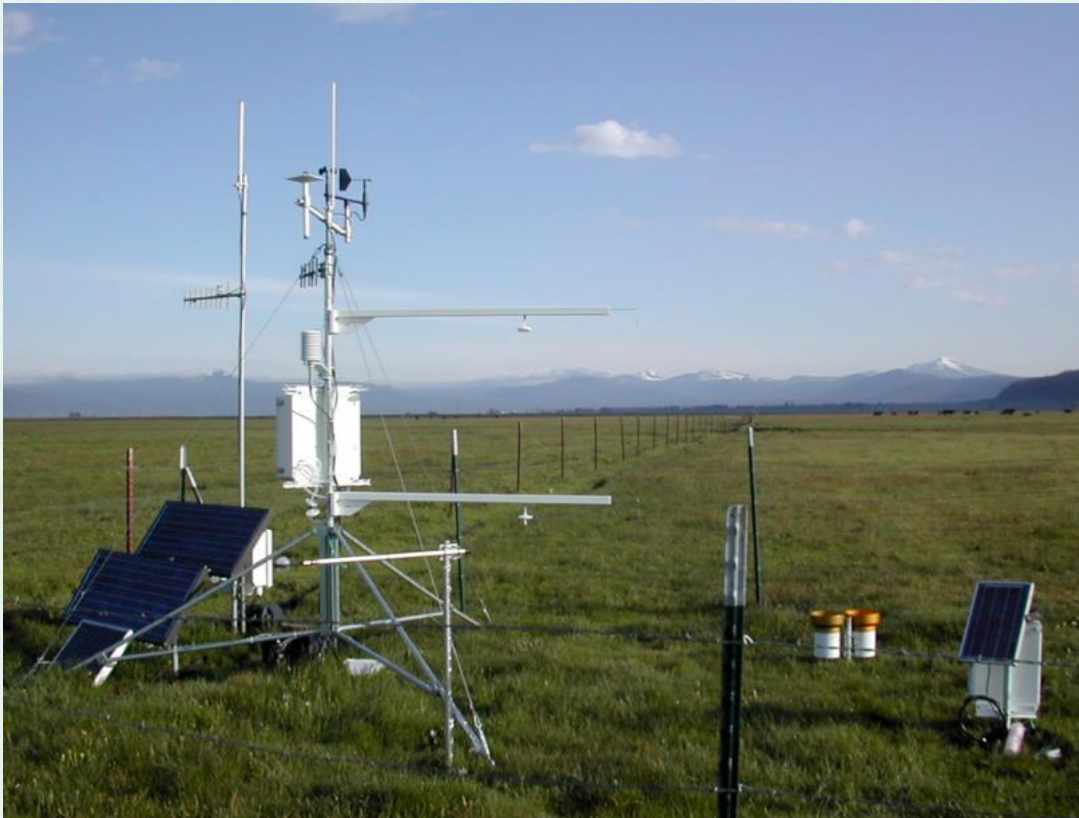
- Sonic anemometer measures **turbulent air**
- Low spatial and temporal resolution
- \*10-15% measurement error with trained expert
- Requires trained operator and analytical scientist
- Expensive





# Methods of Measuring ET

## Bowen Ratio



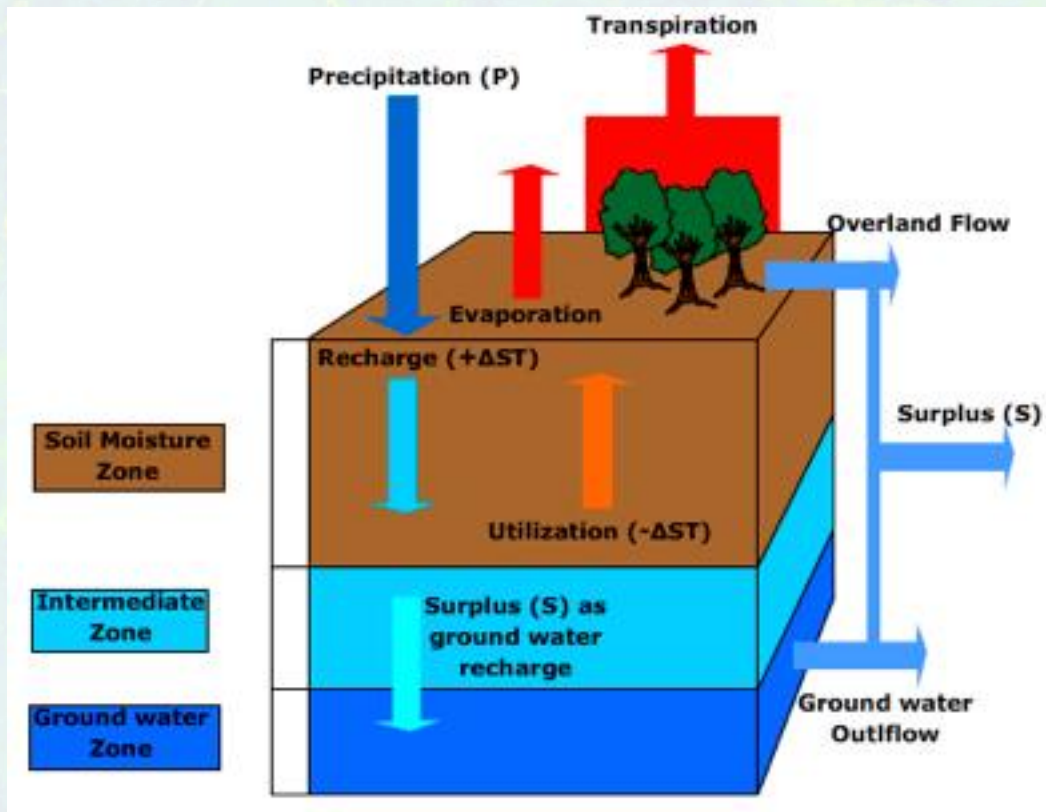
### Research level

- Localized **heat** measurements
- Low spatial and temporal resolution
- \*10% measurement error with trained expert
- Requires trained operator and analytical scientist
- Expensive



# Methods of Measuring ET

## Field Water Balance



### Research or applied

- Requires accounting for all inflow and outflows
- Field scale-high temporal resolution
- Difficult to get quantify all flow paths
- \*10% measurement error with trained expert
- Expensive



# Methods of Measuring ET

## Weather Station and Penman-Monteith Equation

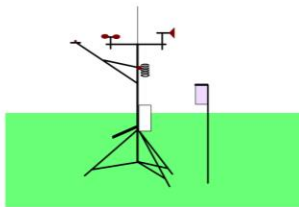
THE ASCE STANDARDIZED REFERENCE  
EVAPOTRANSPIRATION EQUATION

### Appendices A - F

Environmental and Water Resources Institute  
of  
the American Society of Civil Engineers

Standardization of Reference Evapotranspiration Task Committee

December 21, 2001  
revised July 9, 2002  
Draft



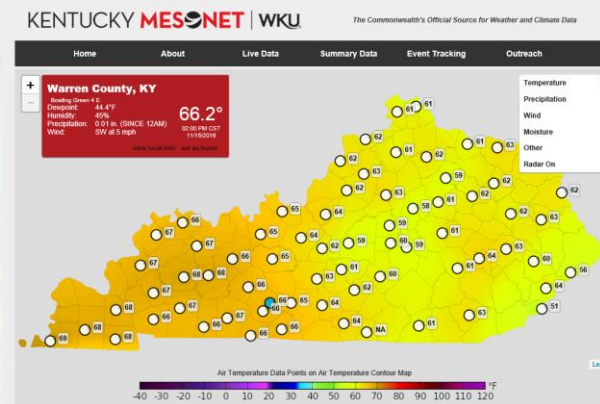
Our Passport to Professional Excellence



- ASCE standard equation.
- Referenced to **grass** or alfalfa.
- Weather inputs used to calculate a time-based reference value.


### Available Data

- Air Temperature
- Relative Humidity
- Solar Radiation
- Wind Speed
- Dew Point Temperature
- Precipitation
- Wind Direction





# Reference ET (ETo) California Dept. of Water Resources



The screenshot shows the CIMIS (California Irrigation Management Information System) website. At the top, there is a navigation bar with tabs for HOME, STATIONS, DATA, SPATIAL, and RESOURCES. Below this, there are sub-tabs for Spatial Overview, Spatial Maps, and Spatial Reports Login. The main content area is divided into sections: Spatial Maps, Solar Radiation Map, ETo Map, and ETo Zone Map. A calendar for June 2019 is displayed, with the 18th highlighted. To the right of the calendar is a map of California labeled 'ETO View' with a color scale ranging from 1.3 mm (dark blue) to 9.6 mm (dark red). The website footer contains links for Back to Top, Contact Us, and Site Map, along with a copyright notice for 2019 State of California.

Log in | Register

## CIMIS

CALIFORNIA IRRIGATION MANAGEMENT INFORMATION SYSTEM  
CALIFORNIA DEPARTMENT OF WATER RESOURCES

HOME STATIONS DATA SPATIAL RESOURCES

Spatial Overview Spatial Maps Spatial Reports Login

### Spatial Maps

Select the calendar on the right to see daily ETo or Solar Radiation maps of California based on Spatial CIMIS data. To retrieve and schedule Spatial CIMIS data, please register, log in, and click on the Spatial Report or Schedule Spatial Report tabs above. Spatial data are available back to 2003.

### Solar Radiation Map

Spatial CIMIS Solar Radiation maps are generated from remotely sensed satellite data from the Geostationary Operational Environmental Satellites (GOES) using the Heliosat-II model. See the Spatial Overview for more details.

### ETo Map

Spatial CIMIS ETo Maps are generated by coupling remotely sensed satellite data from the Geostationary Operational Environmental Satellites (GOES) with interpolated CIMIS station data and using the standardized American Society of Civil Engineers Penman-Monteith equation to calculate ETo at 2-km spatial resolution. See the Spatial Overview tab above for more details.

### ETo Zone Map

The [ETo Zones Map](#) allows users to view the reference evapotranspiration (ETo) Zones for the State of California. The map was developed by DWR and UC Davis and divides the State into 18 zones based on long-term monthly average ETo. The ETo values were calculated using data from various data sources including CIMIS weather stations that had at least five years of archived data. This map can also be viewed and/or downloaded as a PDF document using this link.

☐ Solar Radiation Map (MJ/m<sup>2</sup>)  
☑ ETo Map (mm) ETo 06/18/2019

Sun	Mon	Tue	Wed	Thu	Fri	Sat
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	1	2	3	4	5	6

ETO View

9.6  
7.5  
5.4  
3.4  
1.3  
mm

This is a newly emerging technique and is in the process of being refined. Although the data quality presented here is acceptable for many applications, we do not guarantee its accuracy. Therefore, neither the CIMIS program, the Department of Water Resources (DWR), UC Davis, nor any other party who participated in the development of this product shall be responsible for errors in this data, nor for any resulting consequences from using this data.

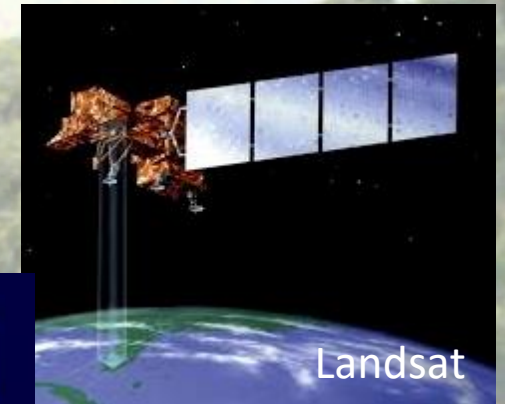
Back to Top Contact Us Site Map

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Copyright © 2019 State of California

- Daily publication of ETo maps at a 2km scale.
- Growers and urban agencies use data for irrigation scheduling.
- Free but requires an account



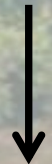
# Methods of Measuring ET Remote Sensing (thermal imaging)



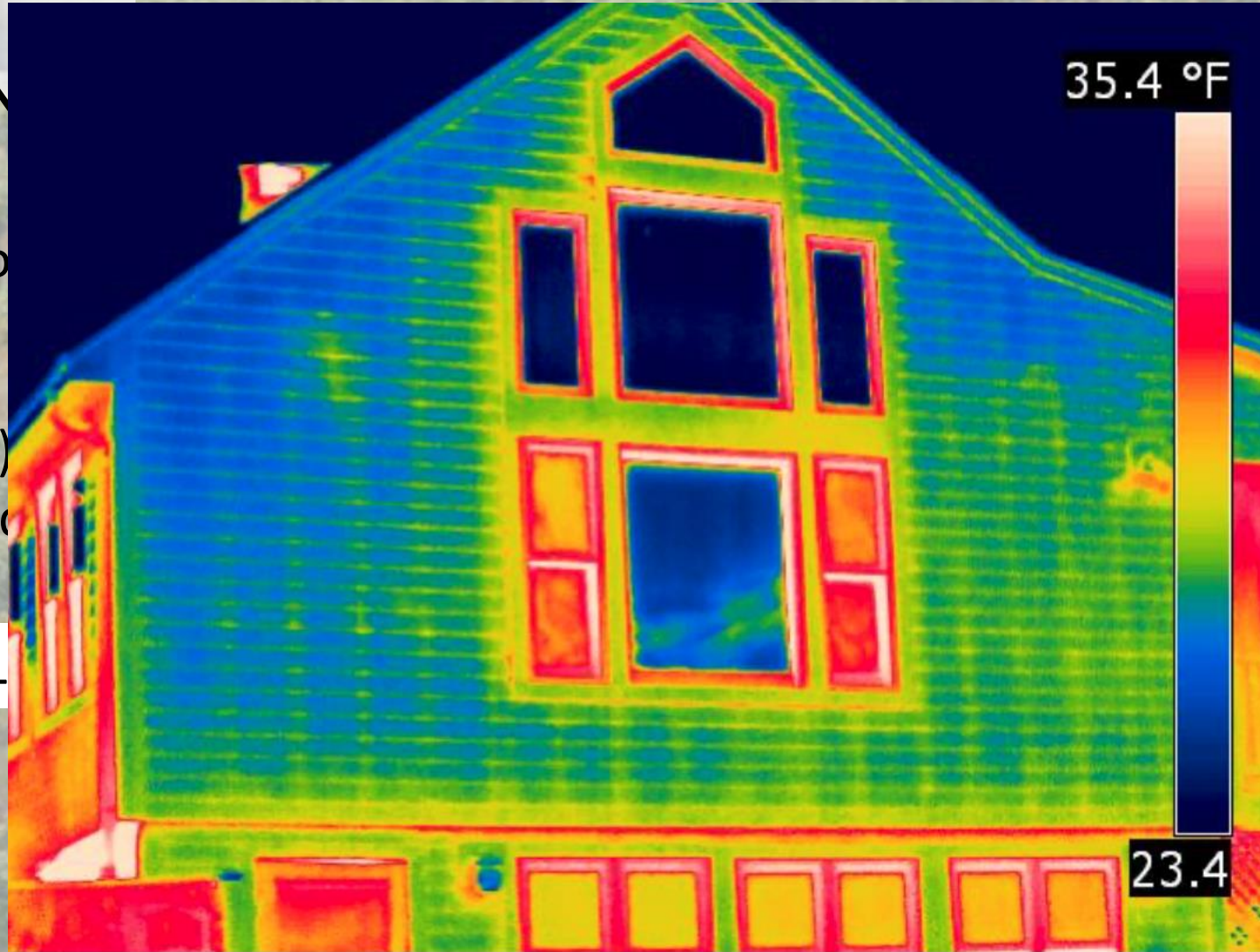
Net Radiation (Rn)  
(energy in from the sun)

Evapotranspiration

Soil Heat Flux (G)  
(warms the ground)



ET (L)



warm the air  
(warming the air)  
(warming the air)  
thermal imager

warm the air (H)



# Accuracy of ET Measurement Methods

**Table 2**

Error, expressed as one standard deviation from the true mean value, expected for various types of ET measurement or retrieval systems.

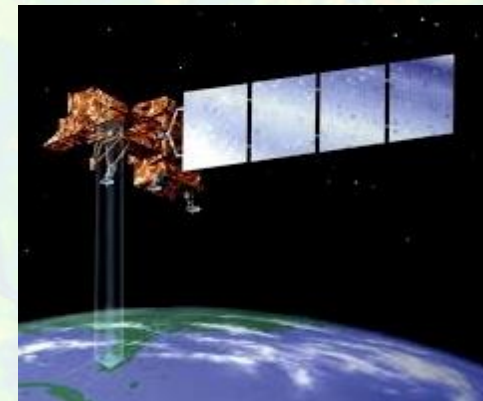
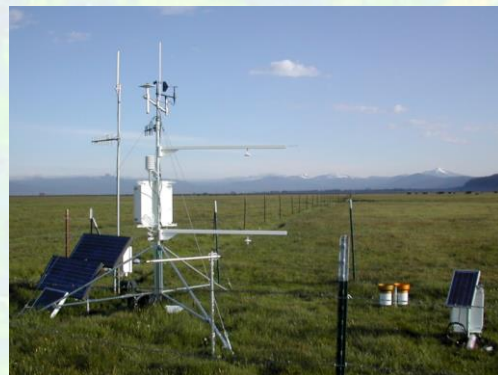
Method	Typical error, %	Error for an experienced expert, trained and steeped in the physics of the process, %	Error for a novice or a person working outside their specialty area, %	Additional error caused by physical or equipment malfunction, %
Lysimeter	5–15	5	20–40	5–40
Soil water balance	10–30	10	20–70	10–40
Bowen ratio	10–20	10	20–50	5–40
Eddy covariance	15–30	10–15	30–50	10–40
Remote sensing energy balance	10–20	5–15	30–40	5–10
Remote sensing using vegetation indices	15–40	10–30	20–40	5–10
Sap flow	15–50	10–40	40–200	20–100
Scintillometers <sup>a</sup>	10–35	10–15	20–50	5–30

<sup>a</sup> Scintillometers measure sensible heat flux, only, and require estimating ET as a residual of the energy balance ( $\lambda E = R_n - G - H$ ).



# Spatial, Temporal, and Cost of Methods of Measuring ET

Method	Resolution		Cost
	Spatial	Temporal	
<b>Research</b>			
Weighing lysimeter	very low	very high	very high
Eddy covariance	very low	high	very high
Surface renewal	very low	high	very high
<b>Applied</b>			
Field water balance	low	high	very high
Weather data	low	high	low
Remote sensing	high	high	low





# Irrigation Scheduling Considerations

- ET varies by crop, time-of-year, and location.
- Meeting a crop's yield potential requires adequate soil water content.
- Coupling ET demand to soil water content is required to ensure adequate soil water.
- Field variability can be significant, and knowledge of the variation is essential for maximizing uniformity of irrigation and fertilizer application.



# Irrigation Scheduling Considerations

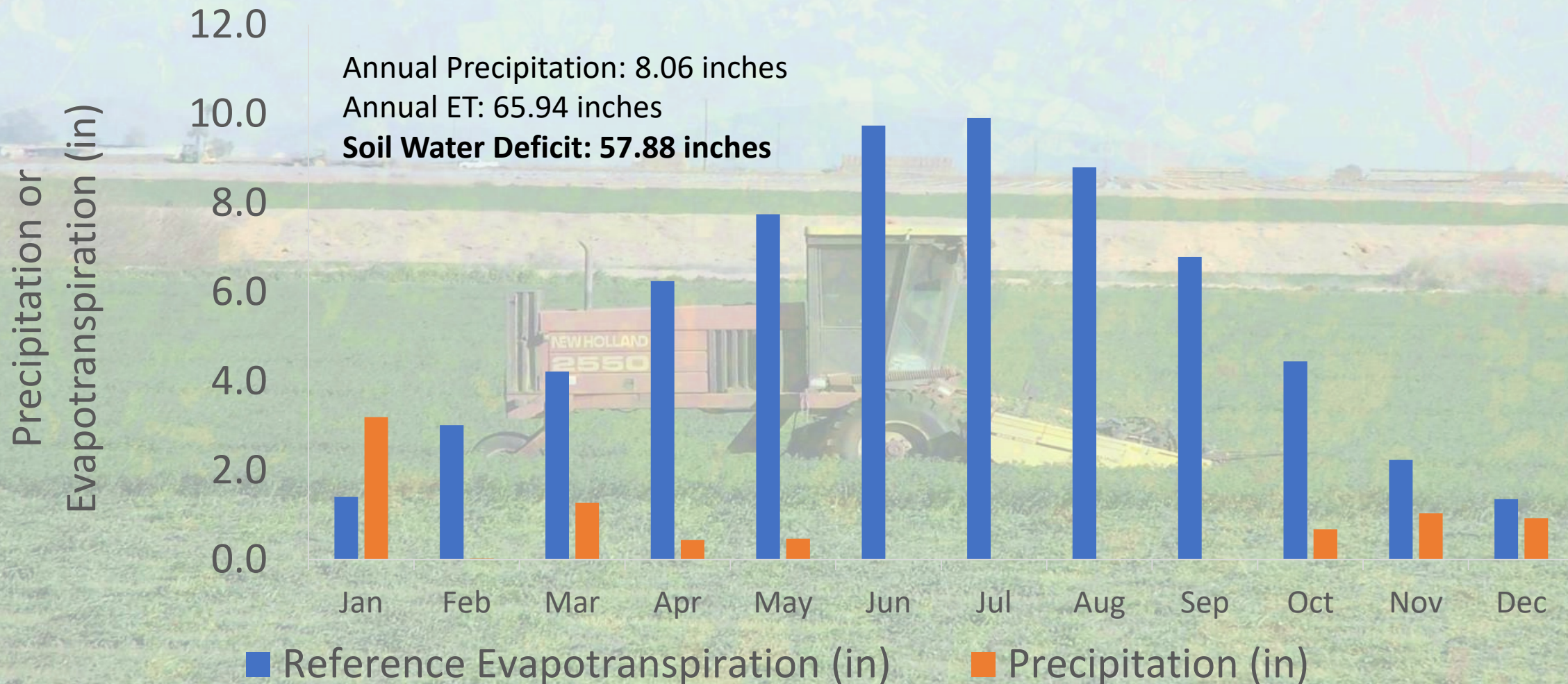
- Providing water for irrigation requires pumping, supply lines, and a method of irrigating (i.e. drip, pivot, sprinkler, or furrow).
- Purchasing, constructing, and operating pumping plants, supply lines, and irrigation systems is expensive and should be sized to minimize cost and maximize profit.
- Take-home message is that you need ET demand information to support irrigation scheduling.





# Fundamentals of Irrigation Scheduling

## Matching demand and supply

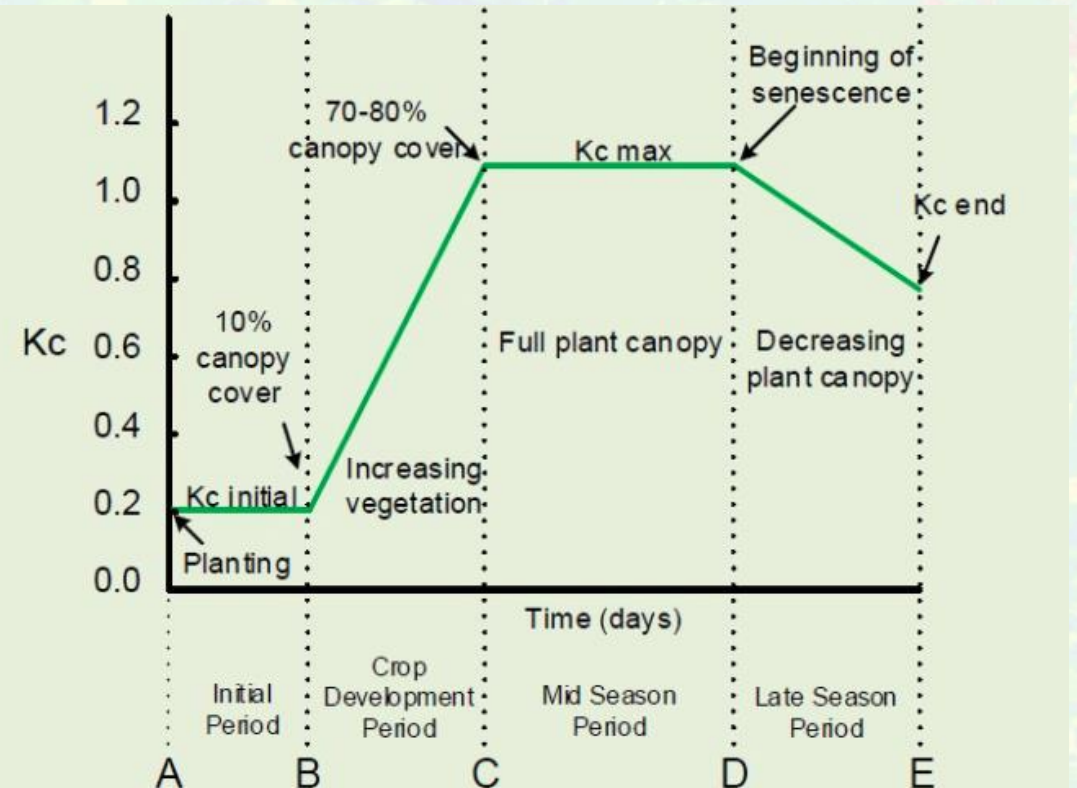
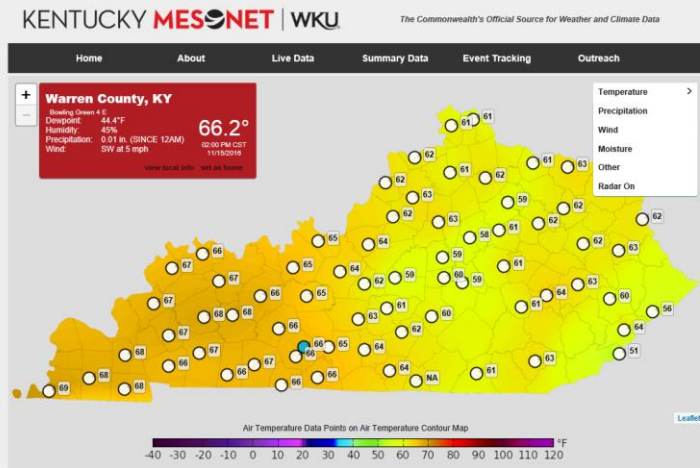




# Fundamentals of Irrigation Scheduling

## Crop ET demand using crop coefficients

$$\text{Crop ET demand (ETc)} = \text{ETo (Reference)} * \text{Crop Coefficient (Kc)}$$





# Irrigation Scheduling Approaches

- Experience (sound, crop appearance)
- Rotation (water availability)
- Equipment (cutters, bailers, rakes)
- Demand and soil water content



# Irrigation Scheduling Checkbook method

Checkbook method tracking outflow (ET) and inflow (irrigation water)

Irrigation water requirement

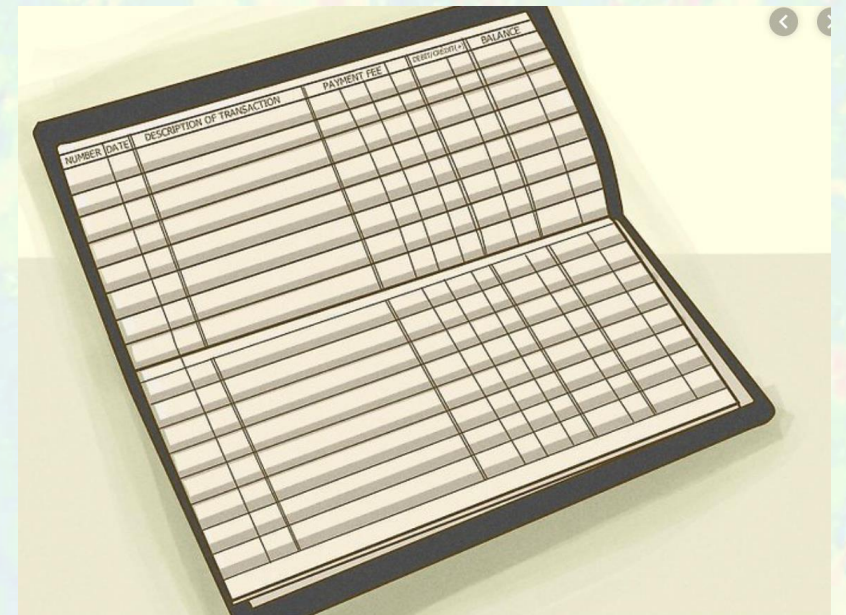
Crop ET demand

+

System efficiency

+

~~Leaching needs (arid zone issue)~~





# Sensor Based Irrigation Scheduling

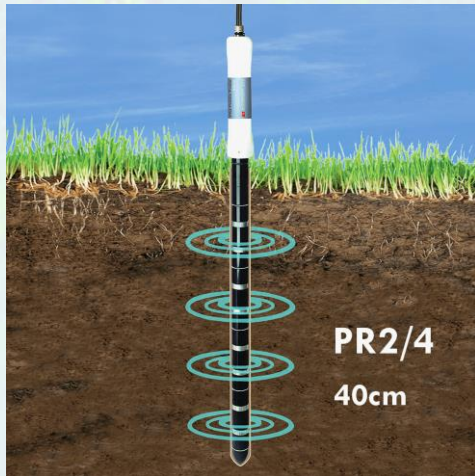


tensiometer



surface renewal

- Point measurements
- Maintenance
- Data collection



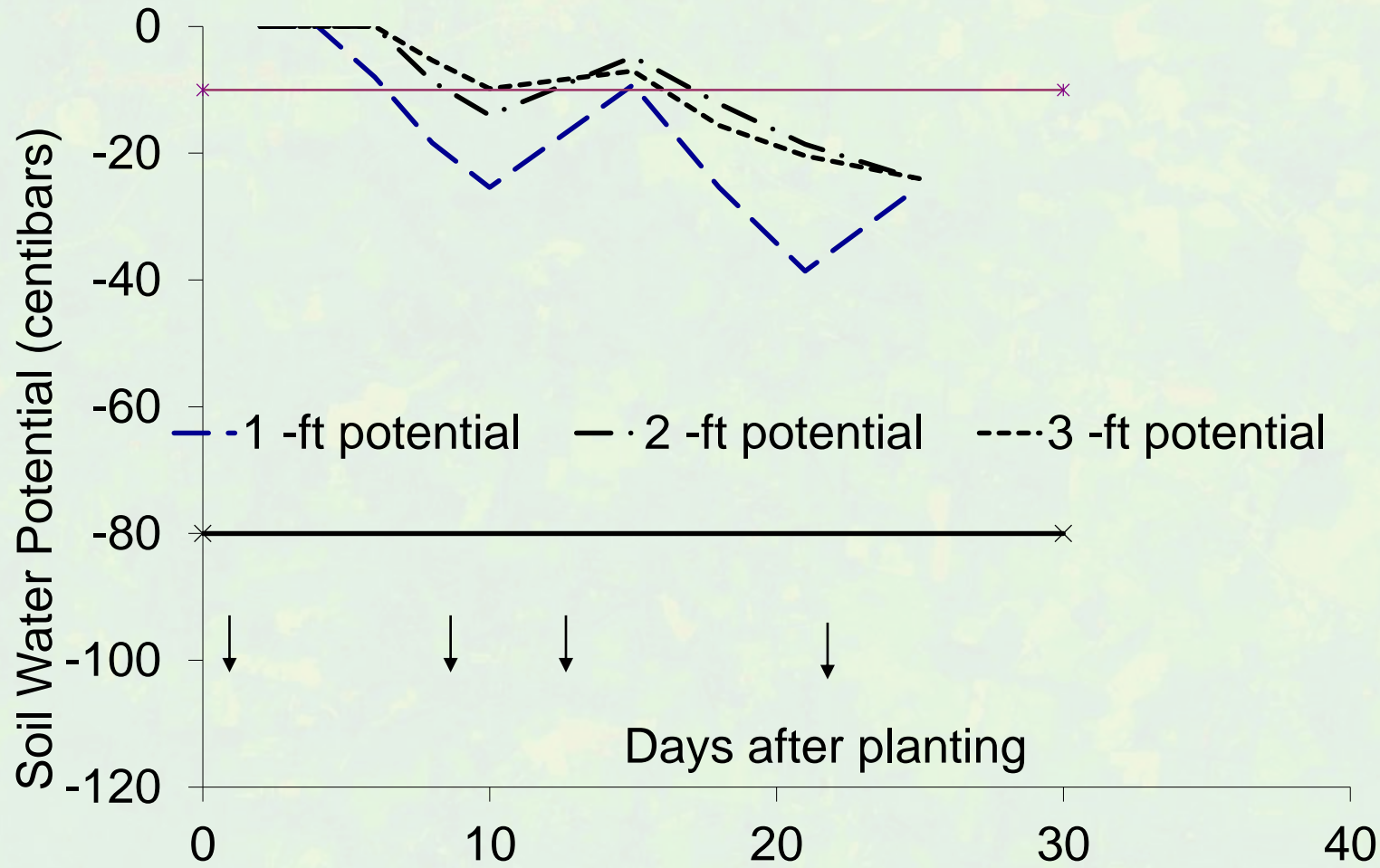
dielectric or capacitance



sap flow thermocouple



# Sensor Based Scheduling



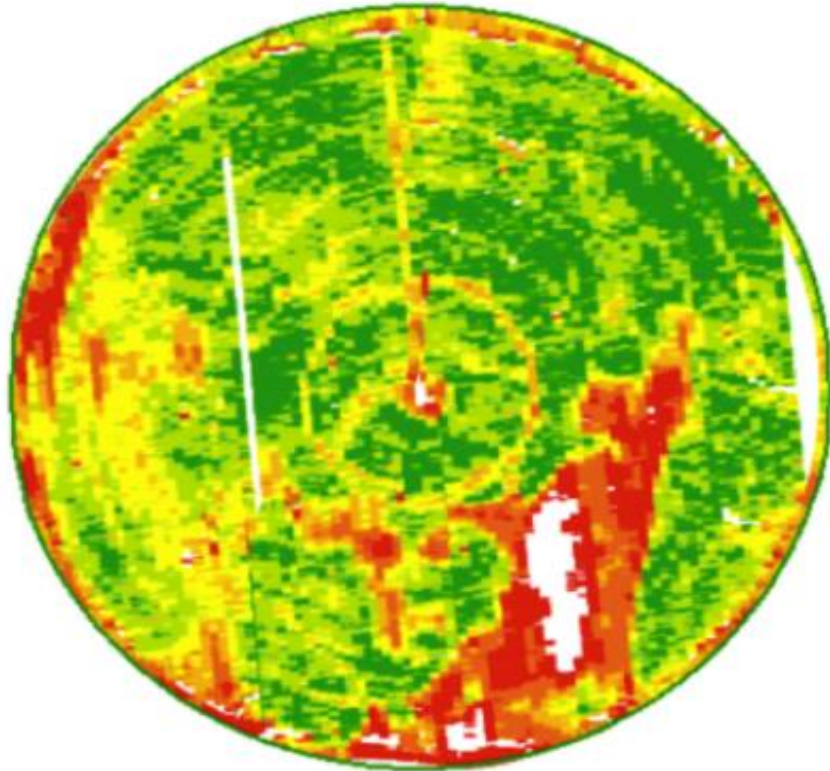
- Data management
- Data analysis
- Scheduling

Figure ( ): Beeman Southern Furrow



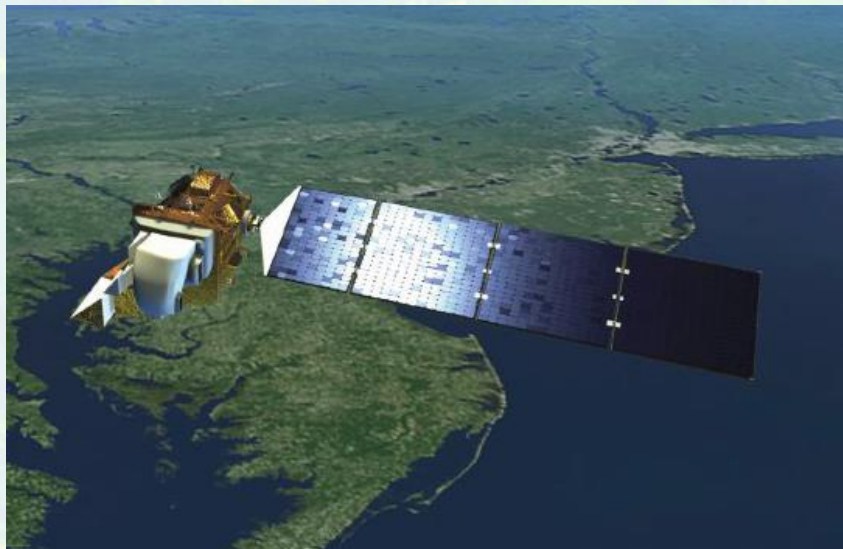
# Sensor Based Scheduling

## Selecting sensor placement



- Selecting the location for sensor placement impacts scheduling decisions.
- Sensors placed in an area with low soil water capacity may result in over watering.
- Sensors placed in an area with a high soil water capacity may result in under watering.

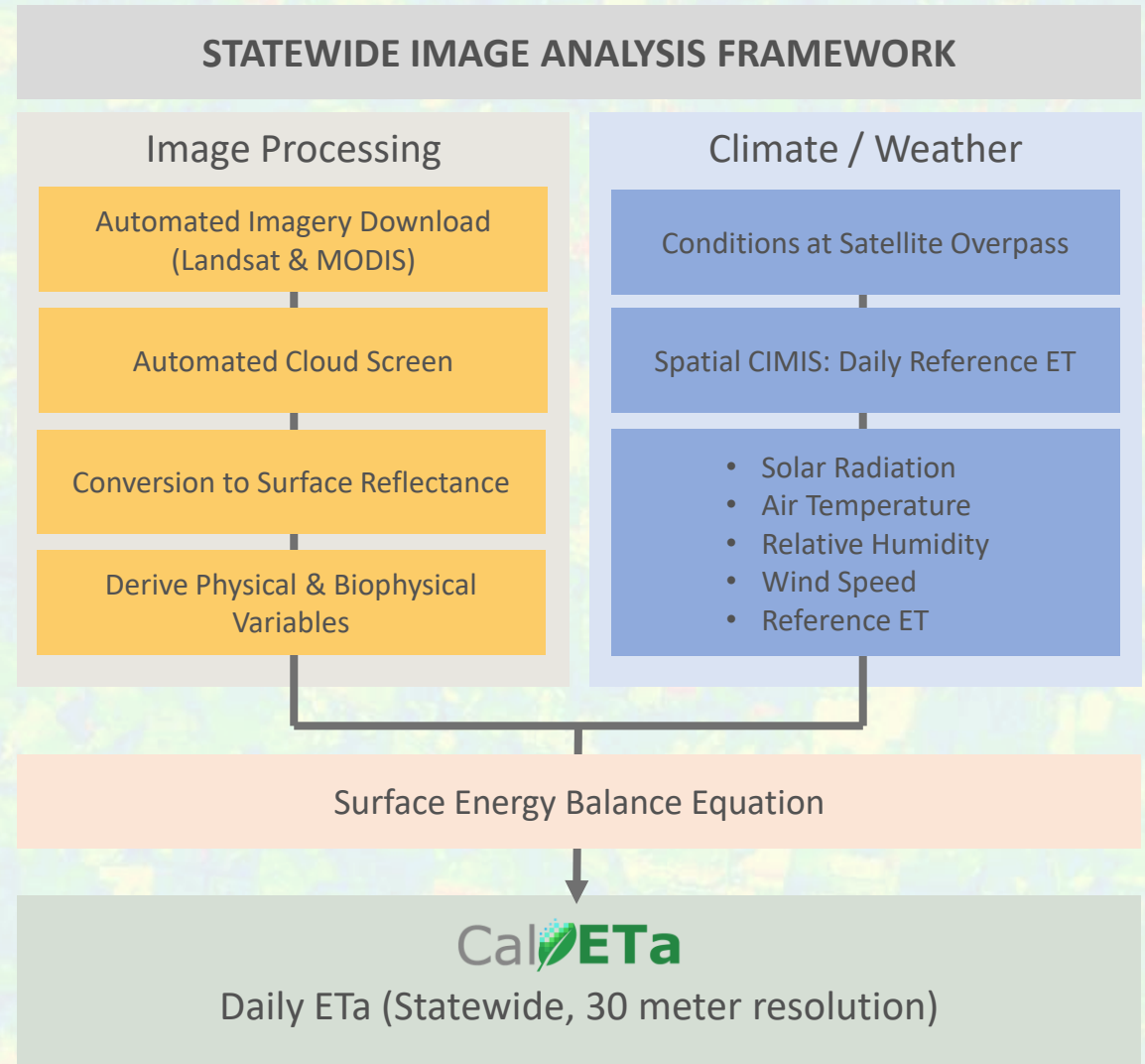
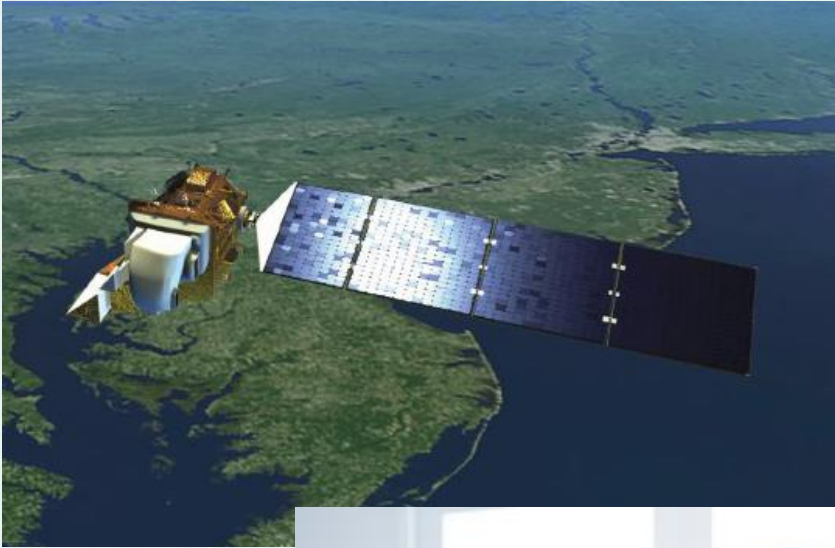




Irrigation scheduling in the age  
of computers and satellites

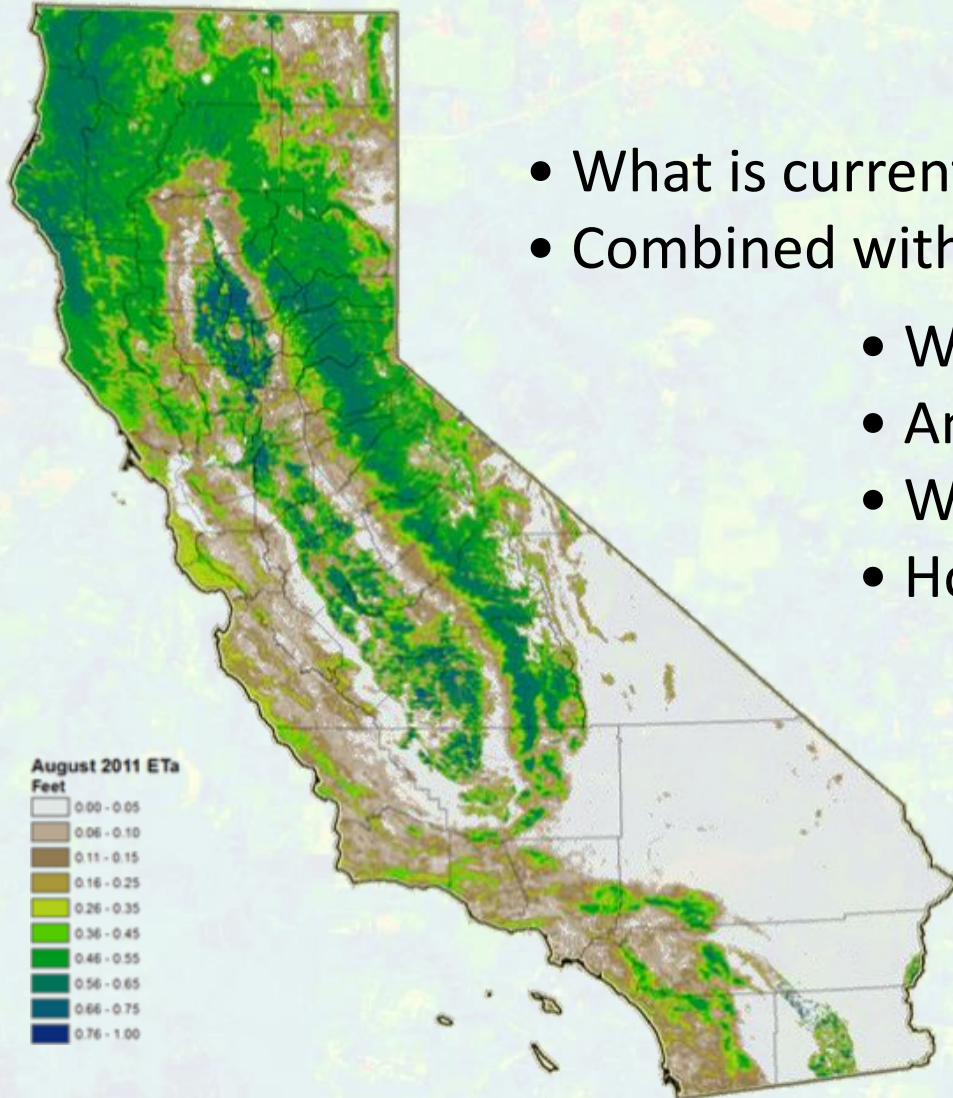




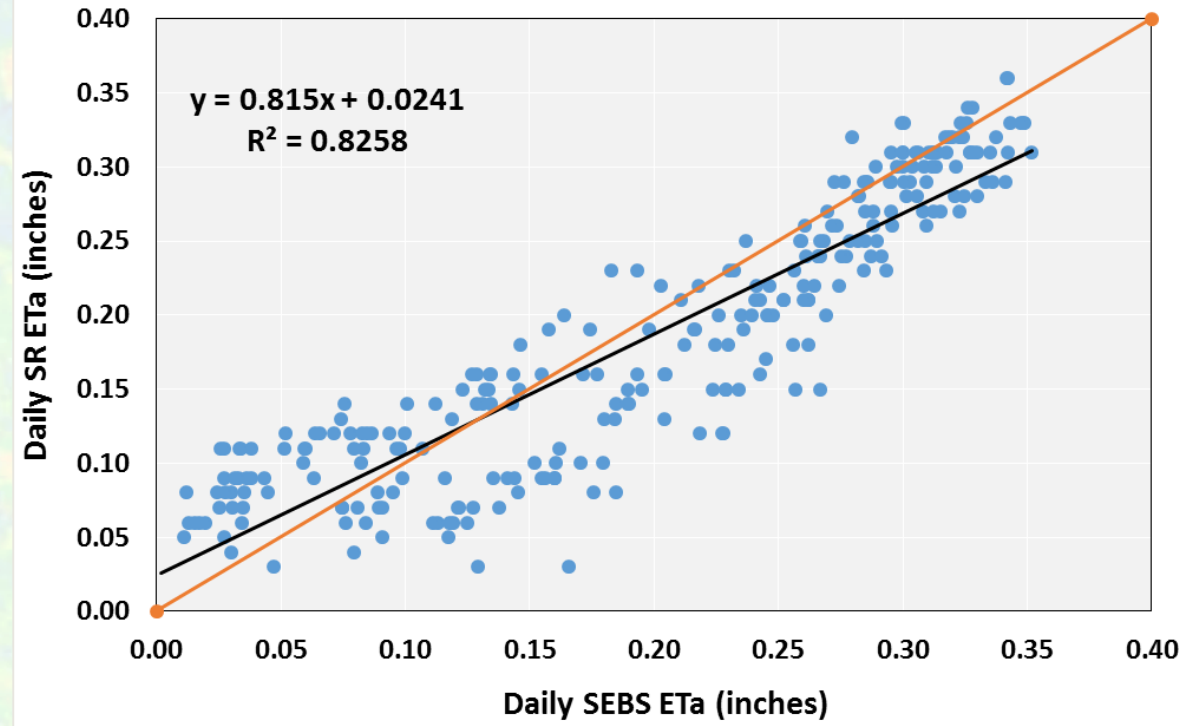
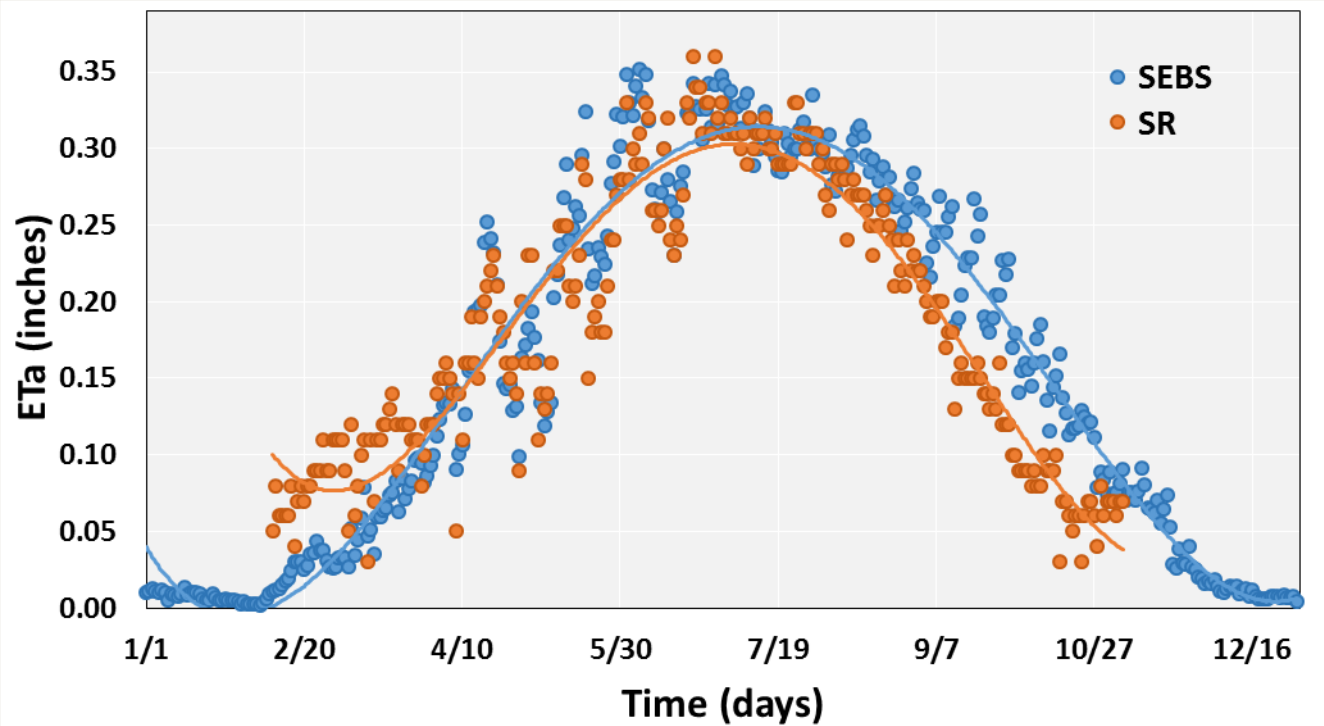




- What is current and historic ETa for specific crop types?
- Combined with surface water, how much groundwater is being used?
  - What is the uniformity of water use?
  - Am I meeting my crop's water needs?
  - Where to locate field-sensors?
  - How to make point-measurements actionable?







Trend and relationship of CalETa and a ground-based surface energy monitoring station (Tule surface renewal) for a fully irrigated pistachio orchard.





30m\*30m measurement

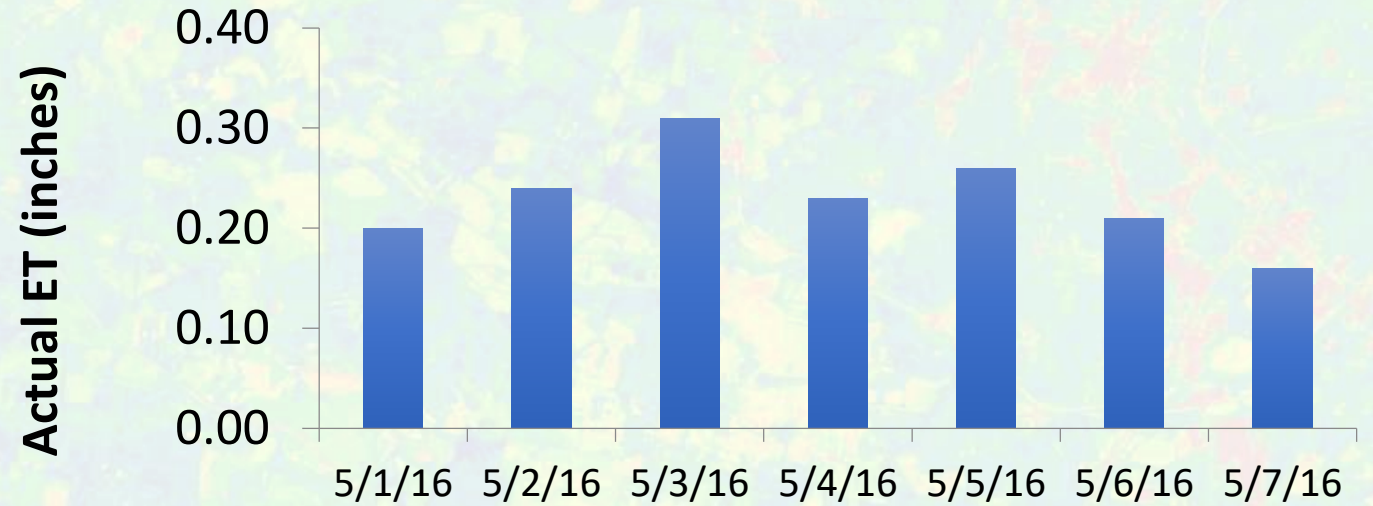
- Color image shows ETa by pixel.
- Color is used to represent the depth of ET.
- Blue (cool) color is high ET.
- Brown (warm) color is low ET.
- A uniform color = uniform ET.





- Image is 169 pixels or 34 acres.
- 169 ET measurements points for analyzing ET.
- Each pixel is the average for all trees within the boundary of the pixel.
- Assuming a planting density of 125 trees/acre each pixel is the average ET of 25 trees.





Weekly demand for May 1-7, 2016 was 1.61 inches or 4.5 acre-feet for the 34 acre orchard.



# DISTRIBUTION UNIFORMITY

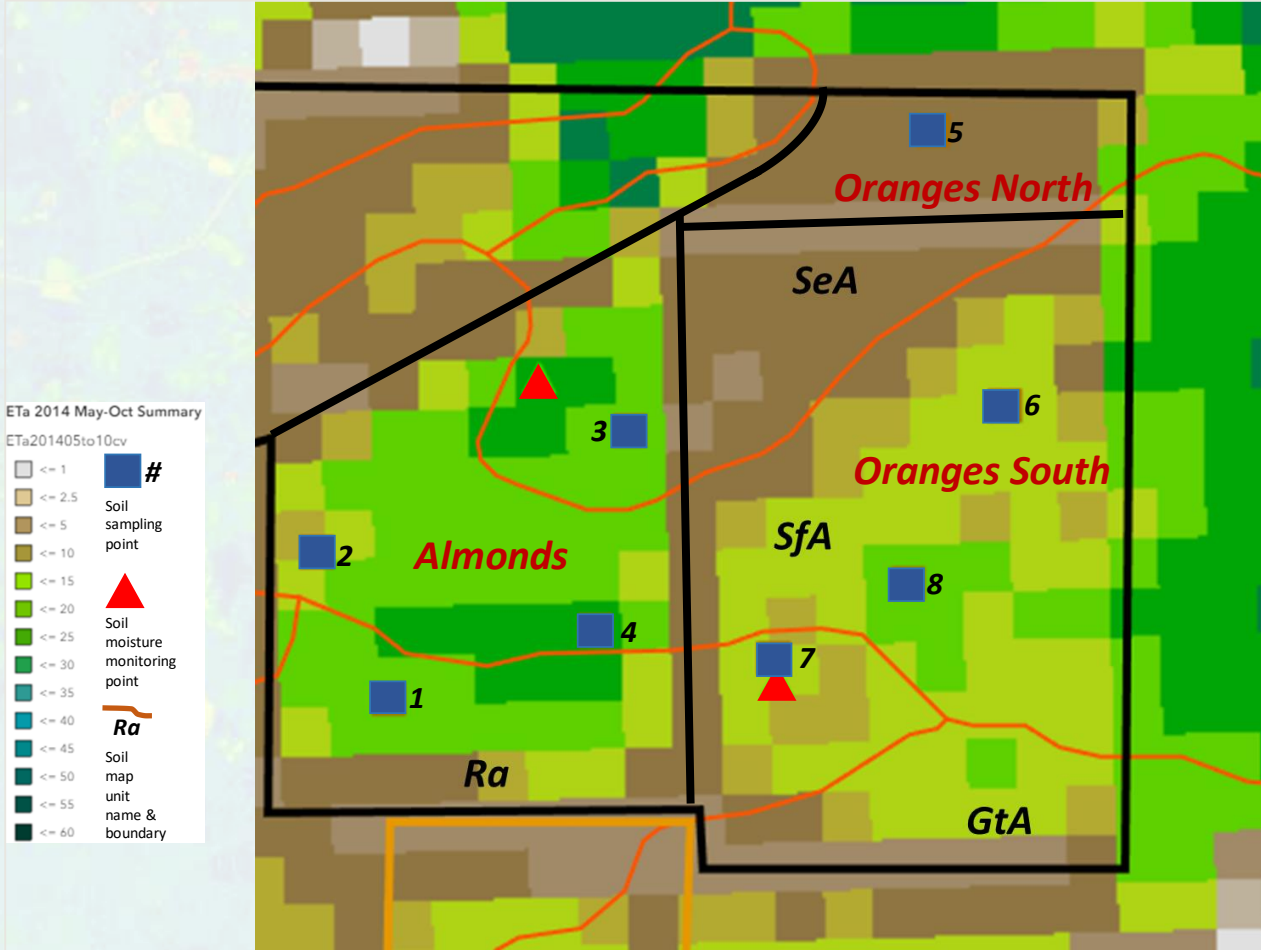
Irrigation system performance: Distribution uniformity (D.U.)

$\% \text{ D.U.} = (\text{inches applied to driest quarter of field} / \text{field average inches applied}) * 100$



Source: Allan Fulton, UCCE





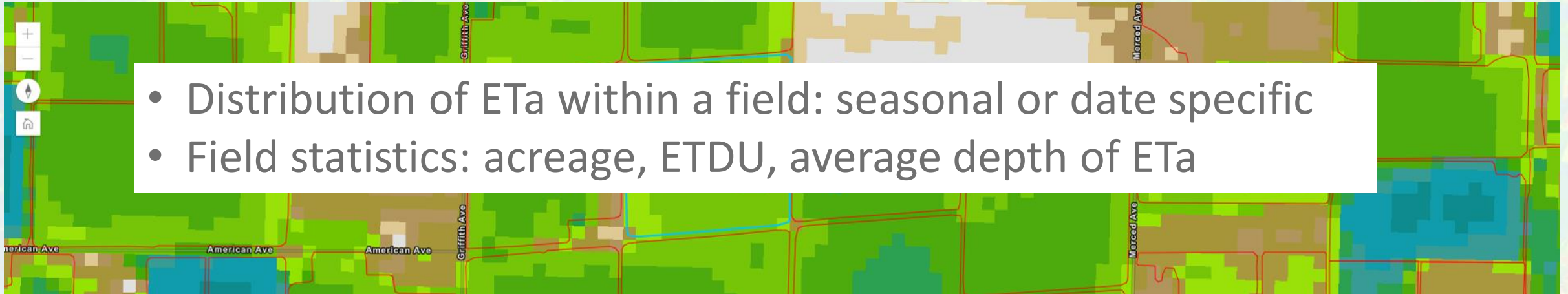
- Soil series delineated to help understand ET variability.
- Grower can use ET variability to investigate problem areas and to target solutions.
- Uniformity is a map – it does not tell you why there is an issue.







- Distribution of ET<sub>a</sub> within a field: seasonal or date specific
- Field statistics: acreage, ETDU, average depth of ET<sub>a</sub>



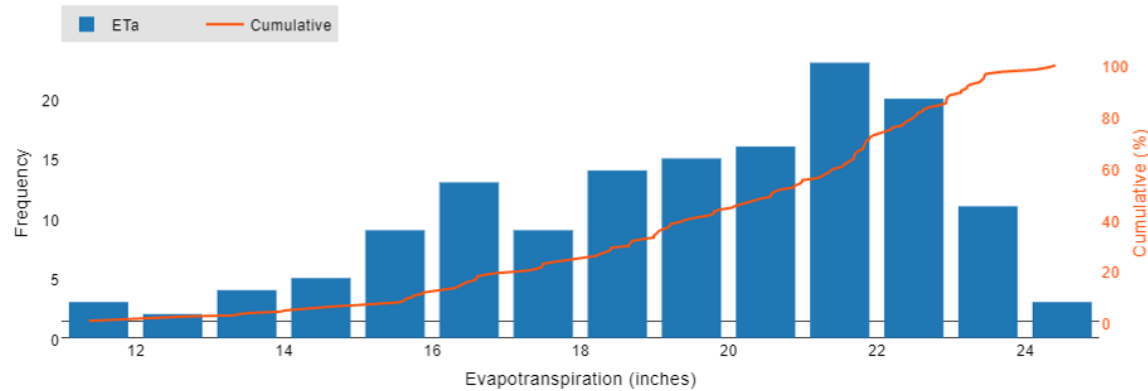
Field Variability Summary (FieldID: 231596, Total Acreage: 37.8)

Show/Hide Charts

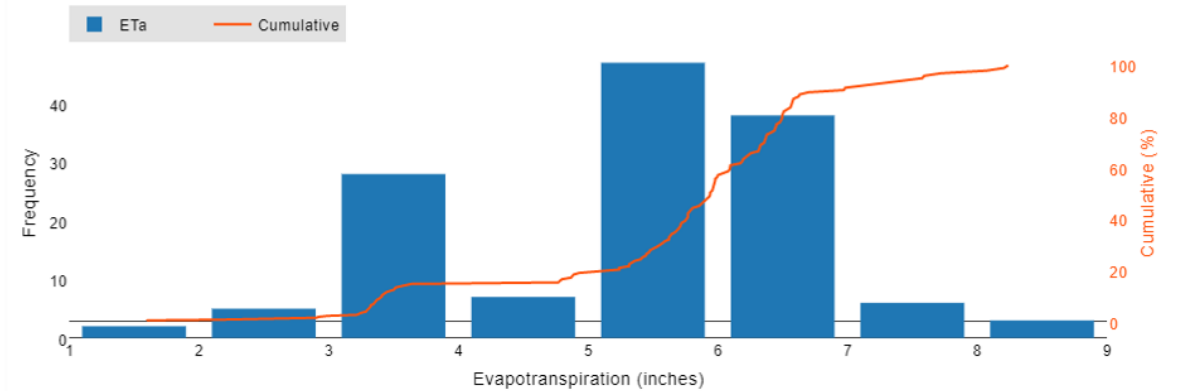
Toggle Basemap Topo Aerial Imagery 2014 May-Oct ET<sub>a</sub> 2014 Jul ET<sub>a</sub>

Note - Legend is visible under the Tools popup Show/Hide Tools

**May-October 2014**  
 Ave. Depth: 19.4", Total Volume: 61.1 acre-ft, ET Distribution Uniformity: 77.6%

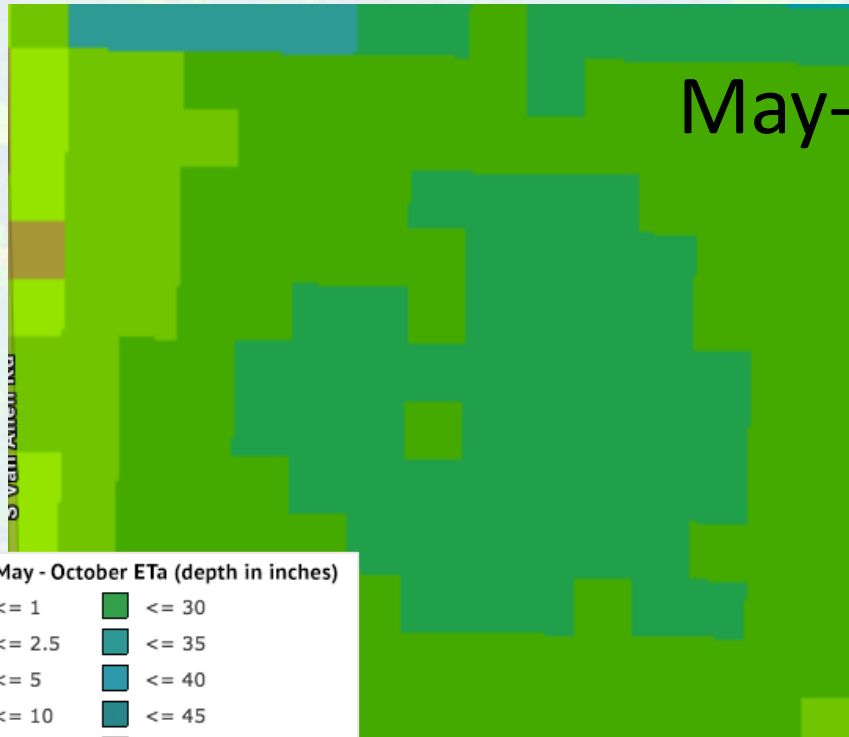


**July 2014**  
 Ave. Depth: 5.4", Total Volume: 17.0 acre-ft, ET Distribution Uniformity: 60.5%



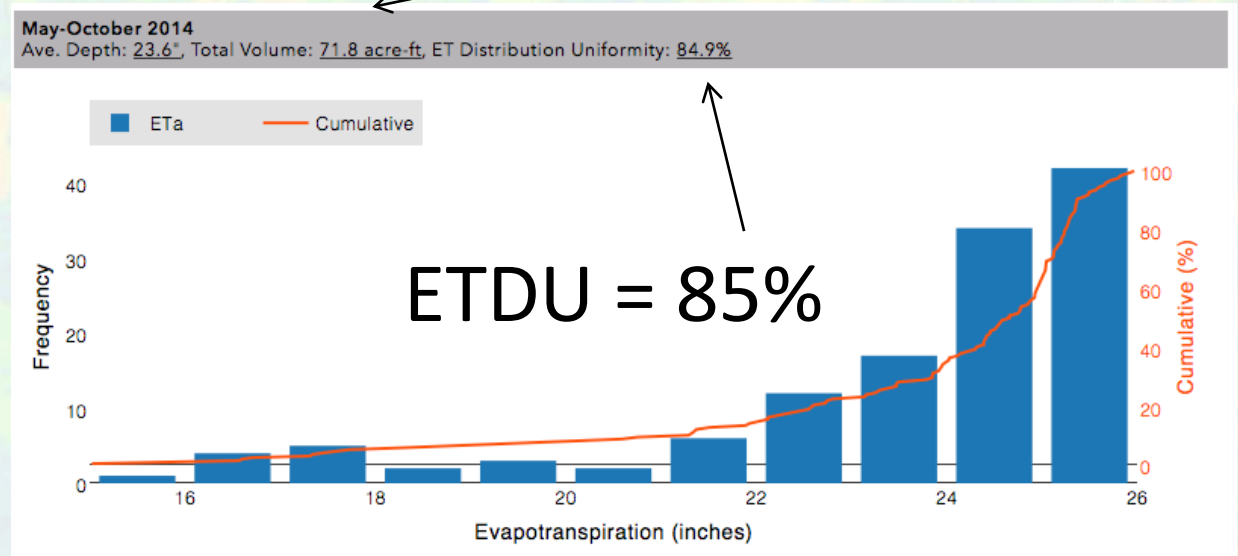
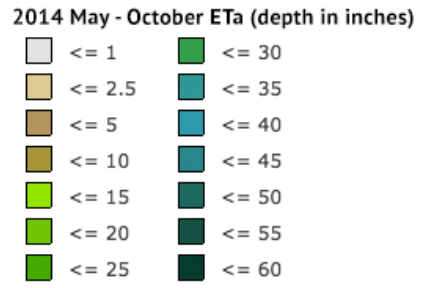


Using the distribution of ET in a field a measurement of irrigation uniformity is calculated using driest/average ET.



May-Oct Avg Depth: 23.6 in

Volume: 72 AF



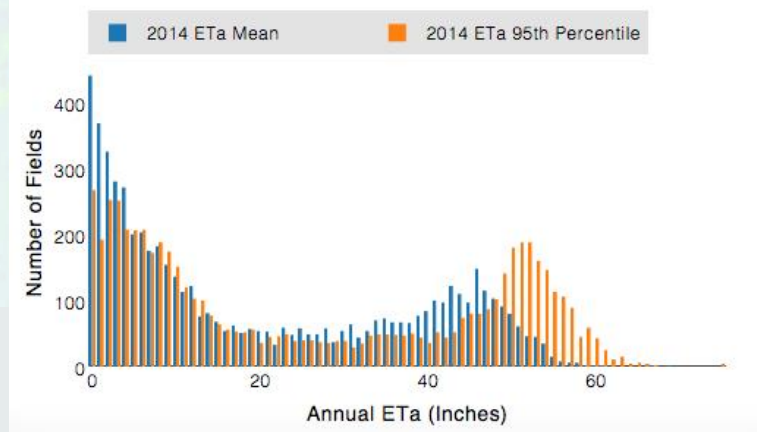




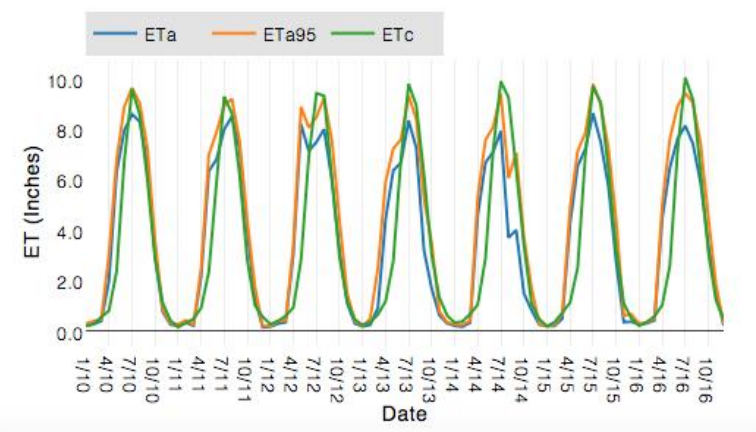
Field Summary for FieldID: 163155 | Acreage: 158.6

2014 Crop: Pistachios, DWR Legend: D | DECIDUOUS FRUITS AND NUTS, County: Kings

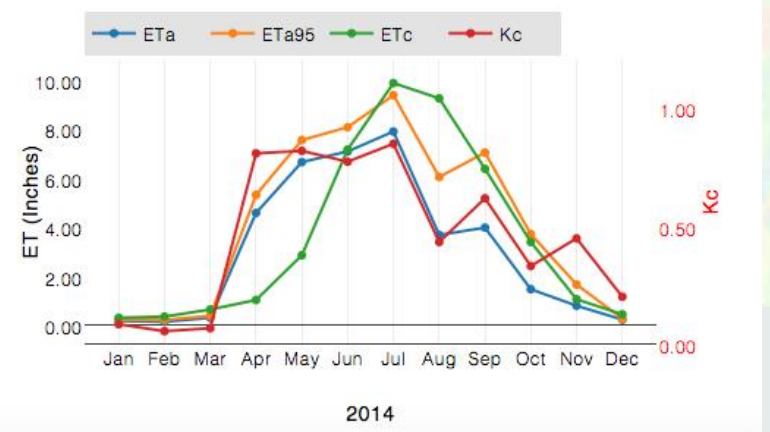
Statewide (5927 fields in 2014):



Selected Field: All Years

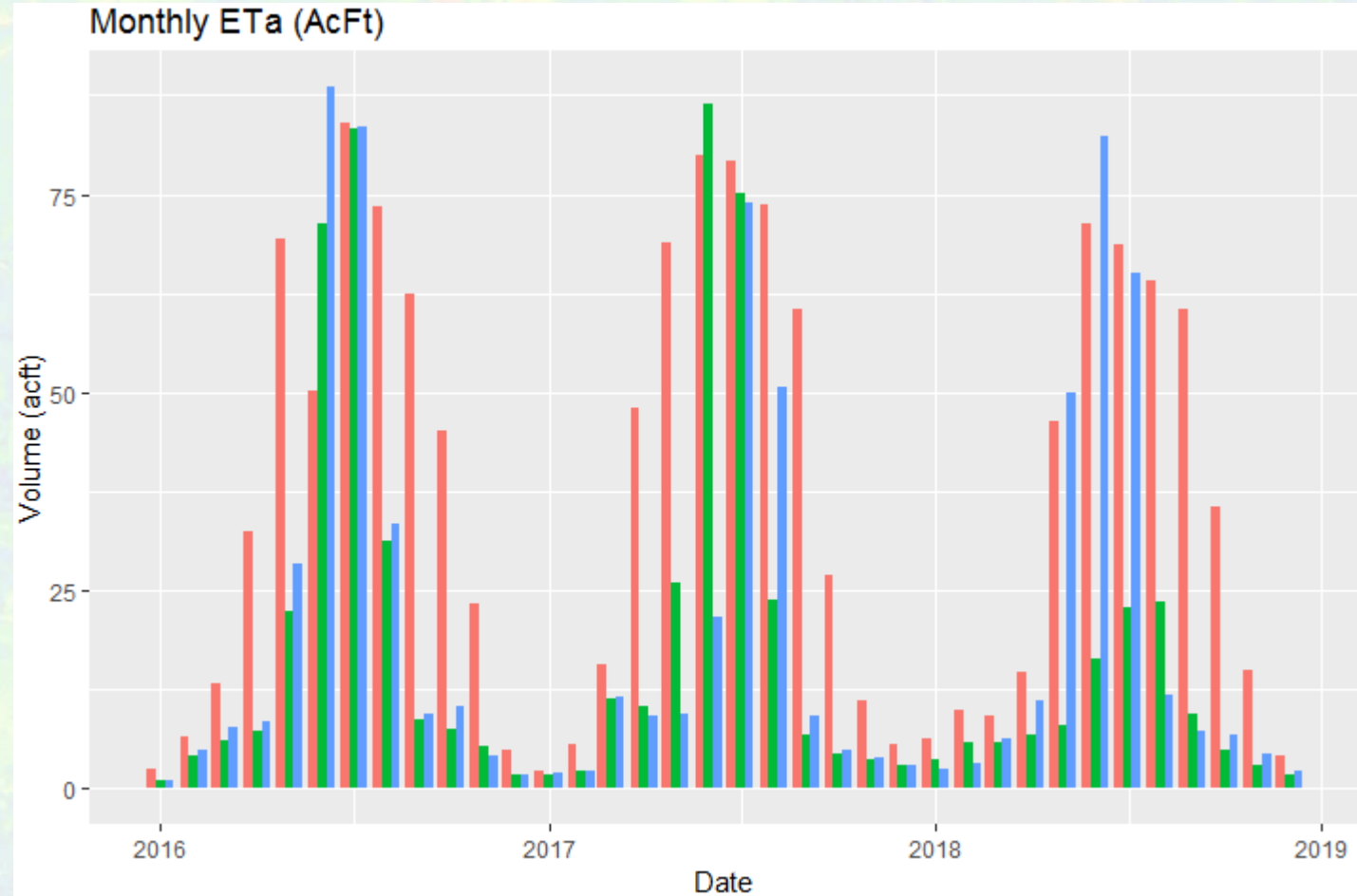
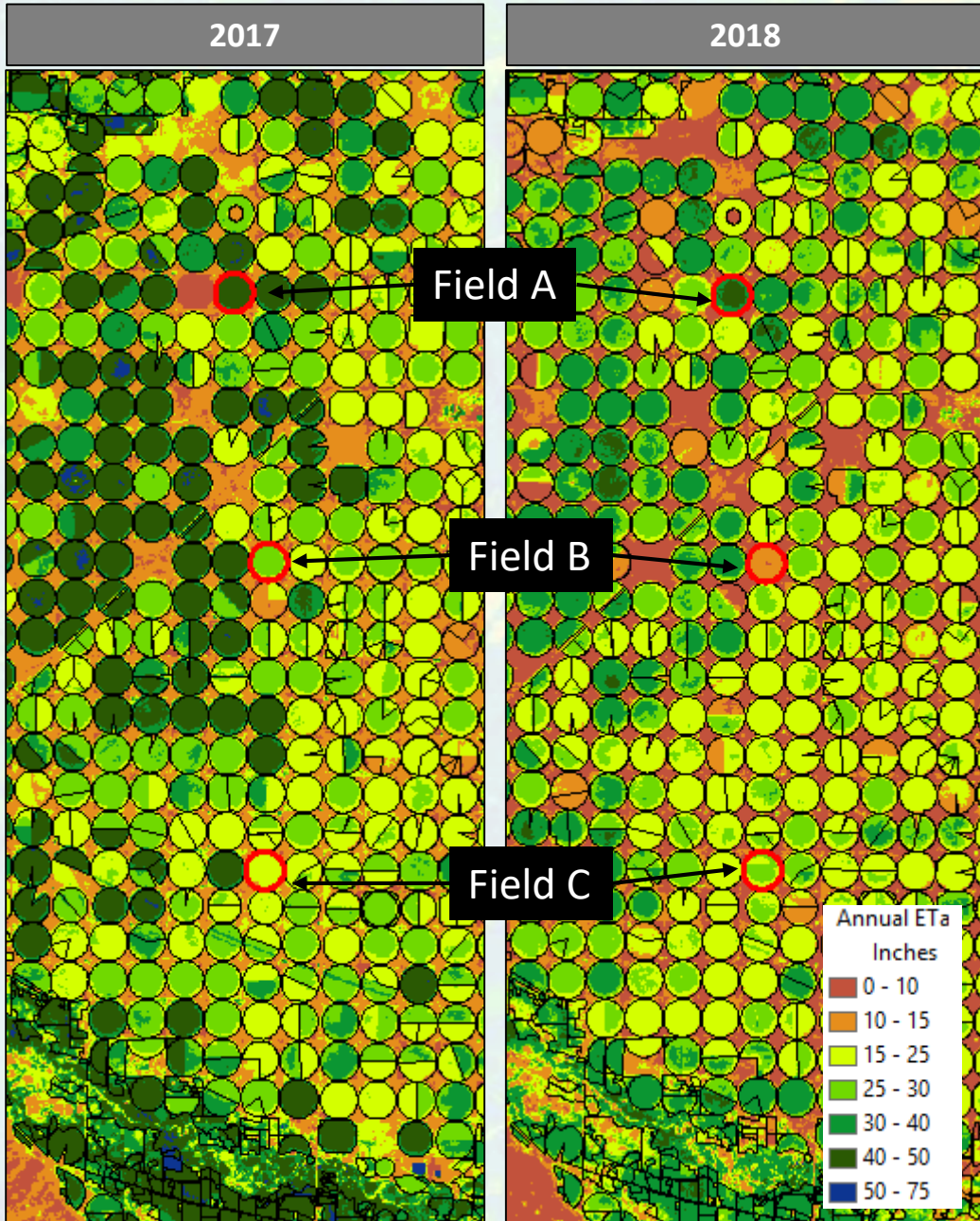


Selected Field: 2014 | Annual Totals: ETc=42.6, ETa=36.9, ET95=49.8





# San Luis Valley CO Pivot Irrigation

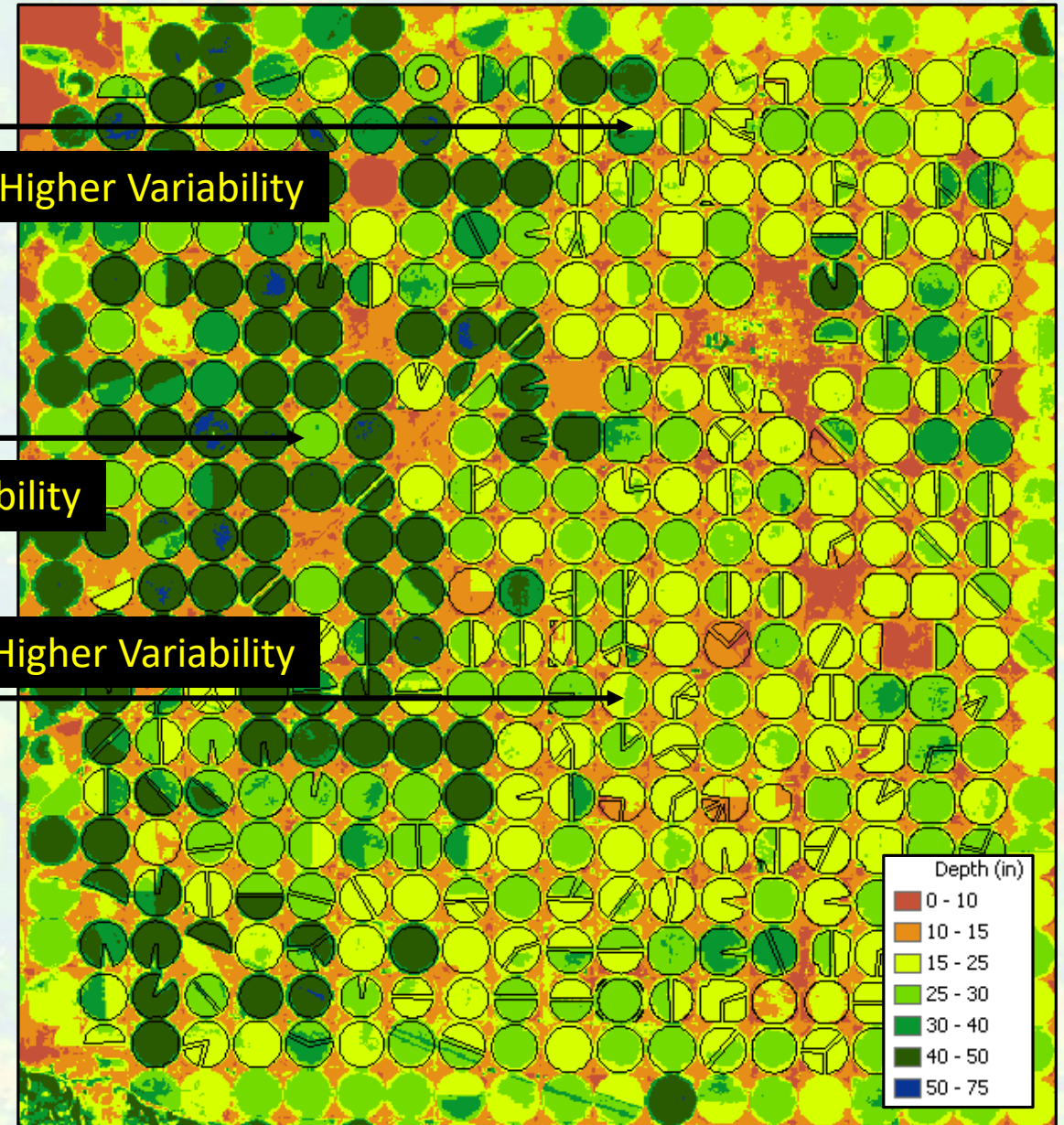
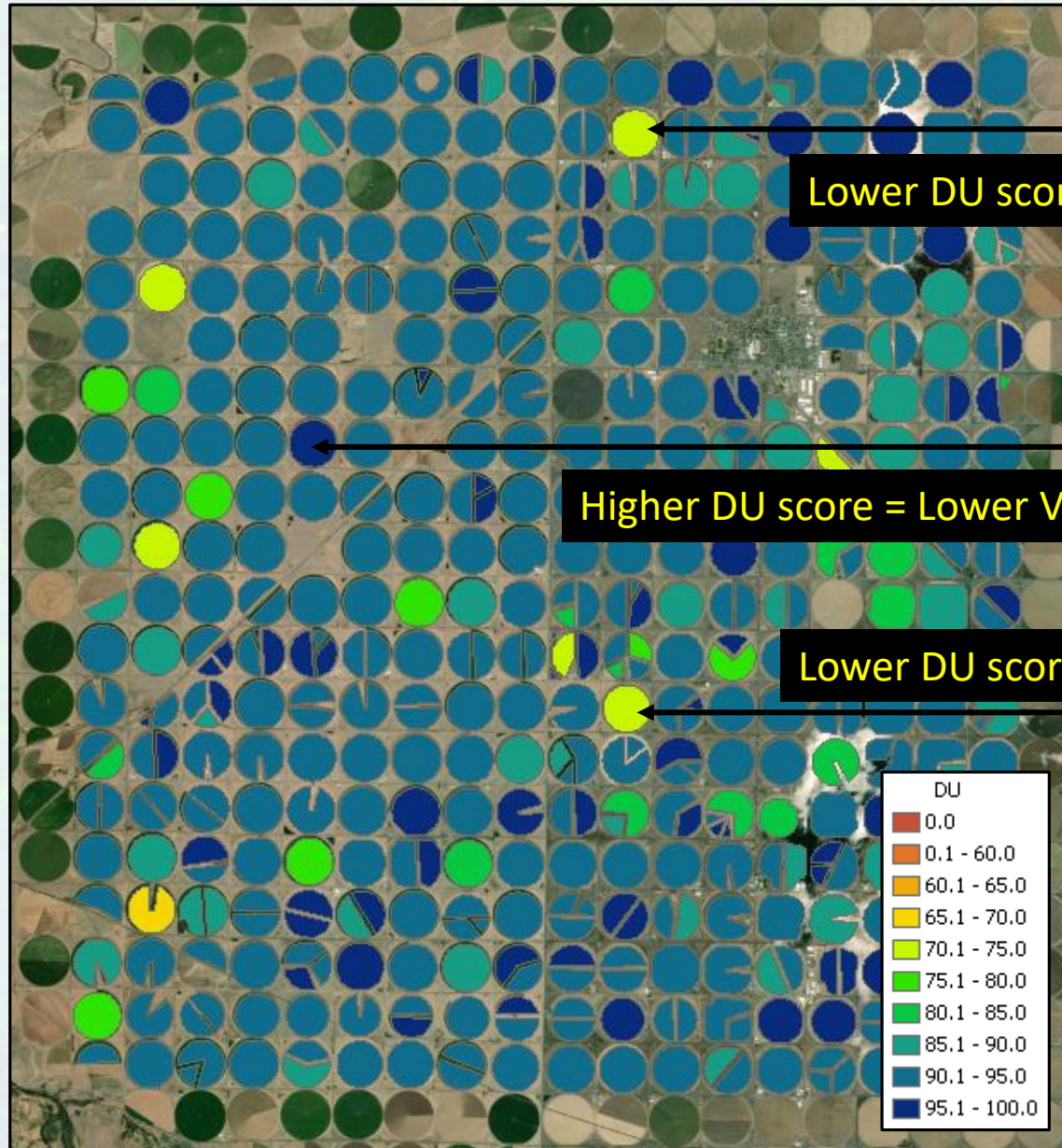


- Field A (Alfalfa)
- Field B (Barley)
- Field C (Potatoes)



Distribution Uniformity (DU)

ETa Depth 2017 (inches)



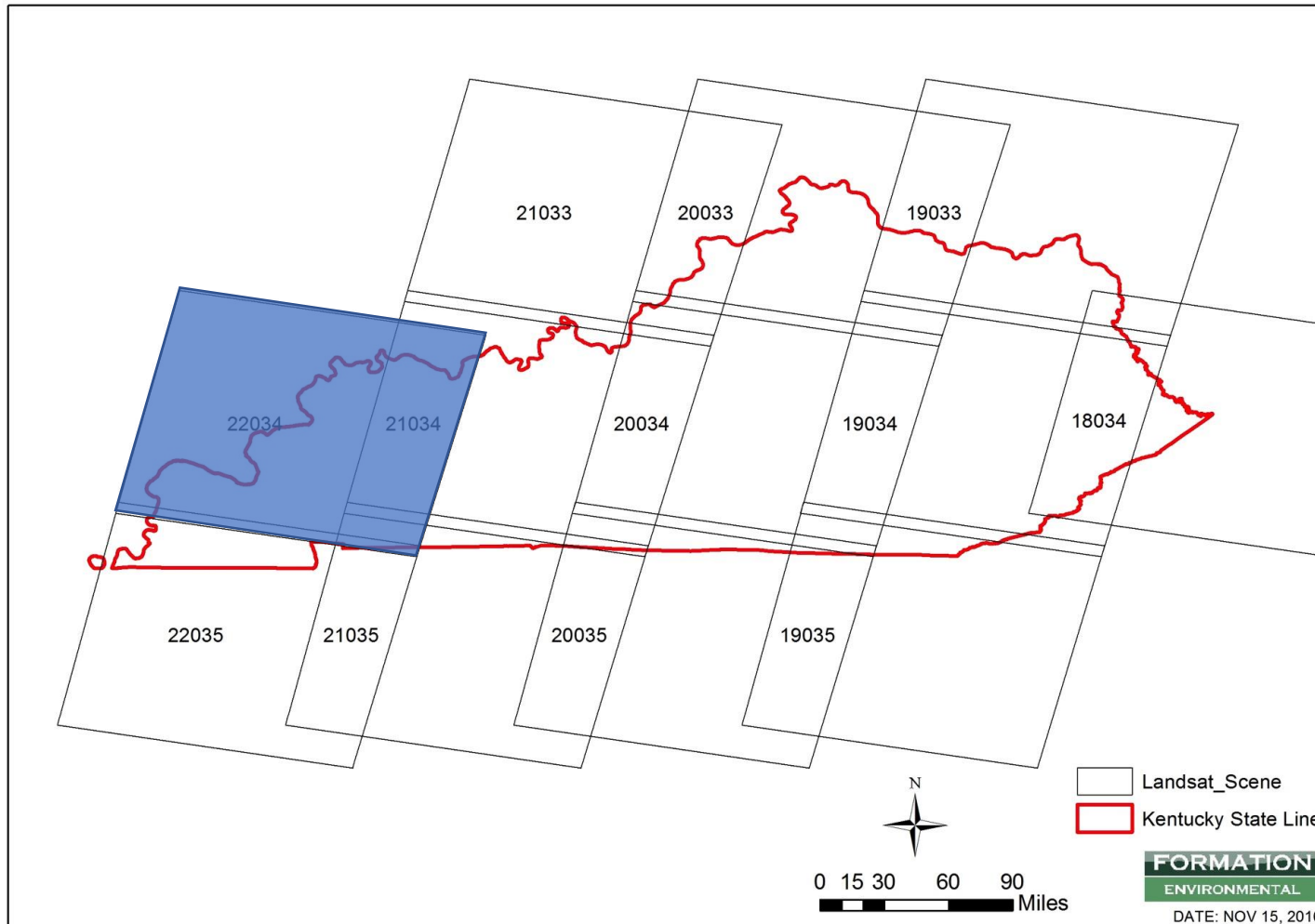
Lower DU score = Higher Variability

Higher DU score = Lower Variability

Lower DU score = Higher Variability



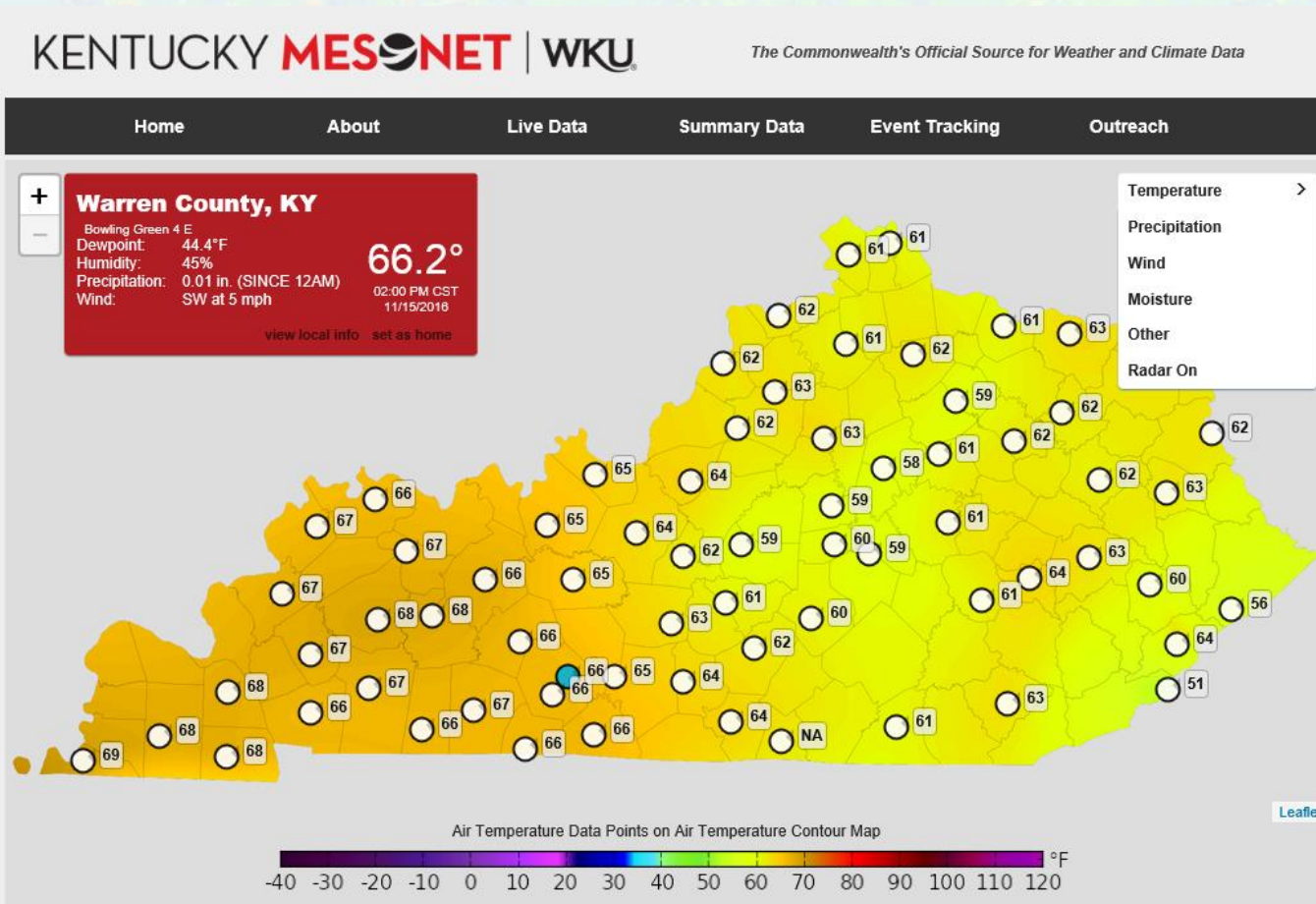
# Remote Sensing of Evapotranspiration Kentucky



- Landsat (NASA via USGS) missions L7, and L8 each on an 8 day return
- Scene is ~ 106 by 114 mi (12,152 mi<sup>2</sup>)
- Imagery is free
- Processed 11/2018-10/2019



# Remote Sensing of Evapotranspiration Ground-based Weather Network

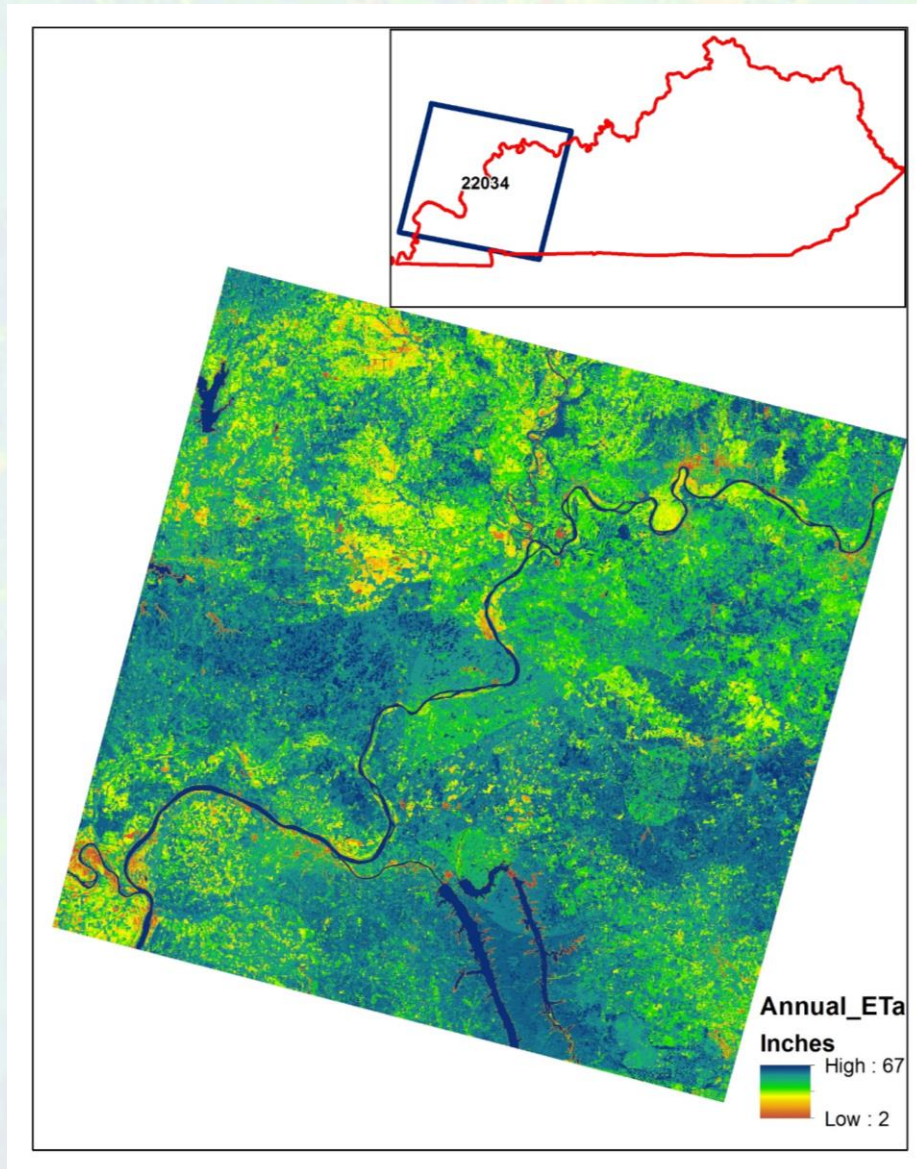


## Available Data

- Air Temperature
- Relative Humidity
- Solar Radiation
- Wind Speed
- Dew Point Temperature
- Precipitation
- Wind Direction



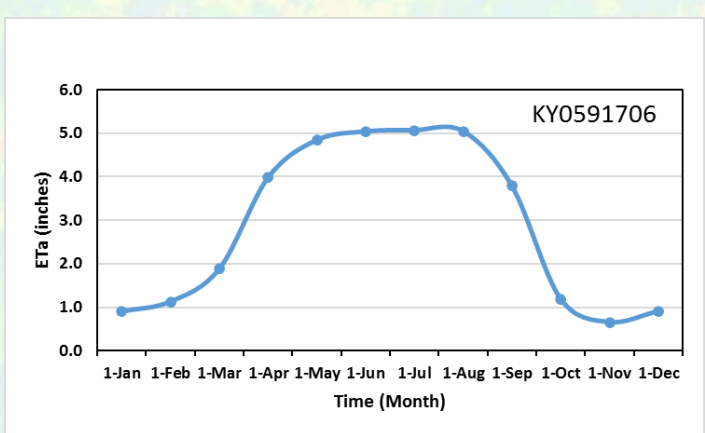
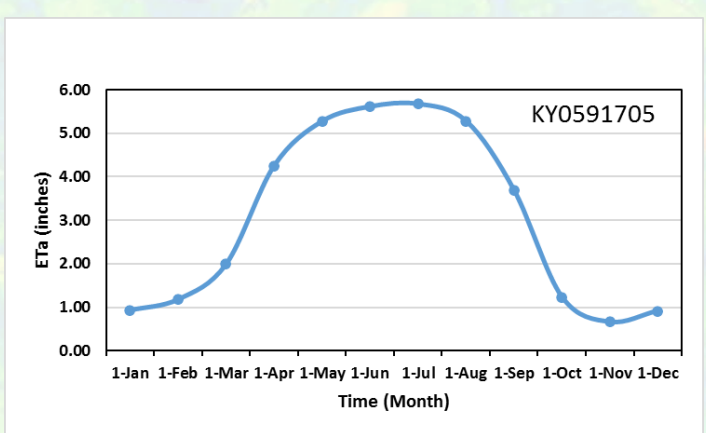
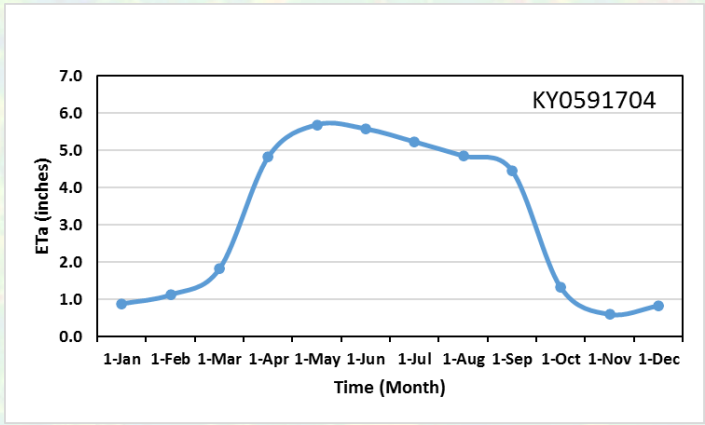
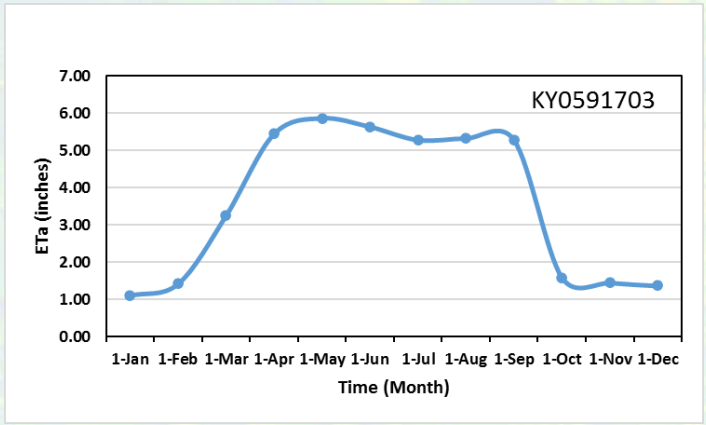
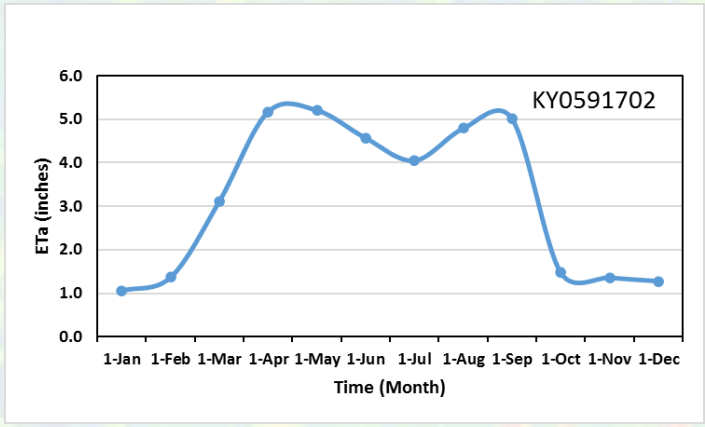
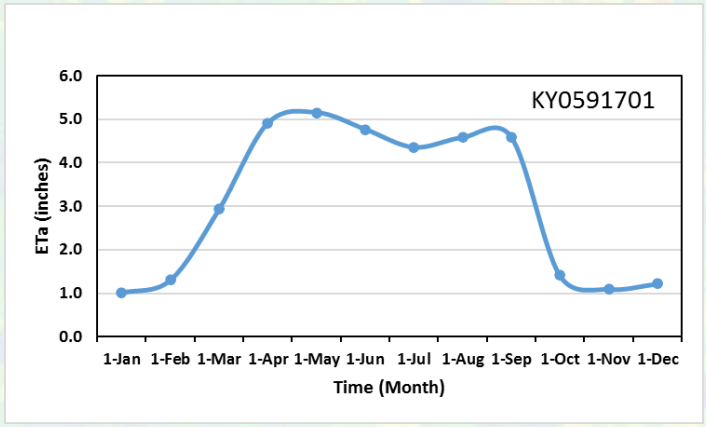
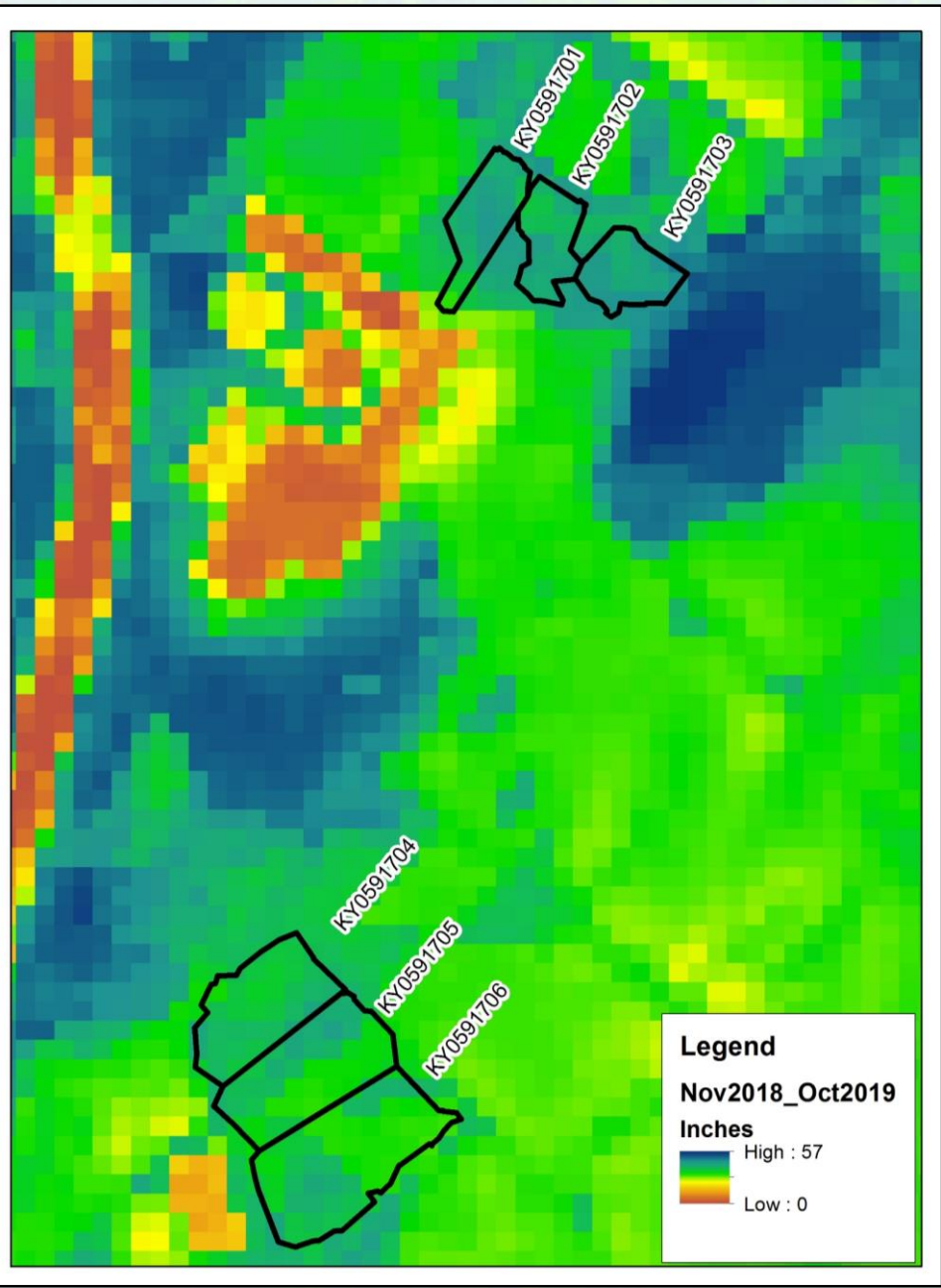
# Remote Sensing of Evapotranspiration Kentucky



- 21 Landsat 7 scenes
- 19 Landsat 8 scenes
- Hourly data from MESONET stations

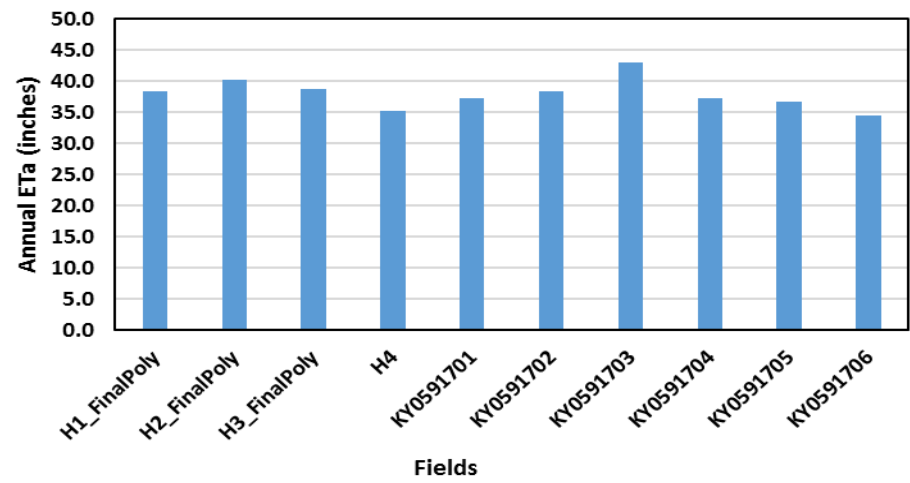
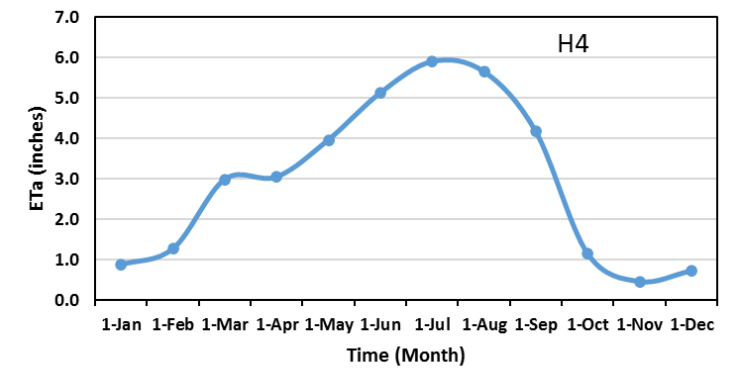
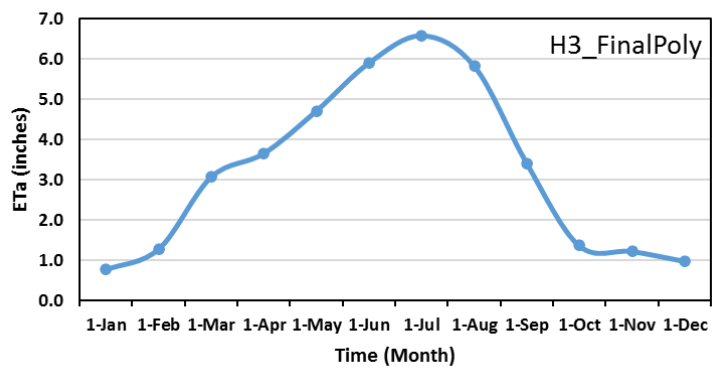
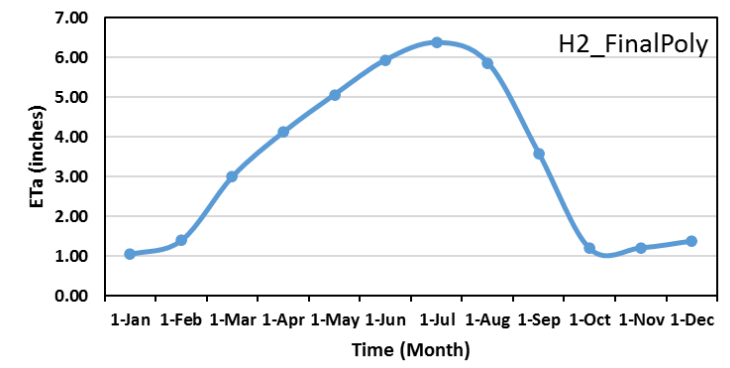
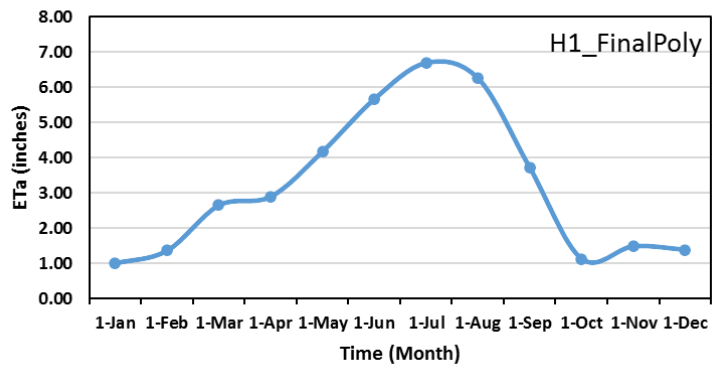
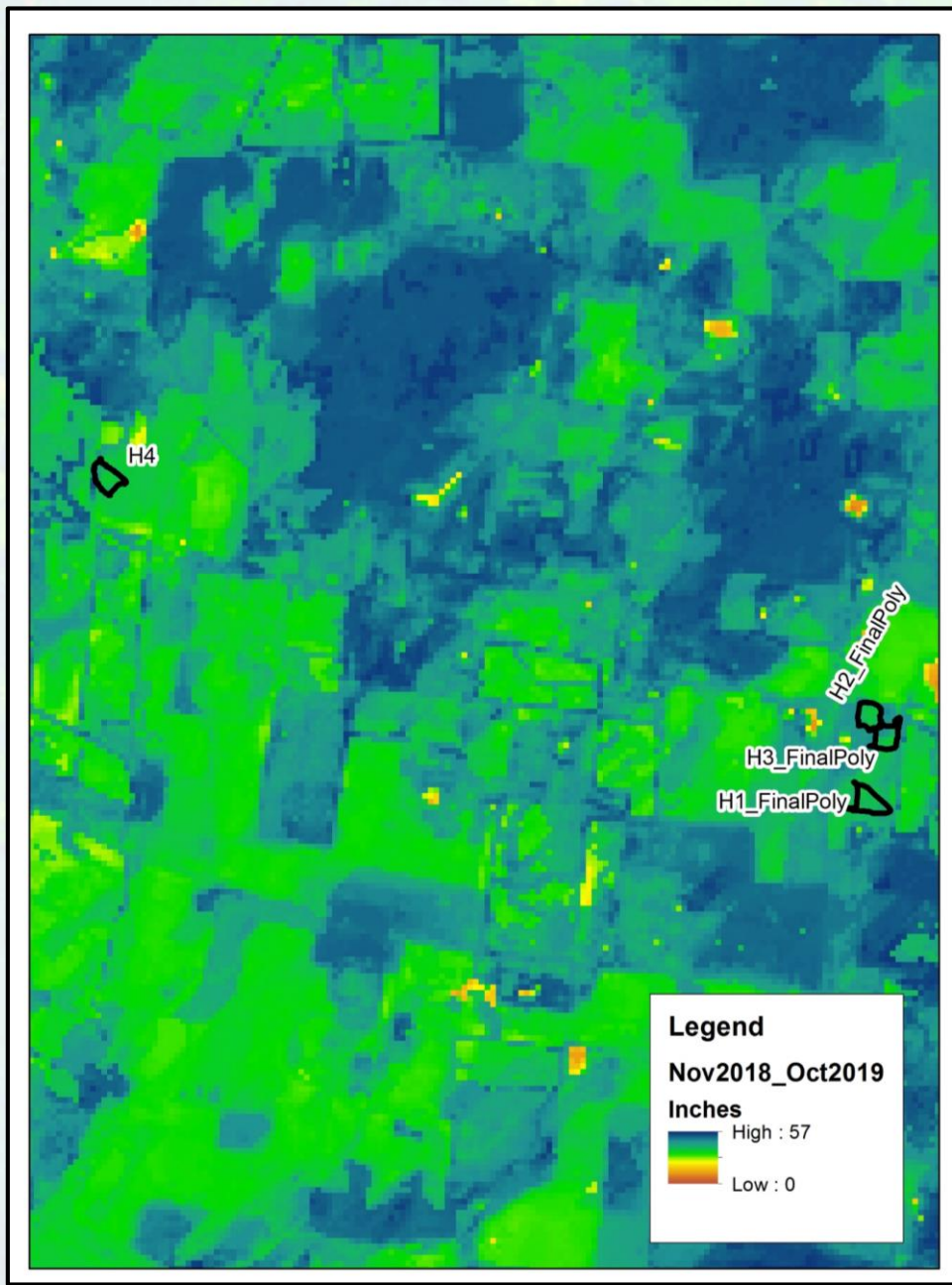


# ET Signature of different fields





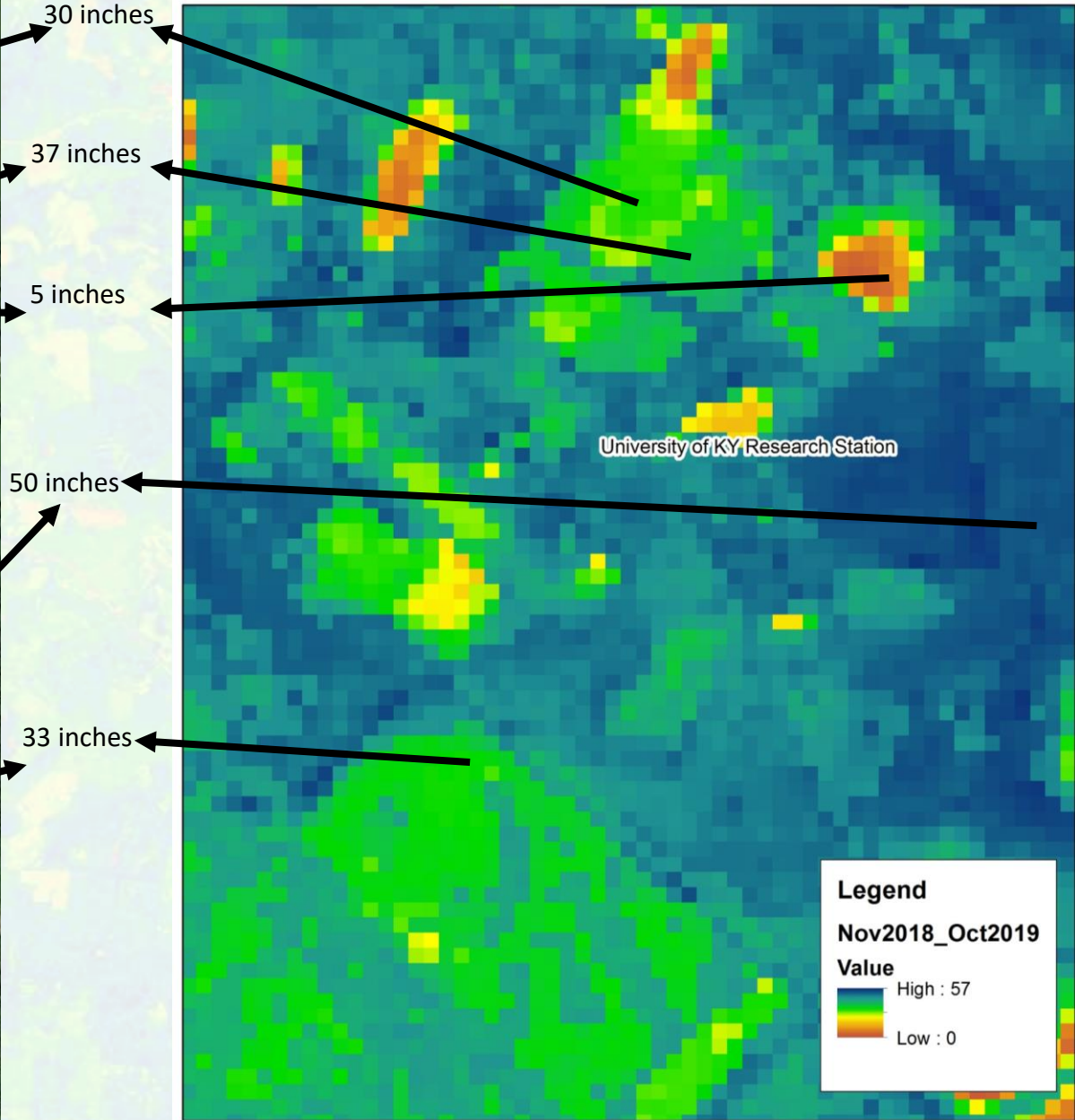
# ET Signature of different fields







2019 Imagery




2019 ETa Map



# Reference ET (ETo)

## California Dept. of Water Resources



The screenshot shows the CIMIS (California Irrigation Management Information System) website. At the top, there is a navigation bar with tabs for HOME, STATIONS, DATA, SPATIAL, and RESOURCES. Below this, there are sub-tabs for Spatial Overview, Spatial Maps, and Spatial Reports Login. The main content area is divided into sections: Spatial Maps, Solar Radiation Map, ETo Map, and ETo Zone Map. A calendar for June 2019 is displayed, with the 18th highlighted. To the right of the calendar is a map of California labeled 'ETO View' with a color scale ranging from 1.3 mm (dark blue) to 9.6 mm (dark red). The website footer contains links for Back to Top, Contact Us, and Site Map, along with a copyright notice for 2019 State of California.

Log in | Register

# CIMIS

CALIFORNIA IRRIGATION MANAGEMENT INFORMATION SYSTEM  
CALIFORNIA DEPARTMENT OF WATER RESOURCES

HOME STATIONS DATA SPATIAL RESOURCES

Spatial Overview Spatial Maps Spatial Reports Login

### Spatial Maps

Select the calendar on the right to see daily ETo or Solar Radiation maps of California based on Spatial CIMIS data. To retrieve and schedule Spatial CIMIS data, please register, log in, and click on the Spatial Report or Schedule Spatial Report tabs above. Spatial data are available back to 2003.

### Solar Radiation Map

Spatial CIMIS Solar Radiation maps are generated from remotely sensed satellite data from the Geostationary Operational Environmental Satellites (GOES) using the Heliosat-II model. See the Spatial Overview for more details.

### ETo Map

Spatial CIMIS ETo Maps are generated by coupling remotely sensed satellite data from the Geostationary Operational Environmental Satellites (GOES) with interpolated CIMIS station data and using the standardized American Society of Civil Engineers Penman-Monteith equation to calculate ETo at 2-km spatial resolution. See the Spatial Overview tab above for more details.

### ETo Zone Map

The [ETo Zones Map](#) allows users to view the reference evapotranspiration (ETo) Zones for the State of California. The map was developed by DWR and UC Davis and divides the State into 18 zones based on long-term monthly average ETo. The ETo values were calculated using data from various data sources including CIMIS weather stations that had at least five years of archived data. This map can also be viewed and/or downloaded as a PDF document using this link.

☐ Solar Radiation Map (MJ/m<sup>2</sup>)  
☑ ETo Map (mm) ETo 06/18/2019

Sun	Mon	Tue	Wed	Thu	Fri	Sat
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	1	2	3	4	5	6

ETO View

9.6  
7.5  
5.4  
3.4  
1.3  
mm

This is a newly emerging technique and is in the process of being refined. Although the data quality presented here is acceptable for many applications, we do not guarantee its accuracy. Therefore, neither the CIMIS program, the Department of Water Resources (DWR), UC Davis, nor any other party who participated in the development of this product shall be responsible for errors in this data, nor for any resulting consequences from using this data.

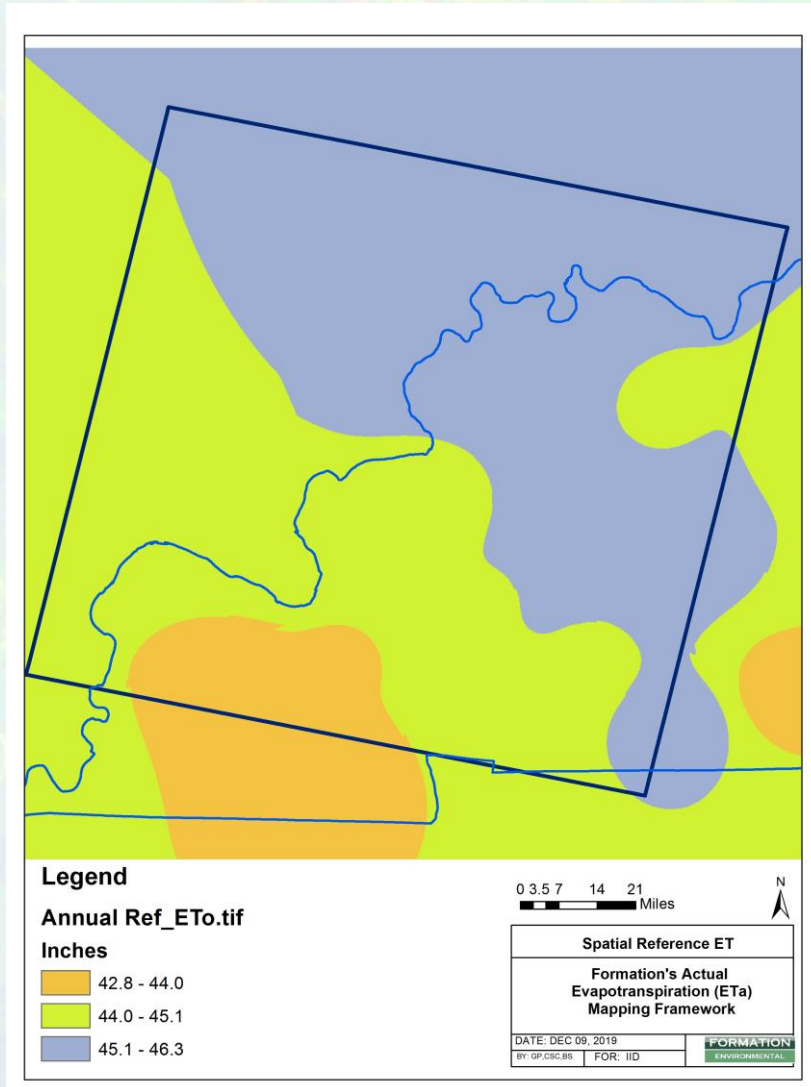
Back to Top Contact Us Site Map

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Copyright © 2019 State of California

- Formation supports CA DWR's publication of daily ETo maps at a 2km scale.
- Growers and urban agencies use data for irrigation scheduling.
- Free but requires an account



# Kentucky ETo Map



- Annual Map
- Based on WKU Mesonet Data and ETa processing framework



# Using Remote Sensing to Support Irrigation Scheduling

What does remote sensing provide?

- Historical crop water requirements and daily crop coefficients ( $K_c$ ).
- Uniformity of ET.
- Understanding the spatial application of in-field sensor data.

What does remote sensing not provide?

- Forecast of ET in the future.



A landscape photograph of an orchard. In the foreground, there is a field of tall, green grasses. A wire fence runs across the middle ground, separating the grass from a dirt path or road. Beyond the fence, there are rows of trees, likely an orchard, with some trees showing autumn-colored foliage. The sky is filled with large, grey, overcast clouds.

Questions, Discussion and

Thank you!