Water Challenges and Opportunities in Climate Change Adaptation

Conference on Water, Climate, and Food Security
for Students and Early Career Scientists
Prairie View A&M University, March 9, 2023

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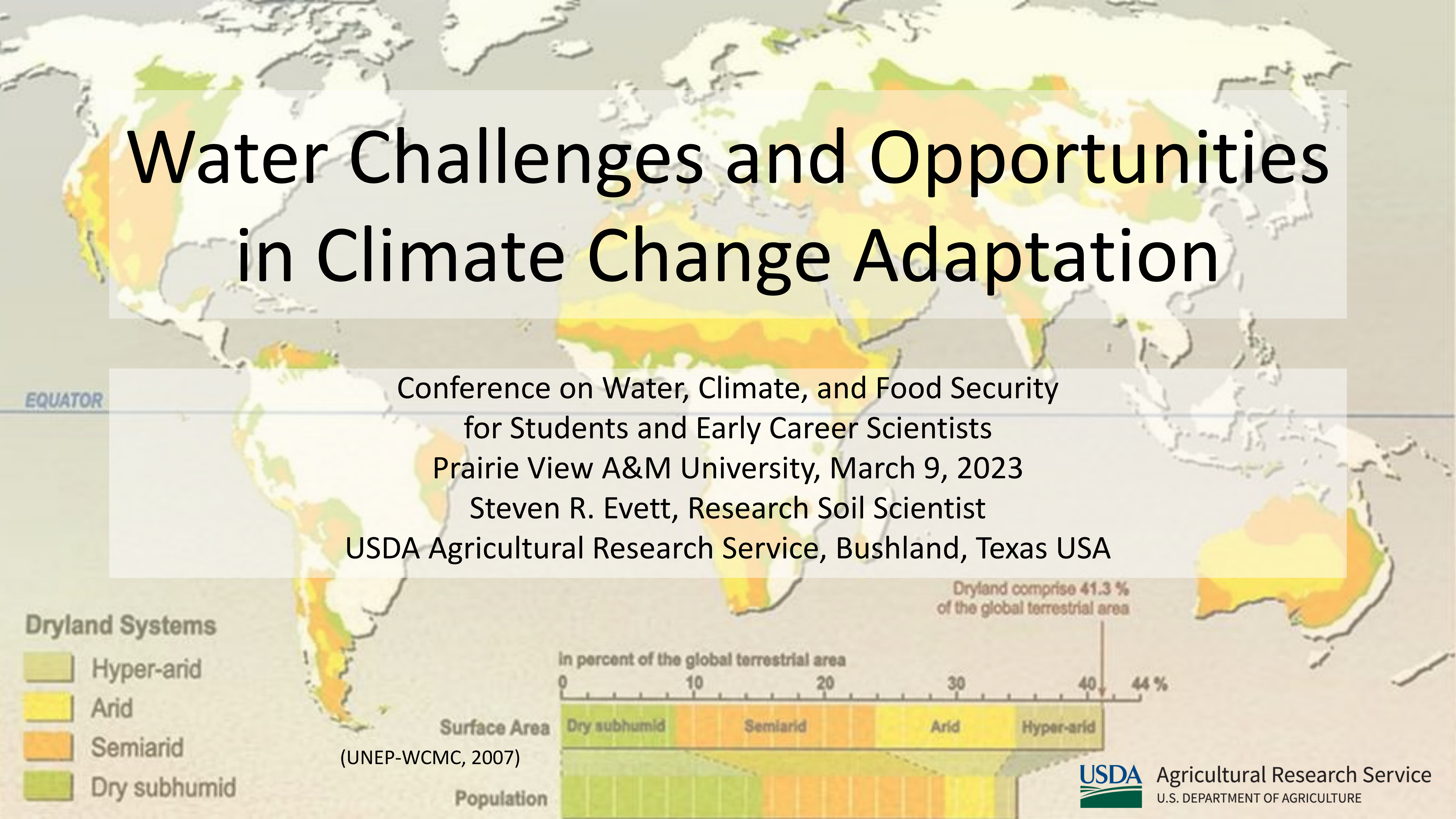

(UNEP-WCMC, 2007)

USDA Agricultural Research Service
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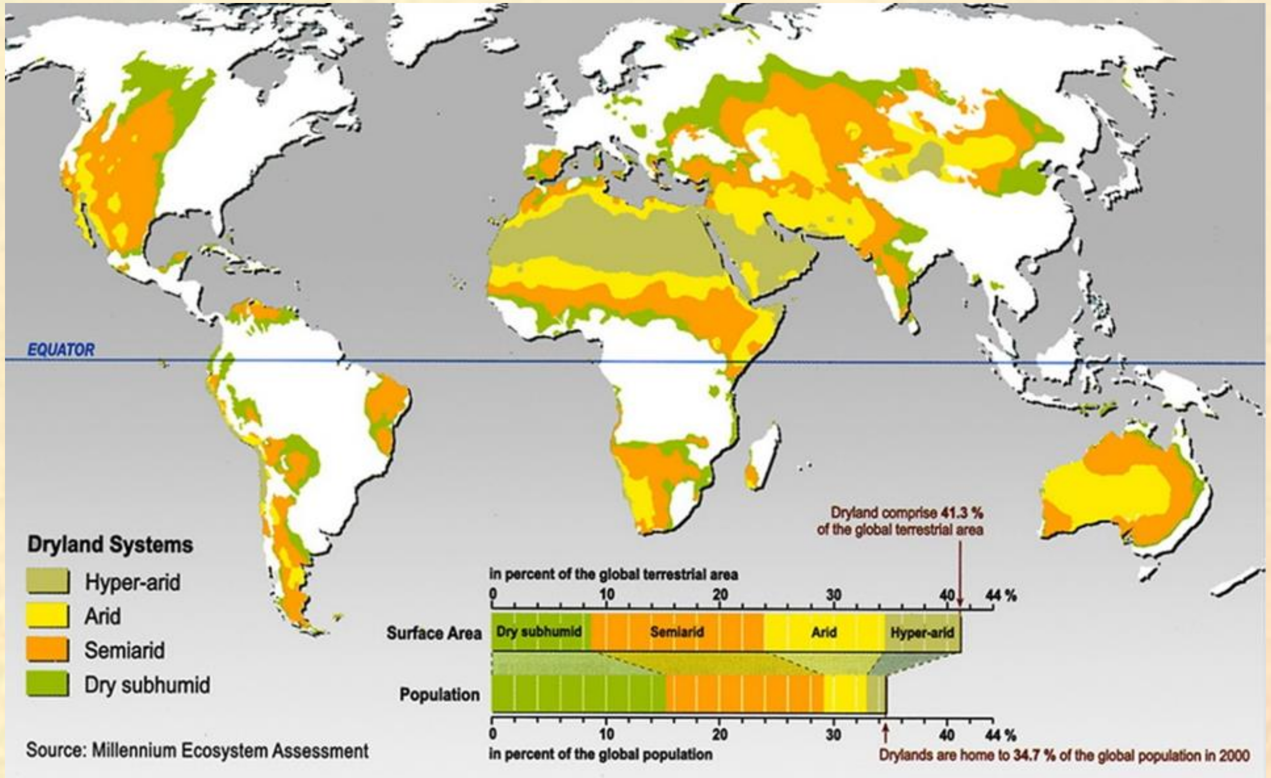
Water challenges and opportunities

- Arid and semiarid regions occupy > 40% of earth's land area
- These regions hold 43% of cultivated area, 1/3 of population (mostly involved in dryland farming and herding) and much of the world's irrigated area
- Climate change imposes critical challenges to management of soil and water resources in dryland and subhumid regions



(UNEP-WCMC, 2007)

Crop Water Productivity (CWP) – Keys to adaptation

- $CWP = Y/ET$; Y = crop yield (economic yield); ET = water used in production
- $ICWP_{ET} = (Y_i - Y_d)/(ET_i - ET_d)$ (Bos, 1980, 1985)
- $ICWP_I = (Y_i - Y_d)/I_i$ (assumes I = ET) (Bos, 1980, 1985)
- $CWP_b = Y/(P_e + I + \Delta S)$ (Howell, 1990, 2000, 2001)

  P_e = effective precipitation; ΔS = change in soil water storage
- $CWP = (HI \times DM)/\{T(1 - WC)[1 + E/(P + I + \Delta S - D - R - E)]\}$ (Irrigated)
- $CWP = (HI \times DM)/\{T(1 - WC)[1 + E/(P + \Delta S - D - R - E)]\}$ (Dryland)
  - HI = harvest index, DM = dry matter used to compute HI, T = transpiration, WC = fractional water content used to compute yield, E = evaporation from soil, P = precipitation, I = irrigation, ΔS = change in soil water storage, D = deep percolation loss, R = sum of surface runon and surface runoff

Howell, T. A. 2000. Irrigation's role in enhancing water use efficiency. In R. G. Evans, B. L. Benham, and T. P. Trooien (eds.), Proc. 4th Decennial Symposium, National Irrigation Symposium, Am. Soc. Agric. Engr., St. Joseph, MI. pp. 66-80.

Agronomic & engineering means to increase CWP

(Wallace and Batchelor, 1997)

- Increase HI through crop breeding and management;
- Reduce transpiration ratio (T/DM) for constant/increased HI
  - Improved species selection, variety selection, or crop breeding;
- Maximize DM for constant or increased HI
  - enhanced fertility/water, disease and pest control, optimum planting
- Reduce other water balance components relative to T; {Y α T}
  - reducing I, D, R, E relative to T = increases T relatively.
- Improve water availability over time to increase T and Y; Y α T

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93(2):281-289. https://doi.org/10.2134/agronj2001.932281x. Wallace, J.S., and CH. Batchelor. 1997. Managing water resources for crop production. Philos. Trans. R Soc. London Ser. B 352:937-947. https://doi.org/10.1098/rstb.1997.0073

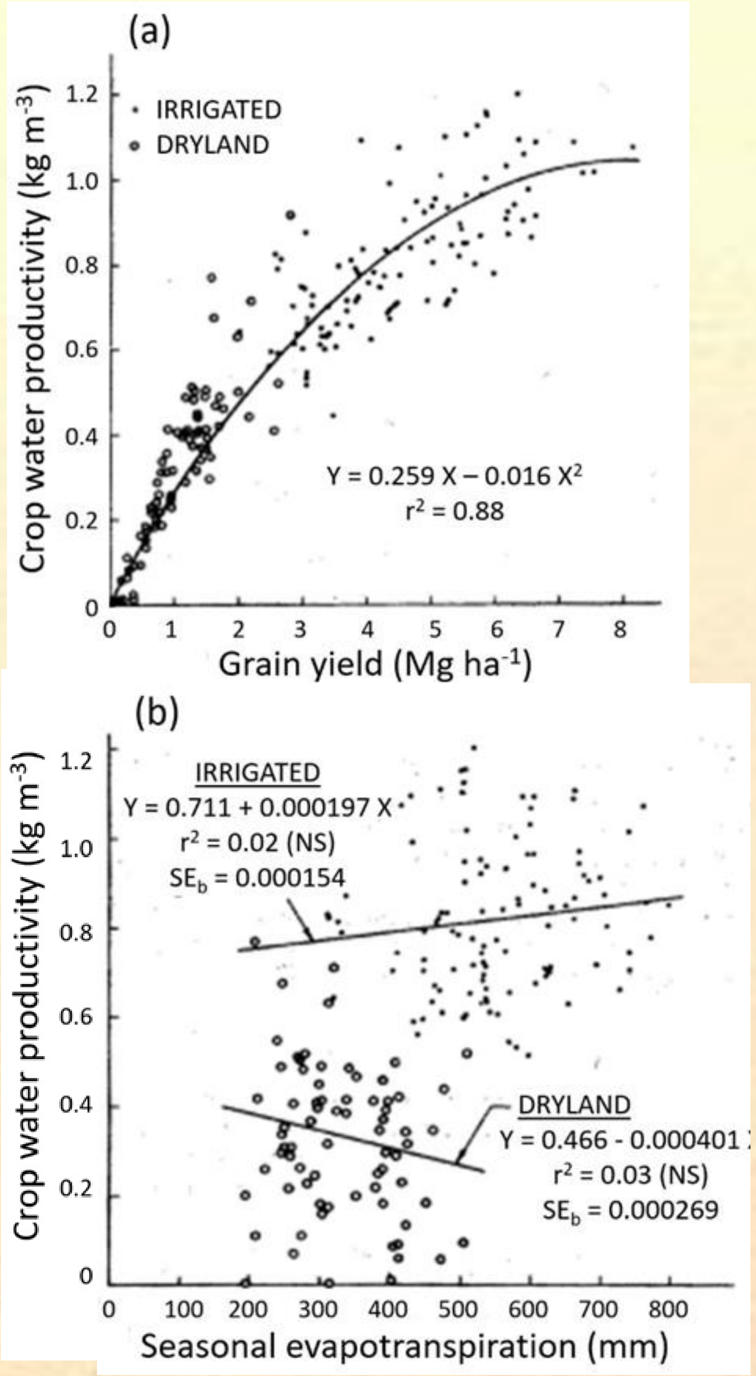
Improve water availability over time:

$Y \alpha T \alpha (P + I + \Delta S - D - R - E)$

- Winter wheat CWP was ~ doubled with irrigation compared to dryland production, and mean Y was more than doubled.
- In the 400 to 500 mm range of water use, water use under dryland conditions equaled that under irrigated conditions, yet irrigation doubled CWP and Y.

Baumhardt et al., 2019:

- For the same amount of water, partitioning irrigated:dryland area by 2:1 or 1:1 produced 30% >Y than irrigating all land at a lesser rate.



Wheat data are from 178 treatment years at Bushland, Texas (adapted from Musick et al., 1994)

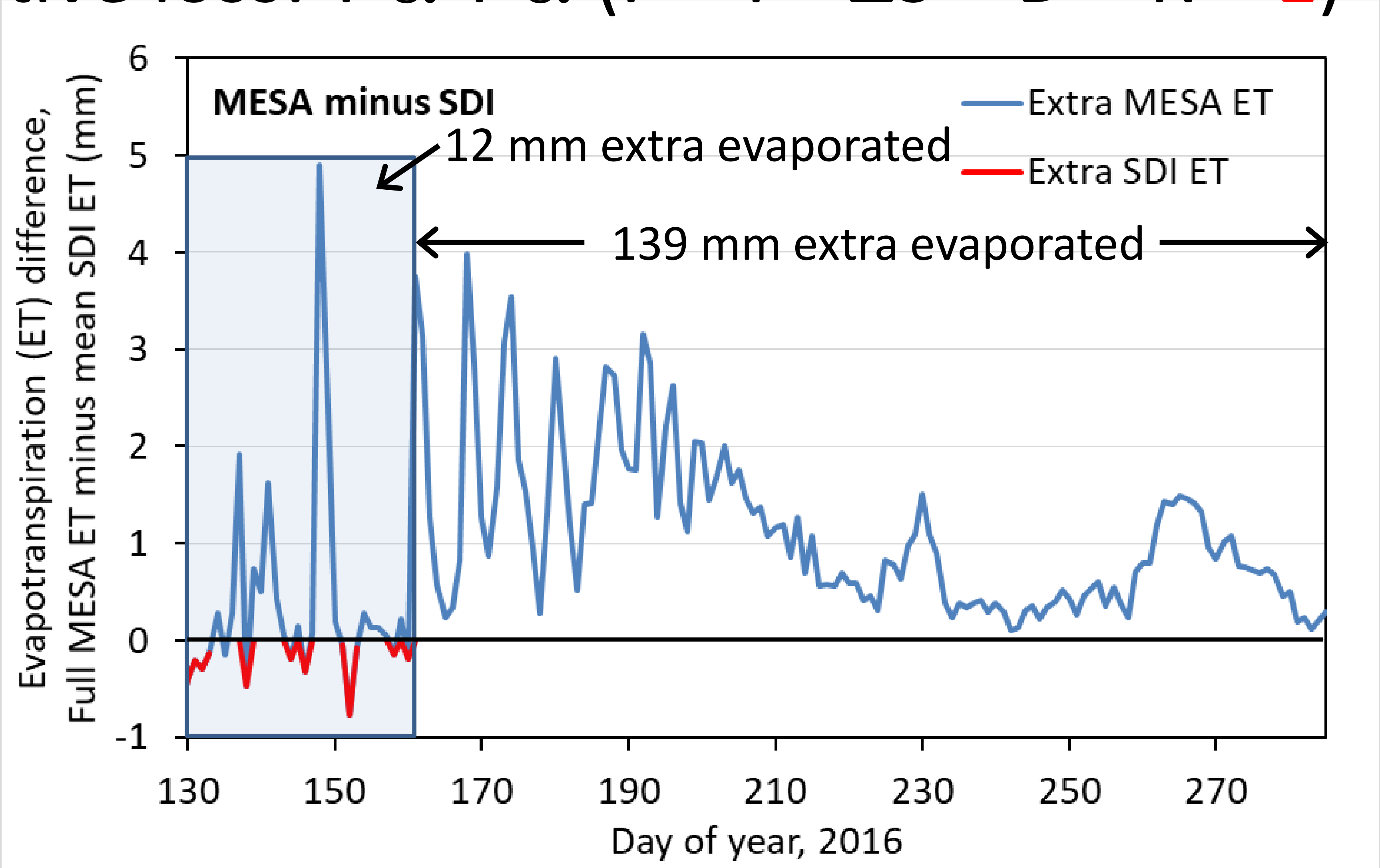
Reduce evaporative loss: Y α T α (P + I + ΔS – D – R – **E**)

<u>2016 example</u>

Application method affects Corn Water Use (ET)

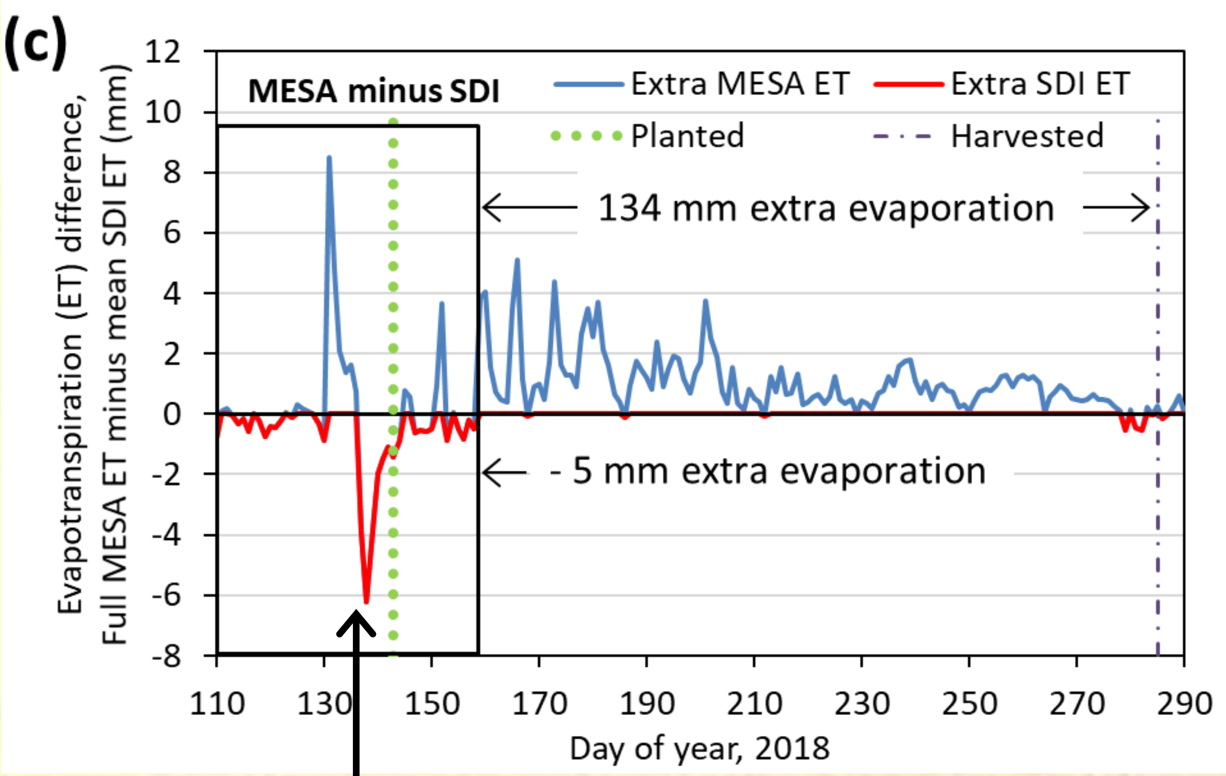
ET MESA minus ET SDI

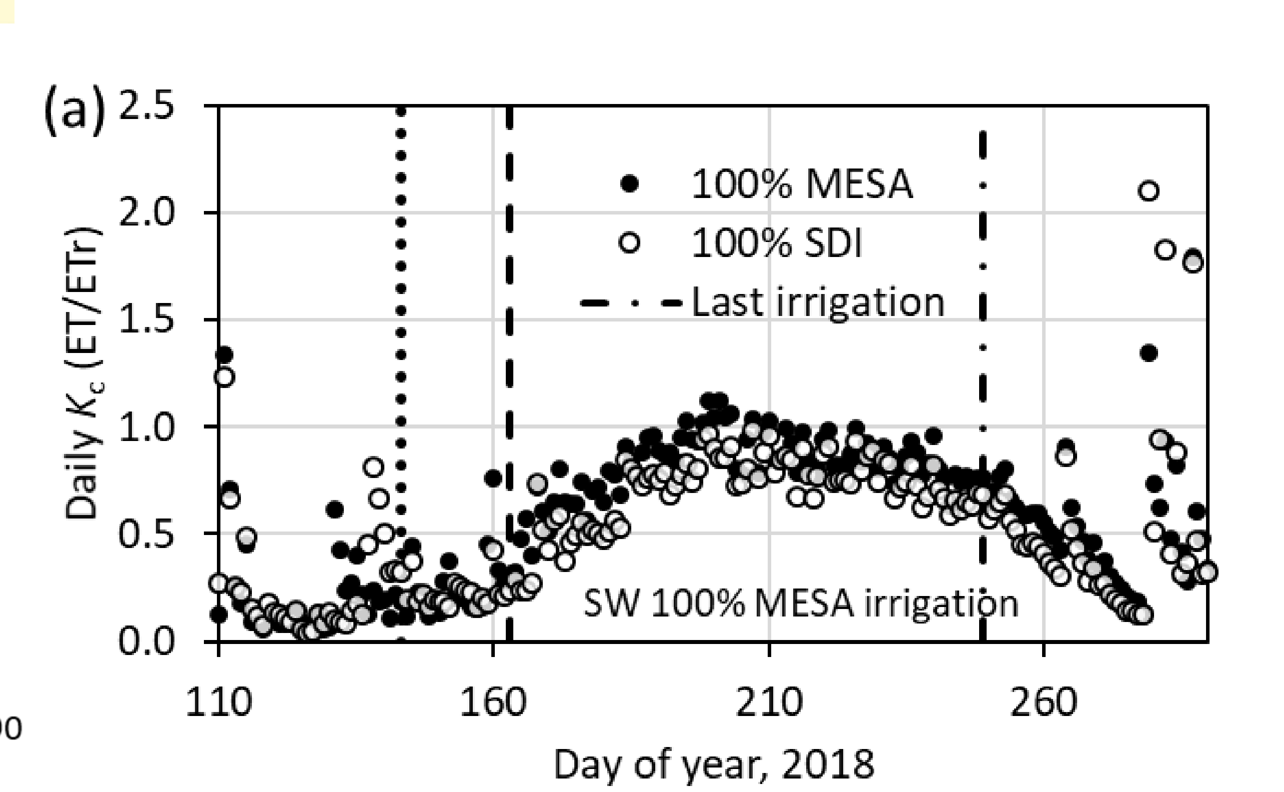
Full Irrigation



Evett, S.R., D.K. Brauer, P.D. Colaizzi, J.A. Tolk, G.W. Marek and S.A. O'Shaughnessy. 2019. Corn and sorghum ET, E, Yield and CWP as affected by irrigation application method: SDI versus mid-elevation spray irrigation. Trans. ASABE 62(5):1377-1393. https://doi.org/10.13031/trans.13314

2018 corn – Very similar results

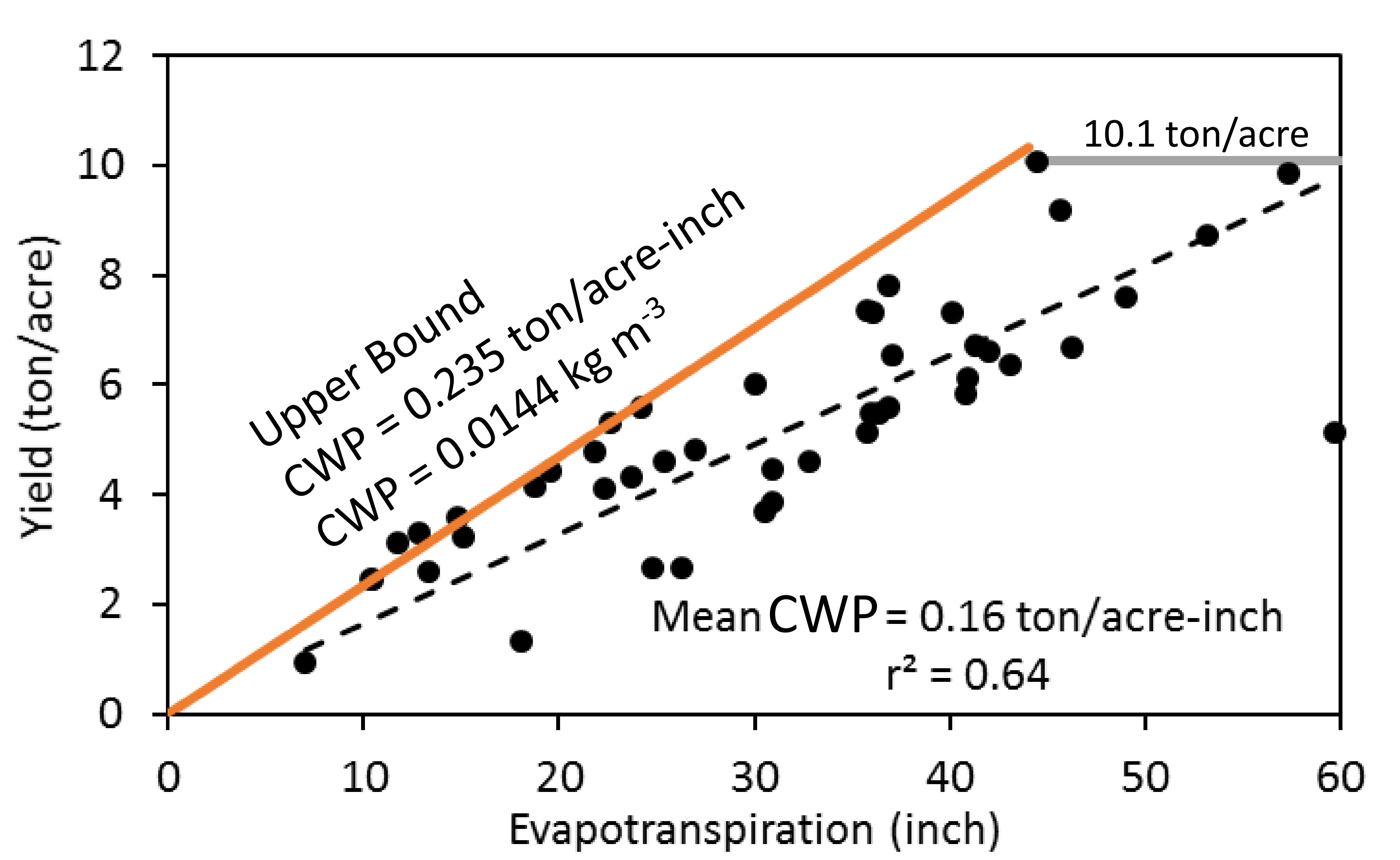




Wet spring

Reduce evaporative loss: Y α T α (P + I + ΔS – D – R – **E**)

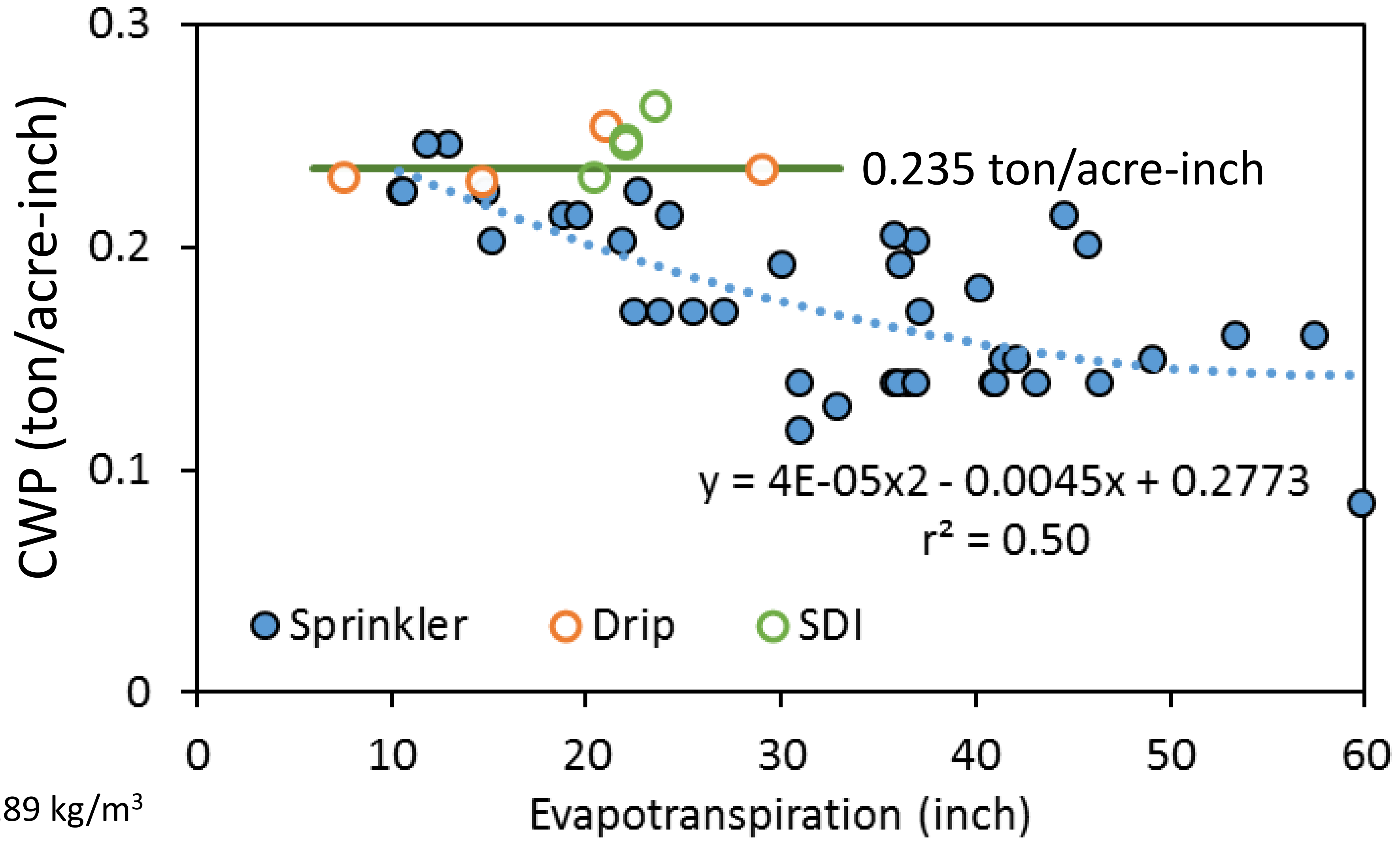
- Bounds on alfalfa CWP and yield
- Surface and subsurface drip deliver high yields with less ET



Adapted from Lindenmayer et al. (2011) – data from NE, ND, UT, NM, MN, TX, ID

Alfalfa CWP Limits – Great Plains & Western USA

- Surface and subsurface drip reduce evaporative losses and maximize CWP



1 ton/acre-inch =0.061289 kg/m^3

Lindenmayer et al. (2011); drip irrigation data from Carter et al. (2013) & Lamm et al. (2012)

Other approaches to increasing CWP

- **Reduce runoff**: conversion to sprinkler, furrow dikes, residue cover
- Shade and greenhouses reduce insolation and wind; increase humidity
  - Increase yield, **reduce T & E without reducing CO_2 uptake**, improve yield quality
  - $CWP = (HI \times DM)/\{\mathbf{T}(1 - WC)[1 + \mathbf{E}/(P + I + \Delta S - D - R - \mathbf{E})]\}$

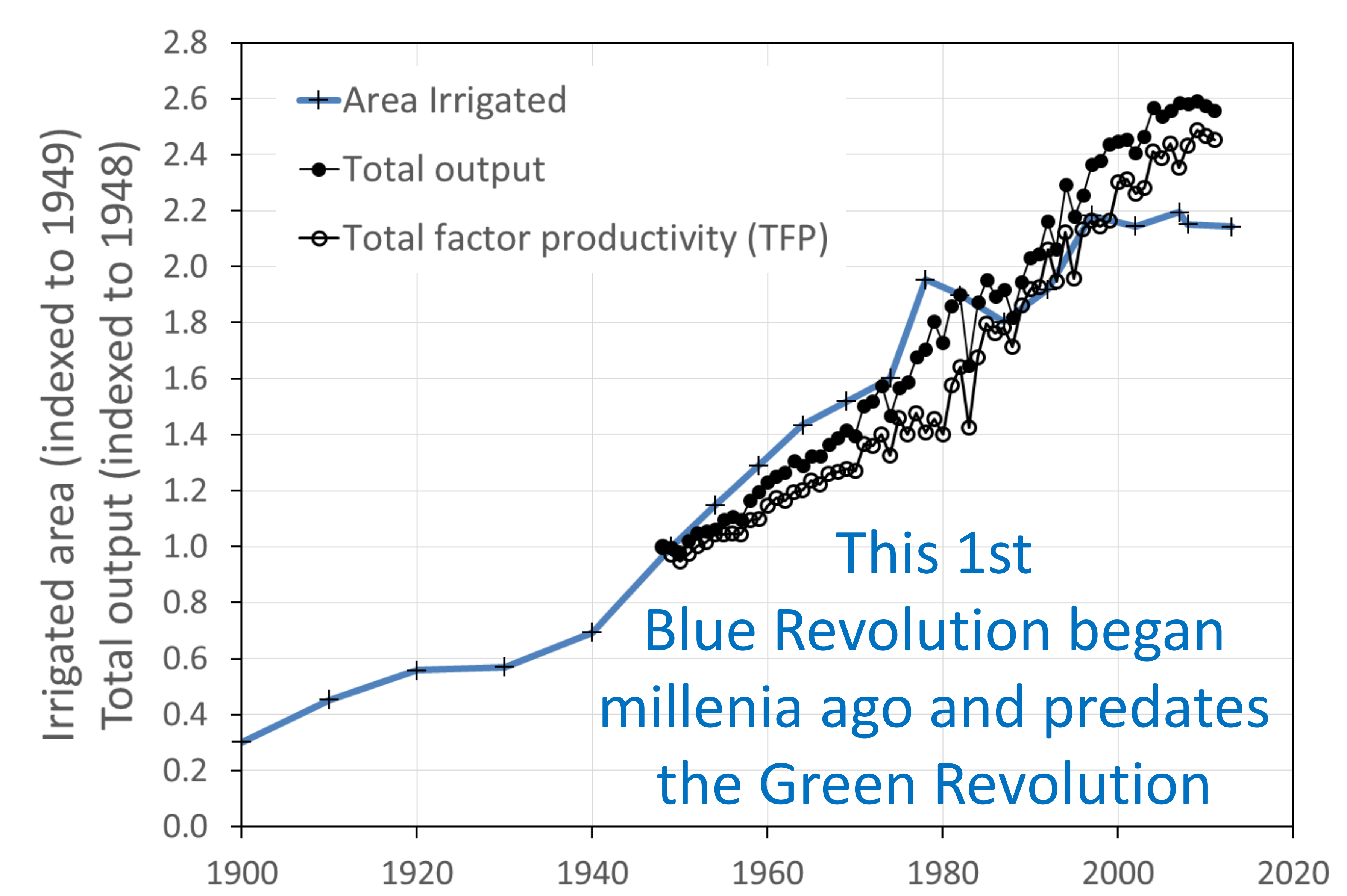
Conclusions from Bushland studies

- SDI reduced evaporative (*E*) losses by 138, 151 & 129 mm in 2013, 2016 and 2018, respectively.
- *E* loss reductions occurred both early and in mid season but were less in mid season.
- SDI reduced overall maize water use by 17 to 18% while increasing yield by 0 to 20% and CWP by 18 to 46%.
- Basal corn crop coefficients for SDI should be 10% to 15% smaller than those for MESA irrigation.
- Seasonal weather (precipitation) strongly affected the degree of SDI water savings.
- Similar results for cotton and sorghum at Bushland, alfalfa elsewhere

Irrigation is an adaptation to climate change

Science- & Water-Driven Productivity Increase

Decoupled from irrigated acreage increase

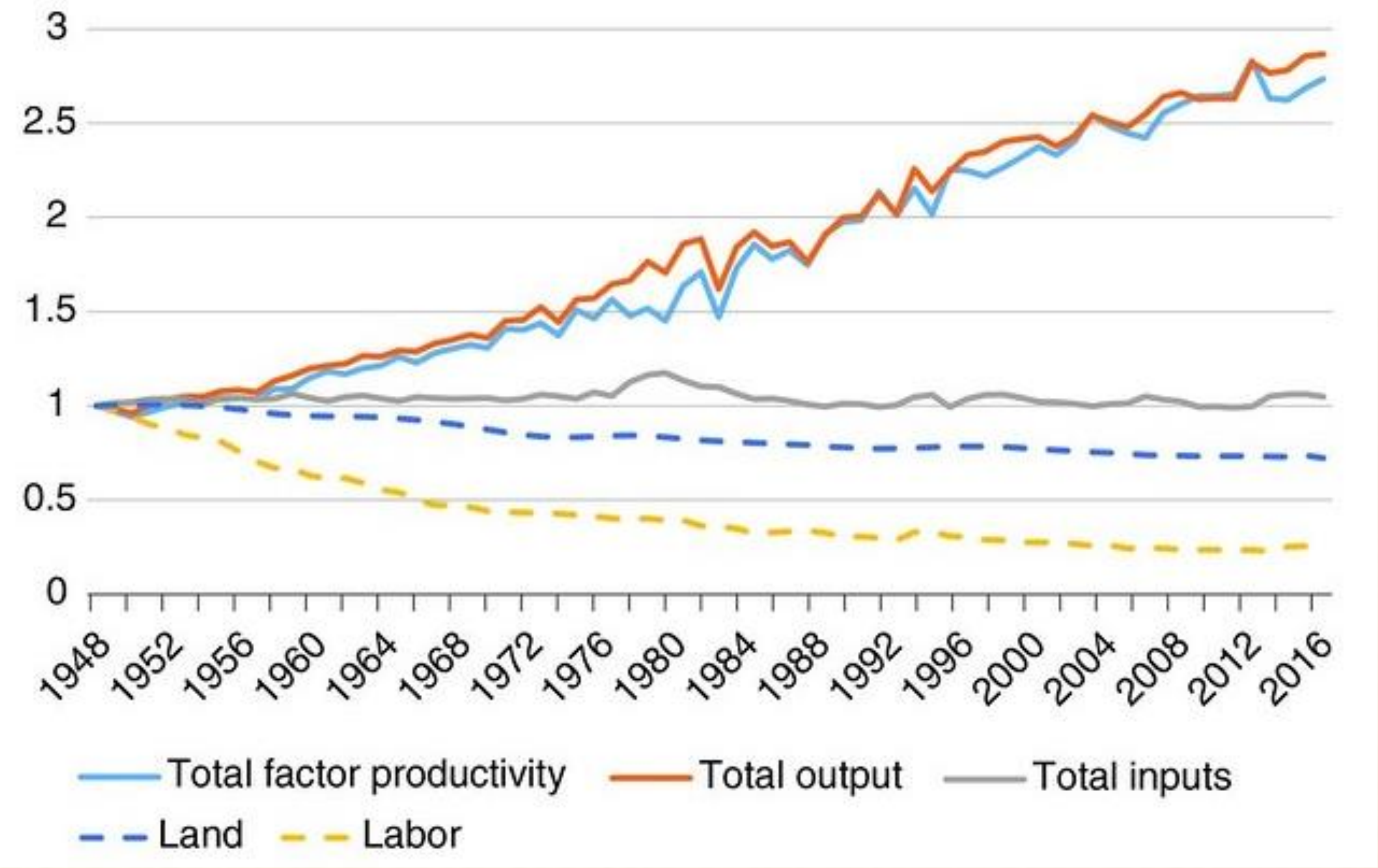


U.S. Agricultural Productivity: 1948-2017

Since WWII in the USA:

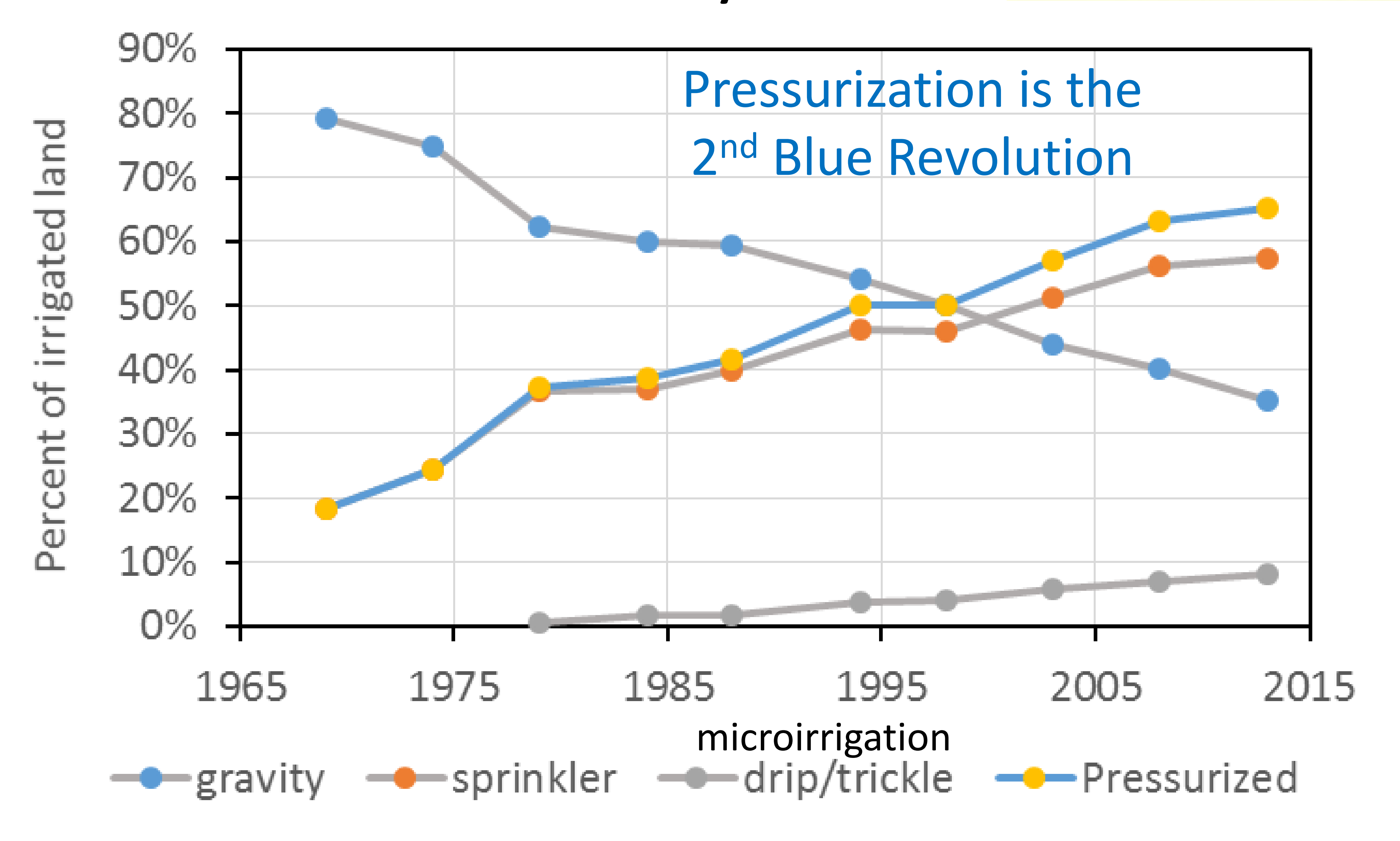
- Agricultural input growth was practically flat
- Growth in output driven by productivity gains
- Productivity growth ~2% per year

Agriculture sector is science driven



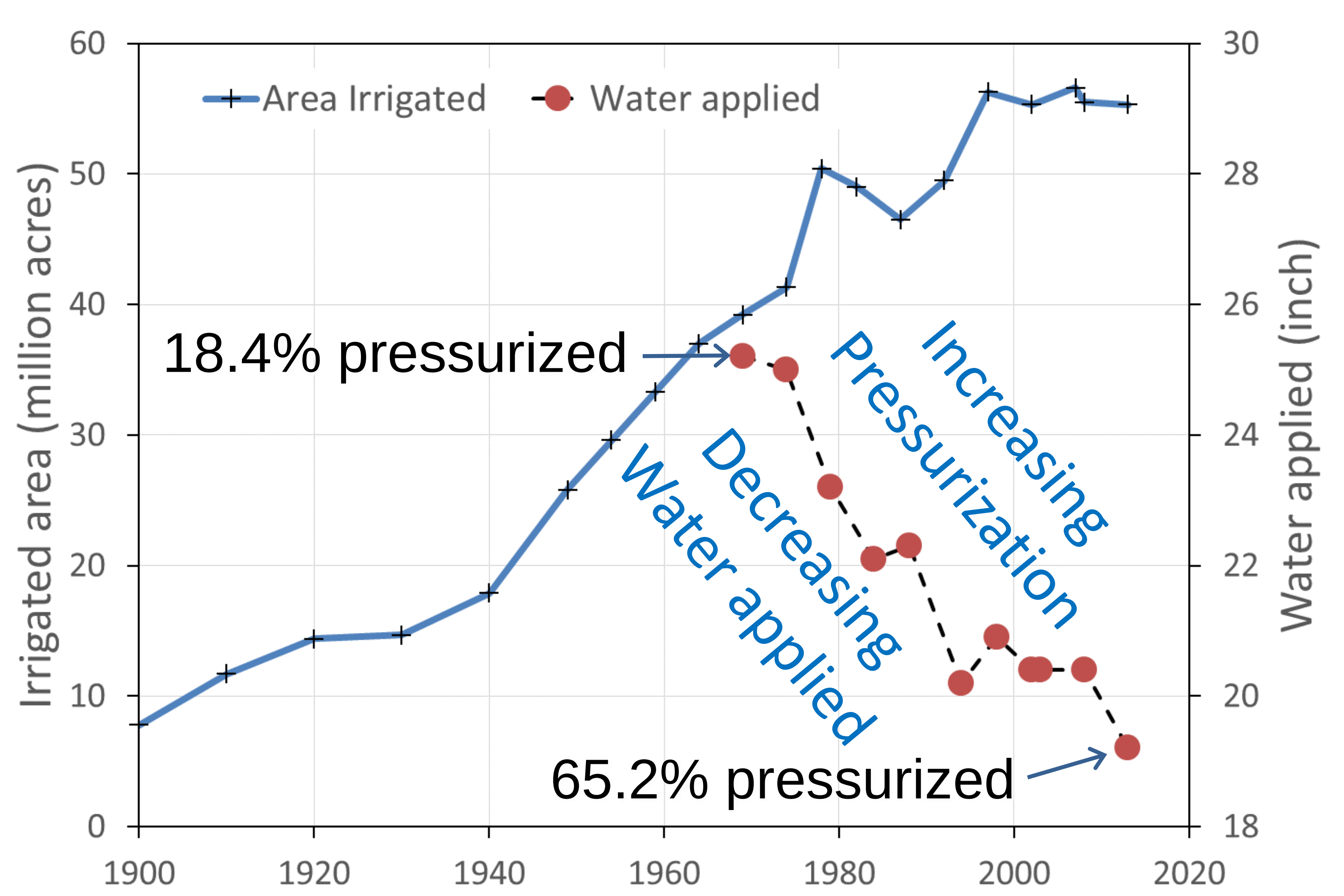
Source: USDA ERS

Conversion to Pressurized Systems



U.S. Irrigation – Pressurization: The 2nd Blue Revolution

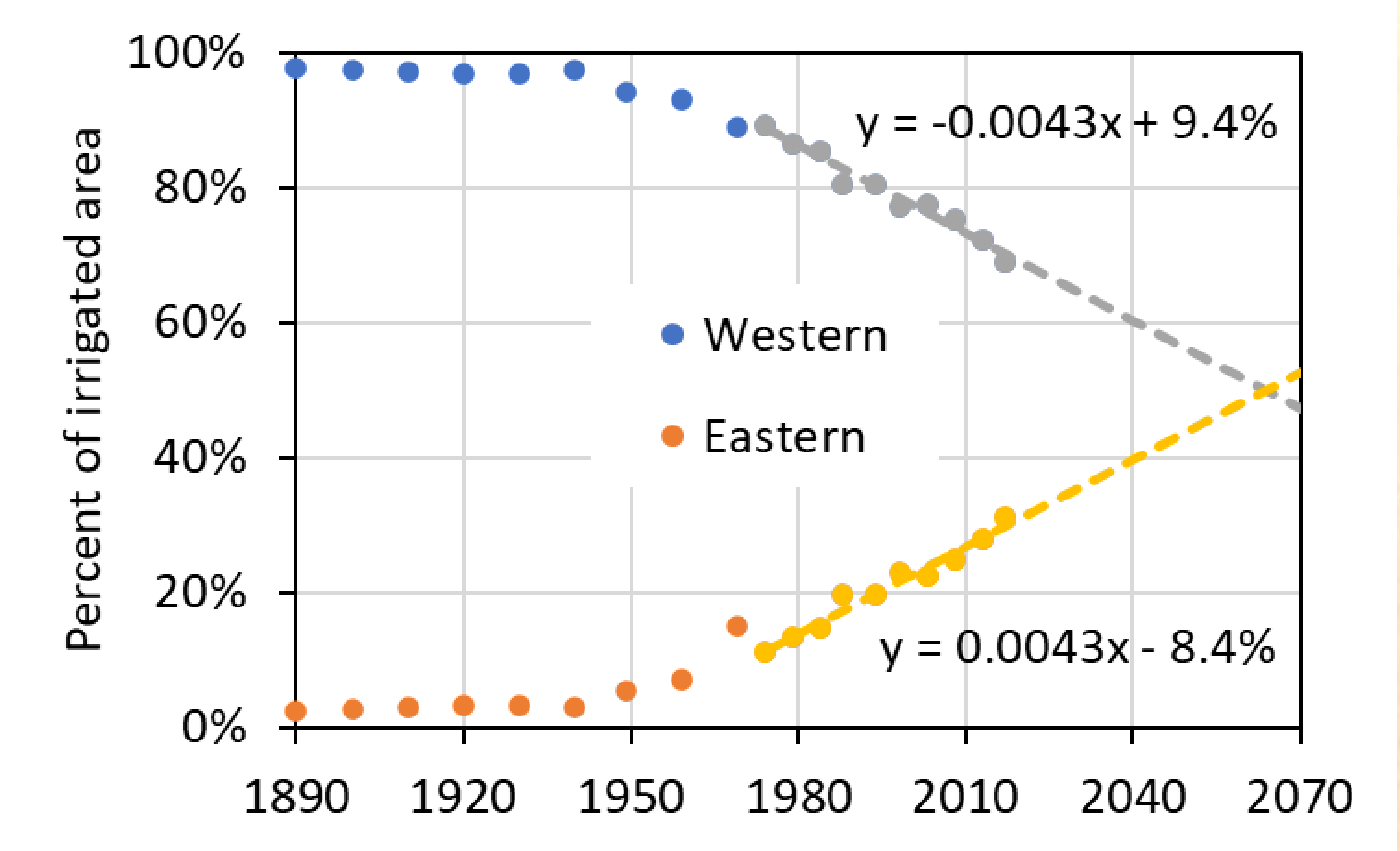
24% decrease in water applied as pressurized irrigation increased from 18.4% to 65.2%, 1974 - 2013



Source: ERS 2002, 2013

Eastward shift in irrigated land: 1974-2017

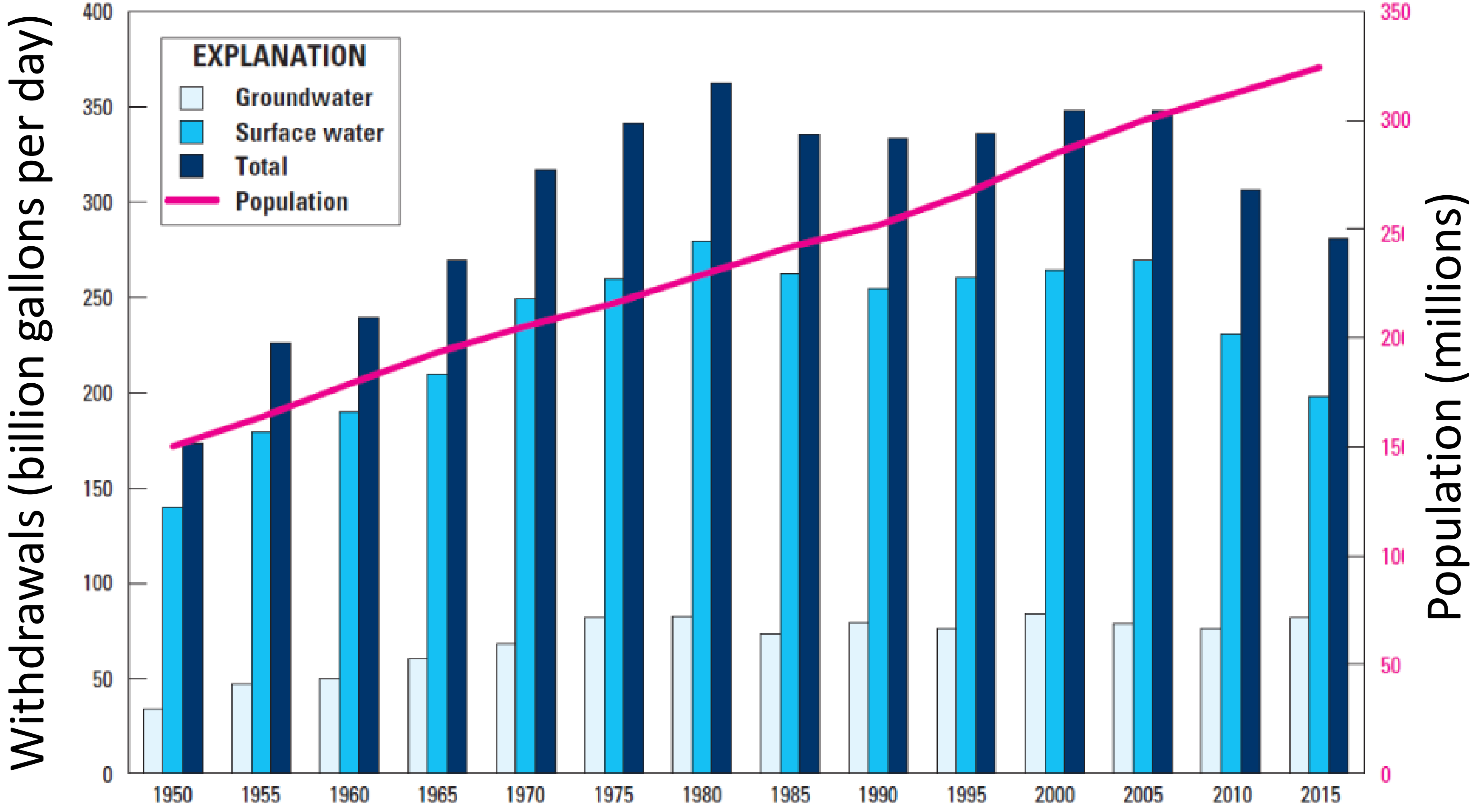
- More humid
- More precip-itation
- Smaller ET for given yield
- Less irrigation for given yield and level of CWP



Trends in population and water withdrawals, 1950-2015

21% decrease in irrigation water withdrawals, 1980 - 2015

Irrigation withdrawals → 150 Bgal/d 118 Bgal/d



Trends in population and freshwater withdrawals by source, 1950–2015

What does all this mean?

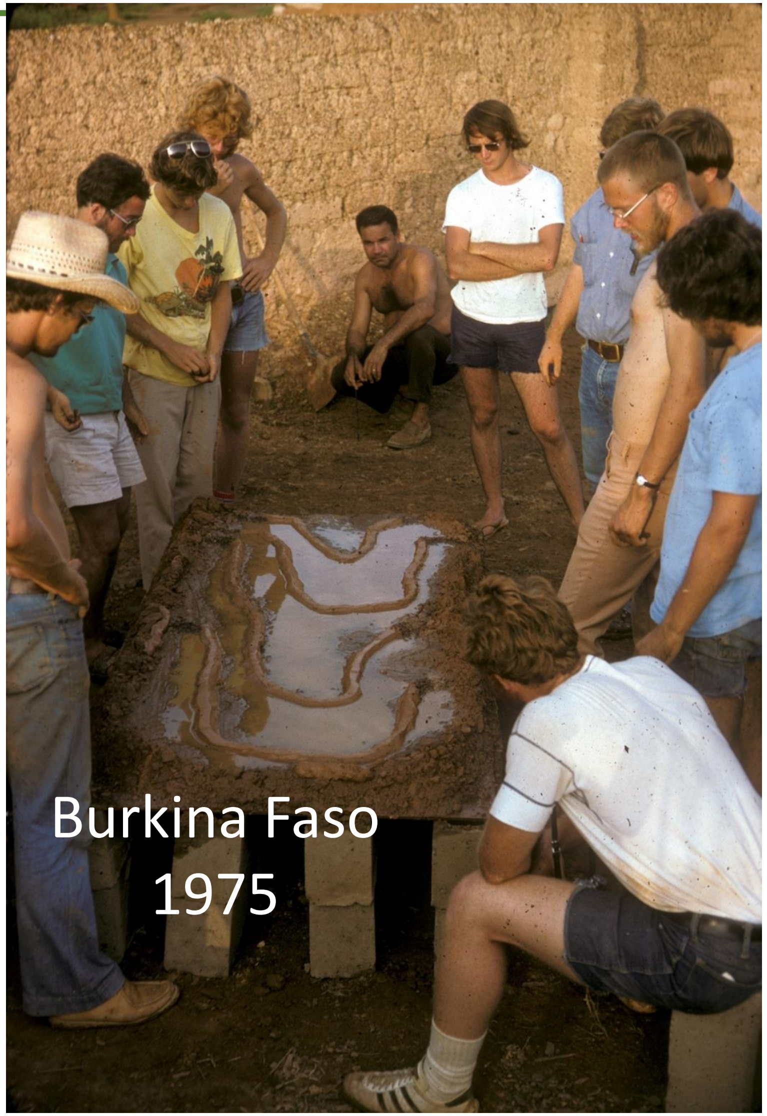
- In arid, semi-arid, subhumid, and even some humid areas:
  - Irrigation tends to increase Crop Water Productivity, often greatly
  - Pressurized irrigation systems have greatly increased irrigation efficiency and total water productivity –
    - much reduced conveyance losses
    - large reductions in water applied, easier metering – better management
    - Improved uniformity of application
    - Increased water and nutrient use productivities
    - Reduced labor cost
- **Recent advances in site-specific, variable-rate irrigation (SSVRI) have brought into play a greatly increased ability to manage water application and use in time and space**

Developing Precision Irrigation

- Precision placement of static water management structures has been and is still relevant
- But modern precision irrigation includes **dynamic**, not only static, **practices**
- **The three irrigation revolutions –**

  Blue Revolutions:

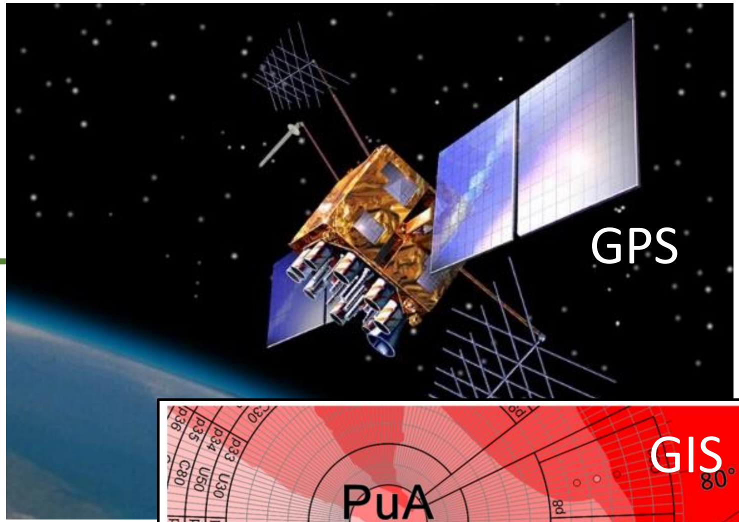
  1. **Rapid expansion in 1800's and 1900's**
  2. **Pressurization beginning circa 1950**
  3. **Precision-variable rate irrigation (VRI) - now**



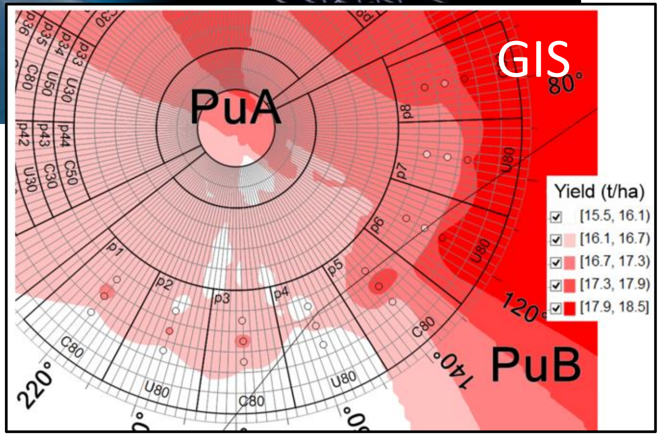
Classic
Irrigation scheduling


- Labor intensive
  - Soil water assessment by “Look and Feel”
  - Neutron probe – mostly by consultants
- Compute intensive
  - Checkbook method – needs a profile water content and ET estimates, can drift from reality
  - ET replenishment methods – Often computer-based Penman or Penman-Monteith.
    - Connection to weather station often needed. Computer needed.
- ET networks. Useful if they stay up, are user-friendly, can be accurate
  - Require time and attention. Not field specific.
- None resulted in easy site-specific irrigation application within a field

VRI Enabling Technologies – Support 3rd Blue Revolution



- Geographical Positioning Systems (**GPS**)
- Geographical Information Systems (**GIS**)
- Miniaturized computing power
- Data in the **Cloud**
  - Soil maps, satellite images, ET maps, weather, plant and soil water status, etc.



- **Cellular networks** allowing data almost anywhere
- Internet-of-Things (**IOT**) - Wireless, low-power, low-cost, distributed **sensor systems**
- **Open Source** Hardware & Software
- **Pressurized Irrigation → VRI**

Site-specific irrigation technologies: What they are and why they are needed

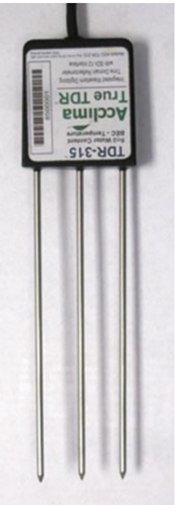
- Variable rate irrigation (VRI) addresses:
  - Spatial variability in the crop environment – increases yield response
  - Temporal variability in crop water stress – increases yield response
- Decision support systems (DSS)
  - VRI machines too complex for highly effective manual control
  - Data on crop response in time and space are:
    - **Too numerous** for easy comprehension – thousands of data per day
    - Require **biophysical understanding** used in algorithms to deliver effective site specific decisions

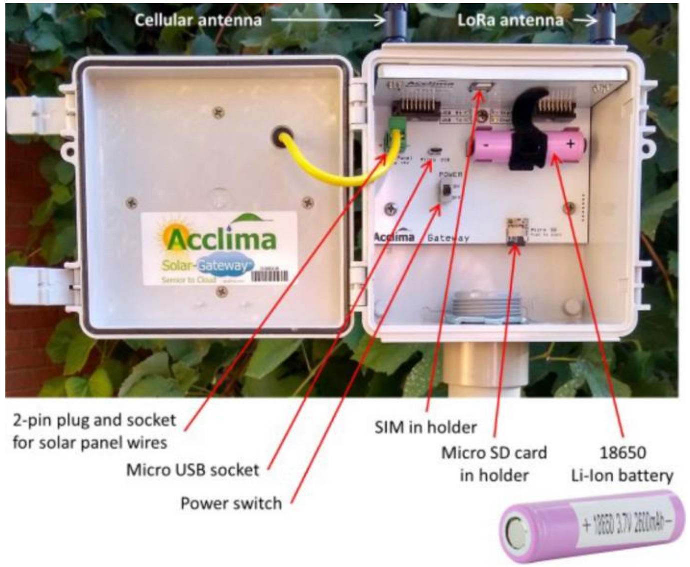
Site-specific irrigation technologies: What they are and why they are needed

- Wireless IOT sensor networks, including satellite data
  - Provide reliable data in time and over space needed by DSS
  - Reduce costs associated with wiring and manual data gathering
- A complete package includes a DSS in software/firmware
  - Reduces complexity to level of a smartphone app – **presents decision points; data available but in the background**.
  - User calculations are minimal or non-existent – freeing up management time.
  - Improves crop water productivity and profitability – approx. three-year payback period

The Bushland system: Sensors, DSS & VRI Systems

- **Georeferenced sensor systems**
- Soil water sensors
  - Positioned in key areas of field
  - Used in hybrid algorithms combining plant and soil water status data
- Wireless canopy temperature sensors
  - Main indicator of crop water stress
  - Integrated crop water stress index (iCWSI) calculated
  - iCWSI used alone or in hybrid mode (humid locations)
- Wireless node and gateway systems - IOT
  - Position nodes where needed – Data goes to cloud



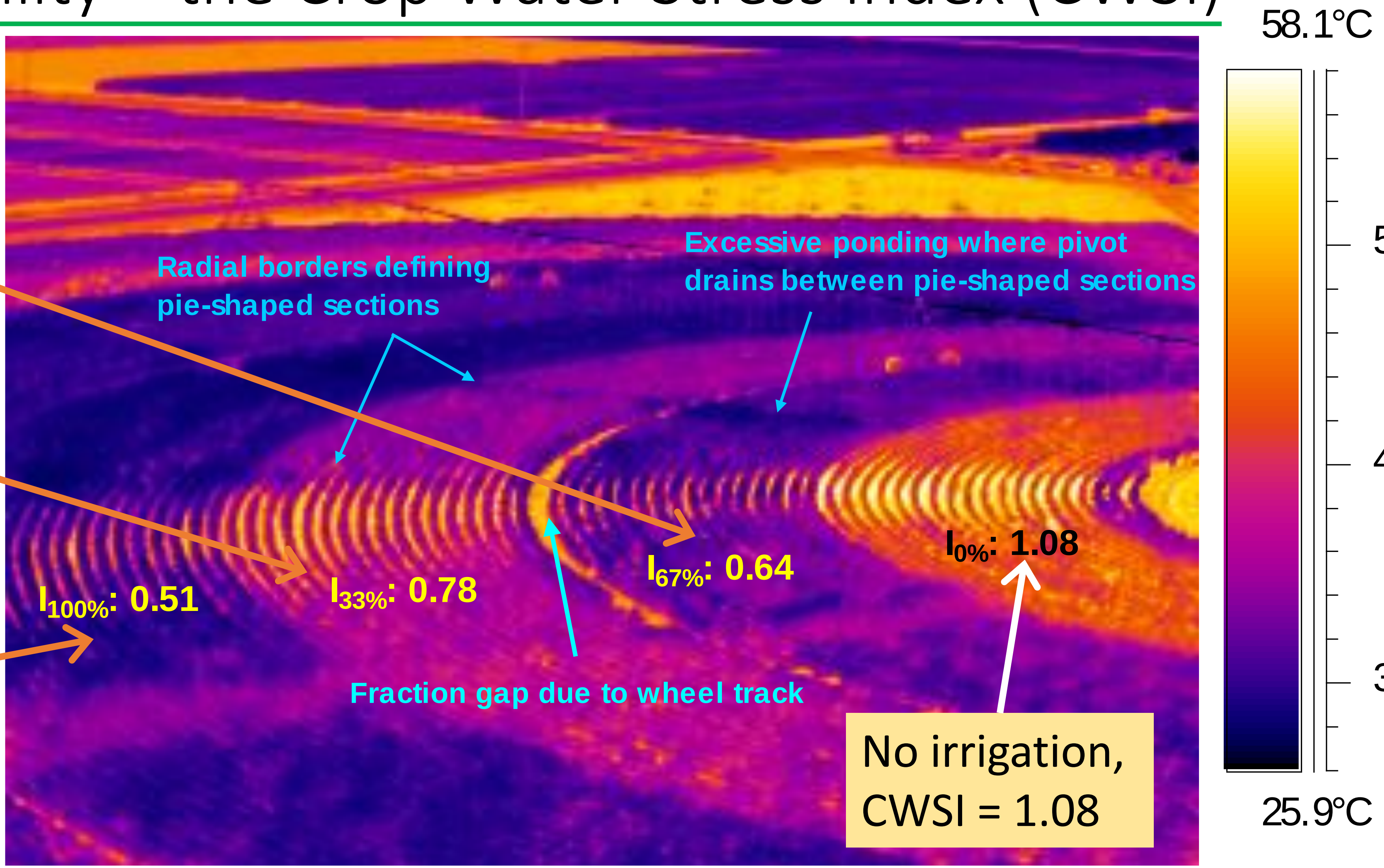


Remote thermal data as a tool for mapping in-field spatial variability – the Crop Water Stress Index (CWSI)

67% irrigation,
CWSI = 0.64

33% irrigation,
CWSI = 0.78

100% irrigation,
CWSI = 0.51

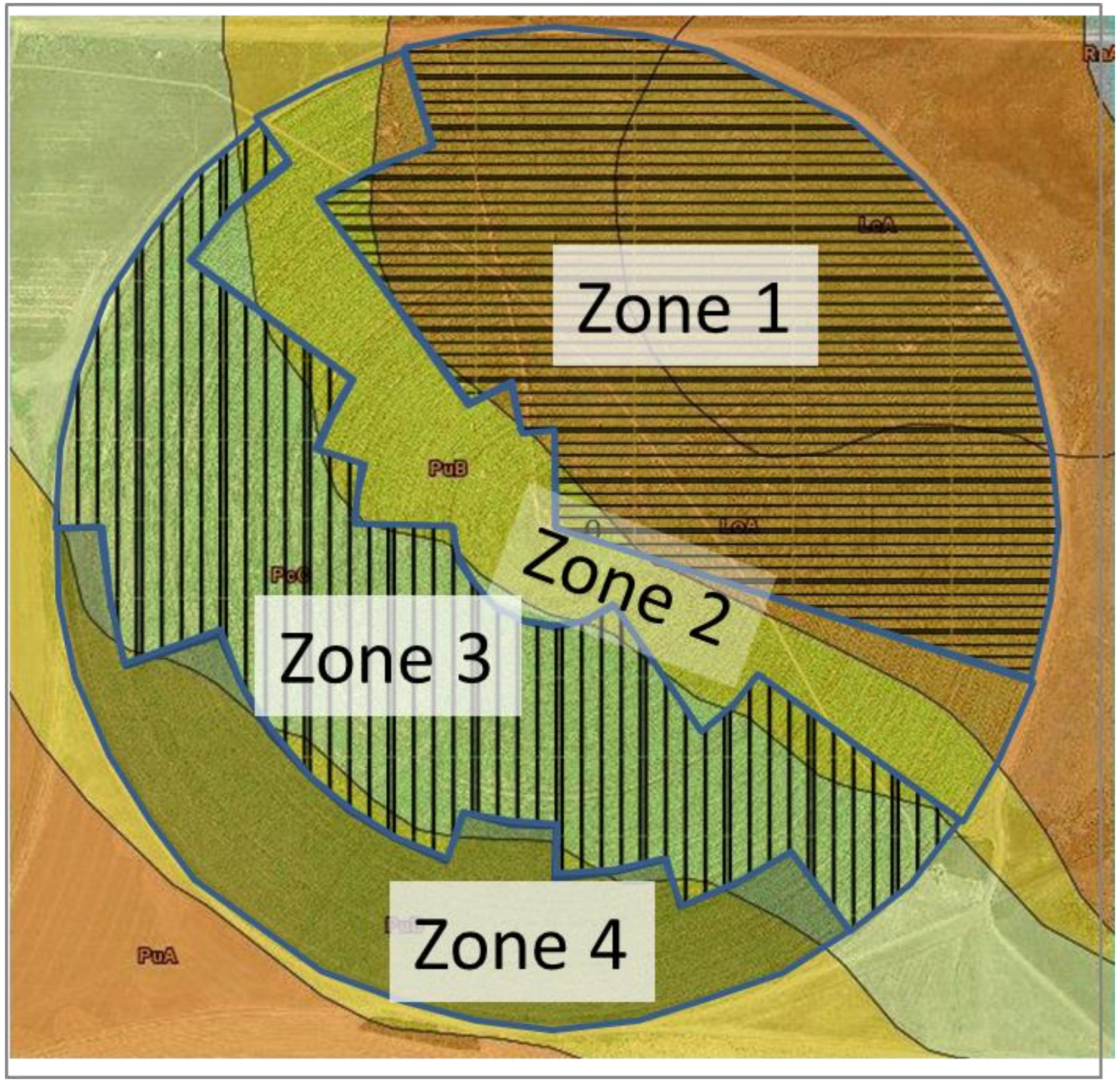


No irrigation,
CWSI = 1.08

Sector & radial control – Implications

- Allows more complex and appropriate **management zone** delineation
- *Each management zone comprises numerous control zones*
- **Control zone** is the smallest area that can be separately sensed/controlled
- *Algorithms applied to a management zone may result in different irrigation in each control zone*
- Cheap, plentiful, site-specific data are needed – without wires

Thus: Wireless IOT sensor networks

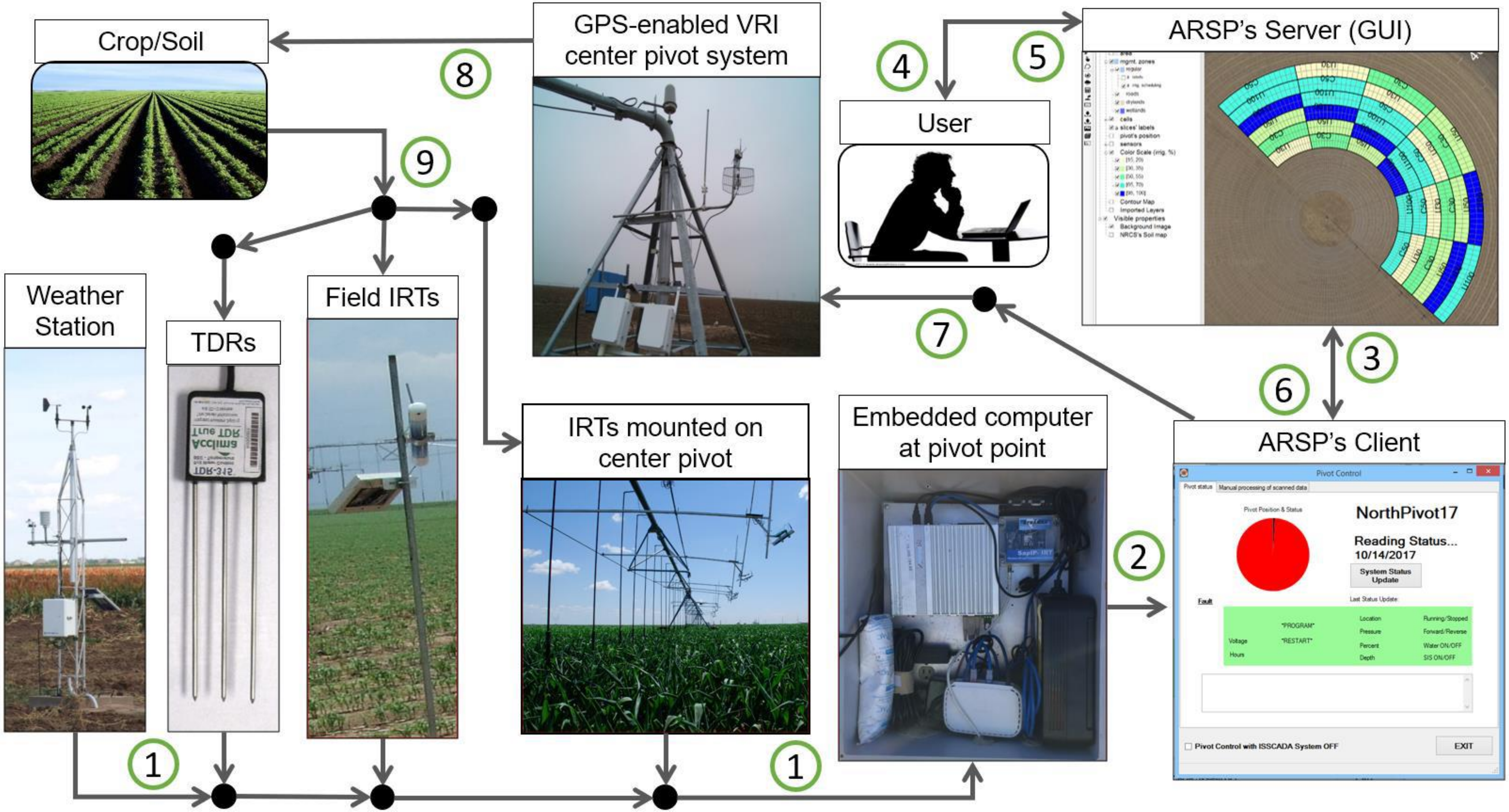


ARSPivot – A VRI Decision Support System

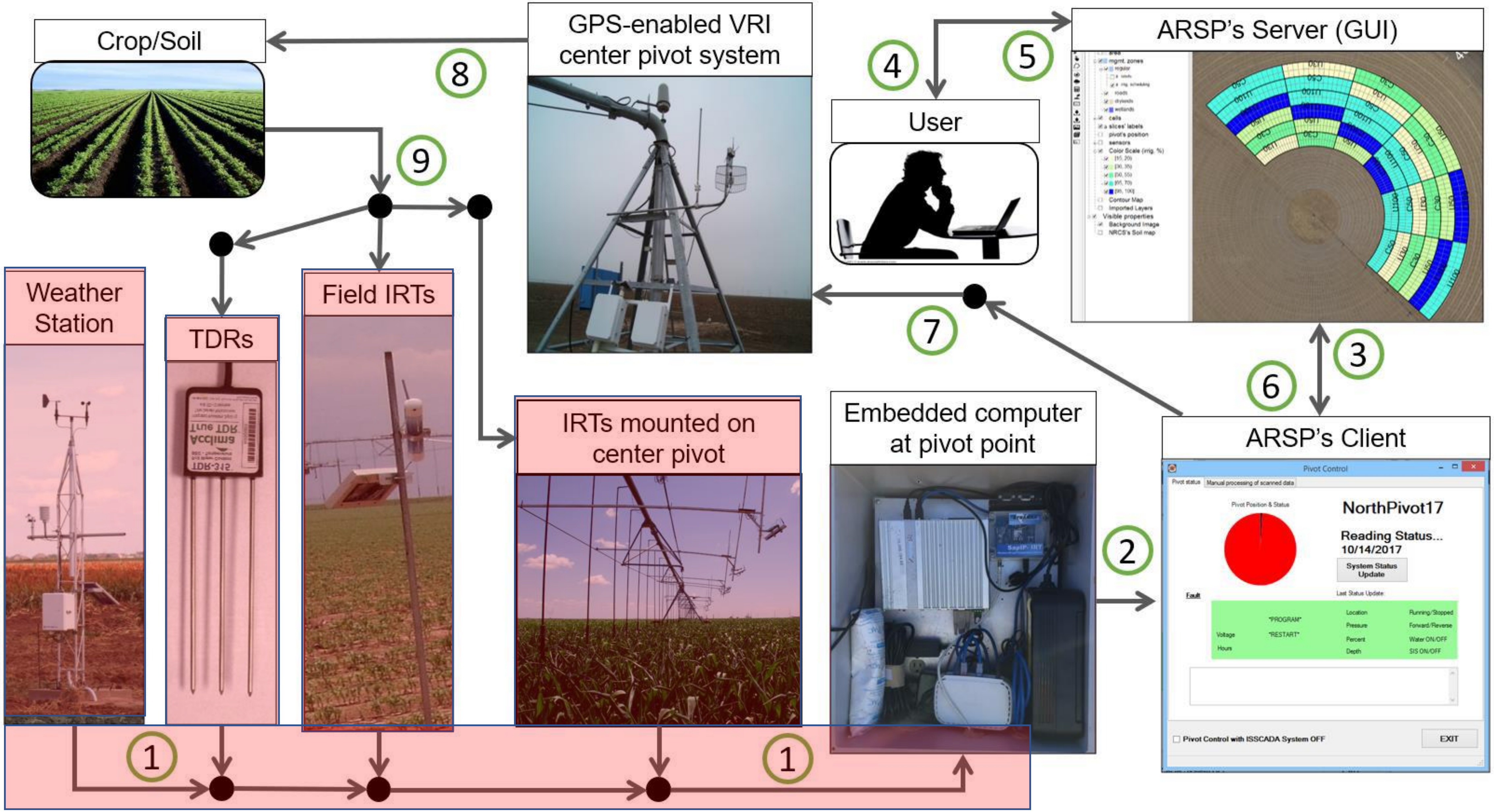
- ARSPivot (ARSP) is a computer program that embodies an **Irrigation Scheduling Supervisory Control And Data Acquisition** (ISSCADA) system as a decision support system.
- It is the software part of a patented hardware/software decision support system (Evett et al., 2014)
- Objectives of ARSPivot:
  - **Automate the collection of data** from plant, weather and soil sensing systems
  - Serve as a **communication tool** between users, sensing systems, external data sources, and center pivot controls
  - Use site-specific **irrigation scheduling** algorithms based on plant and soil data
  - Provide additional **decision support tools** that improve irrigation management
  - **Control** variable rate irrigation (VRI) center pivot systems

Evett, S.R., S.A. O'Shaughnessy and R.T. Peters. 2014. Irrigation Scheduling and Supervisory Control Data Acquisition System for Moving and Static Irrigation Systems. United States Patent No.: US 8,924,031 B1.

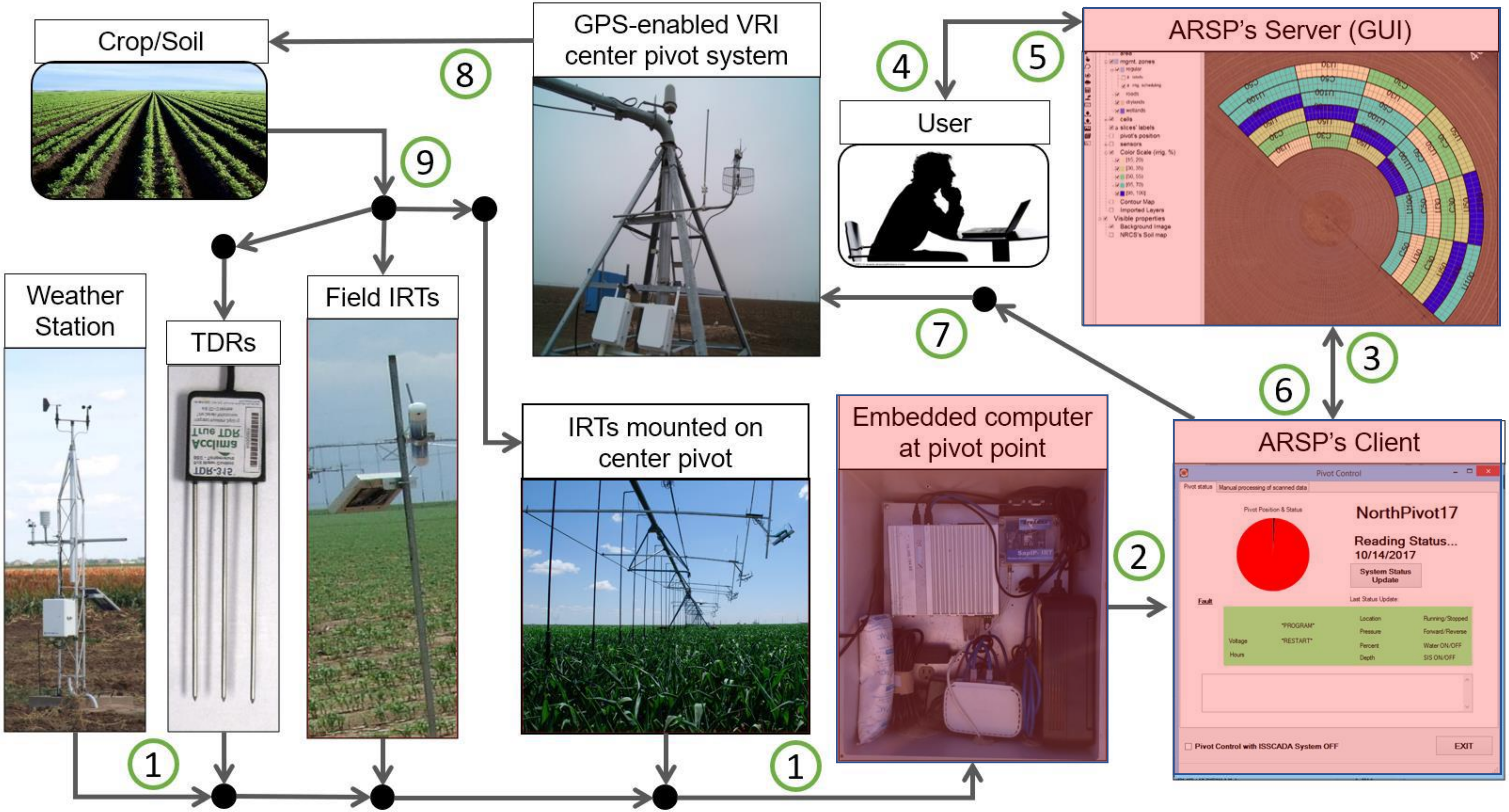
ARSPivot – A hardware/software DSS



ARSPivot – Wireless Data Transmission

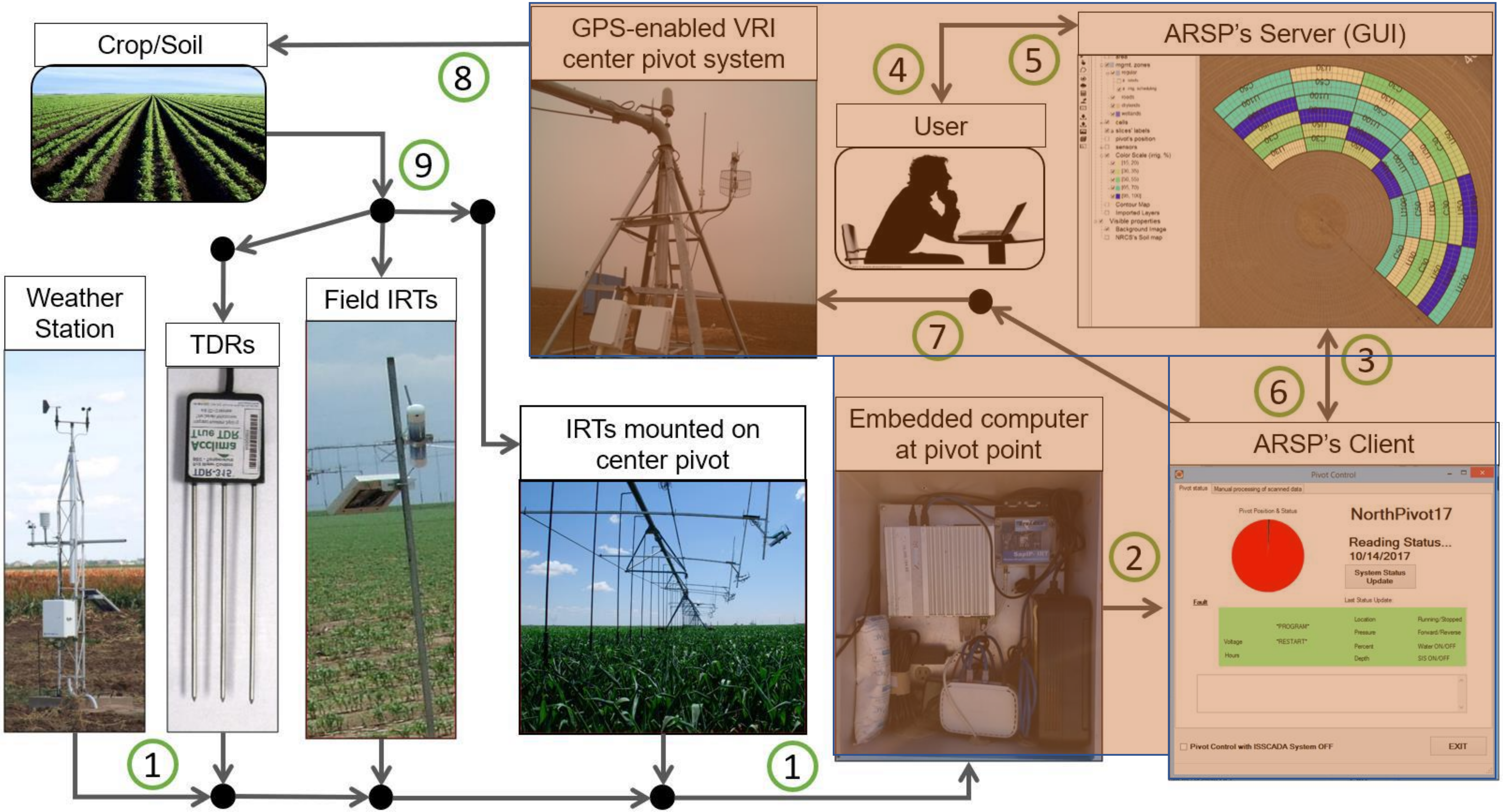


ARSPivot – Decision Making



ARSPivot – Wireless transmission

Andrade et al. (2020a,b)
O'Shaughnessy et al. (2020a,b)



ARSPivot – Wireless transmission

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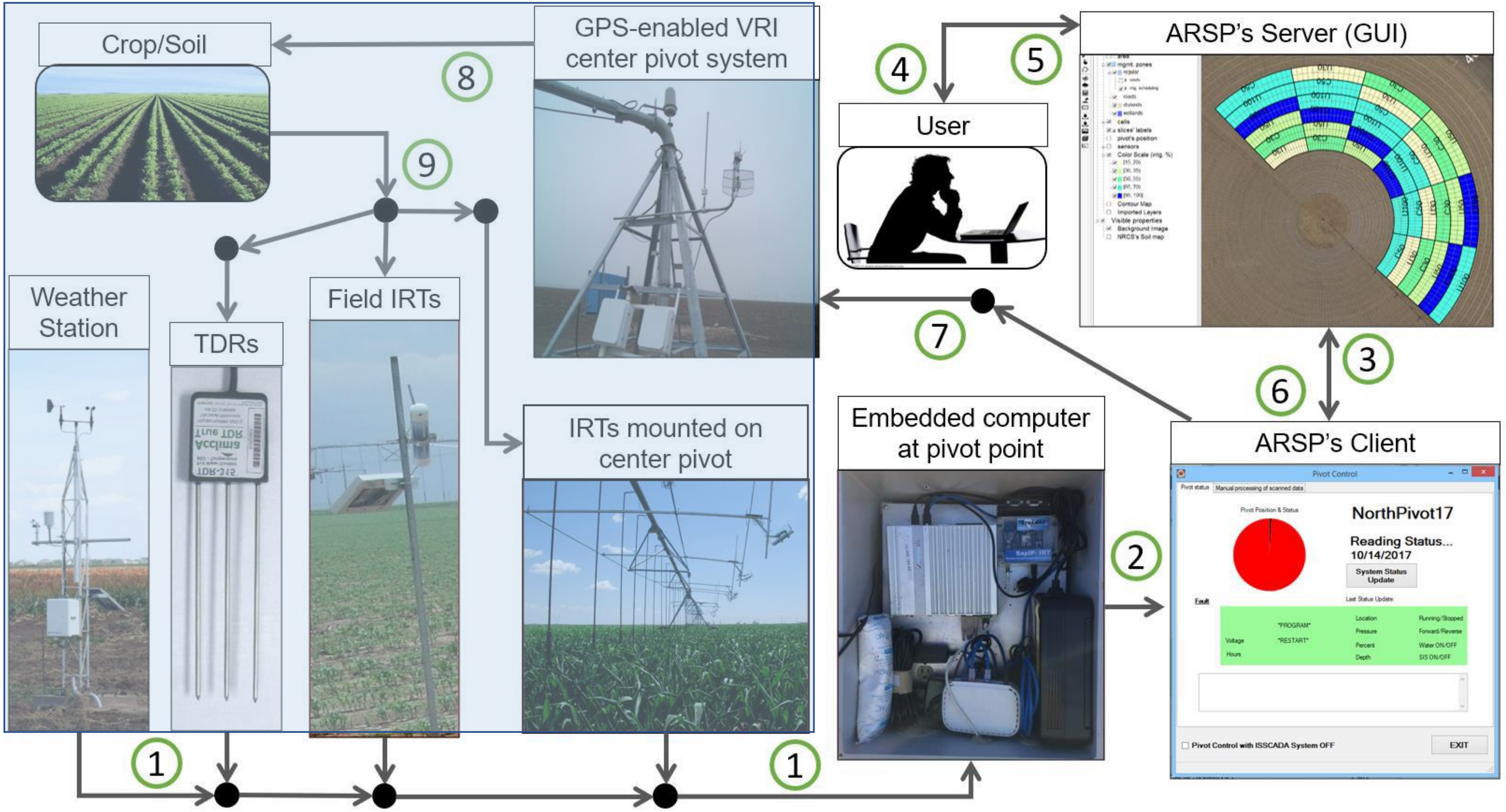

So what?

- System shown to be widely applicable in semi-arid to humid climates: Texas, Missouri, Mississippi, South Carolina…
- System tested with cotton, corn, potato, sorghum, soybean.
- Yield and crop water productivity typically better than conventional center pivot irrigation
- Payback period from 3 to 5 years due to:
  - Decreased pumping costs
  - Increased yield

Resources to Support Modeling for DSS

- Agroecosystem modeling holds some keys to understanding consequences of climate change in view of adaptations
- Successful modeling depends on high quality datasets for both inputs and for verification of model outputs
- We can explore systems under dryland/rainfed, fully irrigated, and deficit irrigated conditions
- 30+ years of high quality datasets from Bushland, Texas, provide opportunities for system modeling involving alfalfa, corn (maize), cotton, sorghum, soybean, sunflower, and winter wheat

Bushland Crop Growth, Yield, ET, Weather, and Energy and Water Balance Database: The Bushland Weighing Lysimeter Datasets

Steve Evett, Gary Marek, Karen Copeland, Brice Ruthardt, Paul Colaizzi, David Brauer, Terry Howell, Sr.

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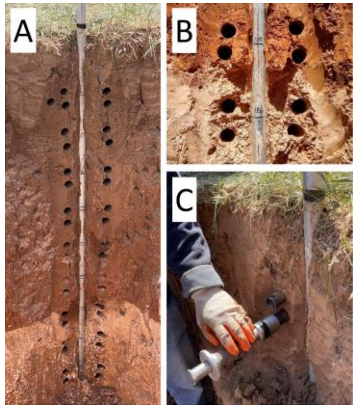
USDA Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE

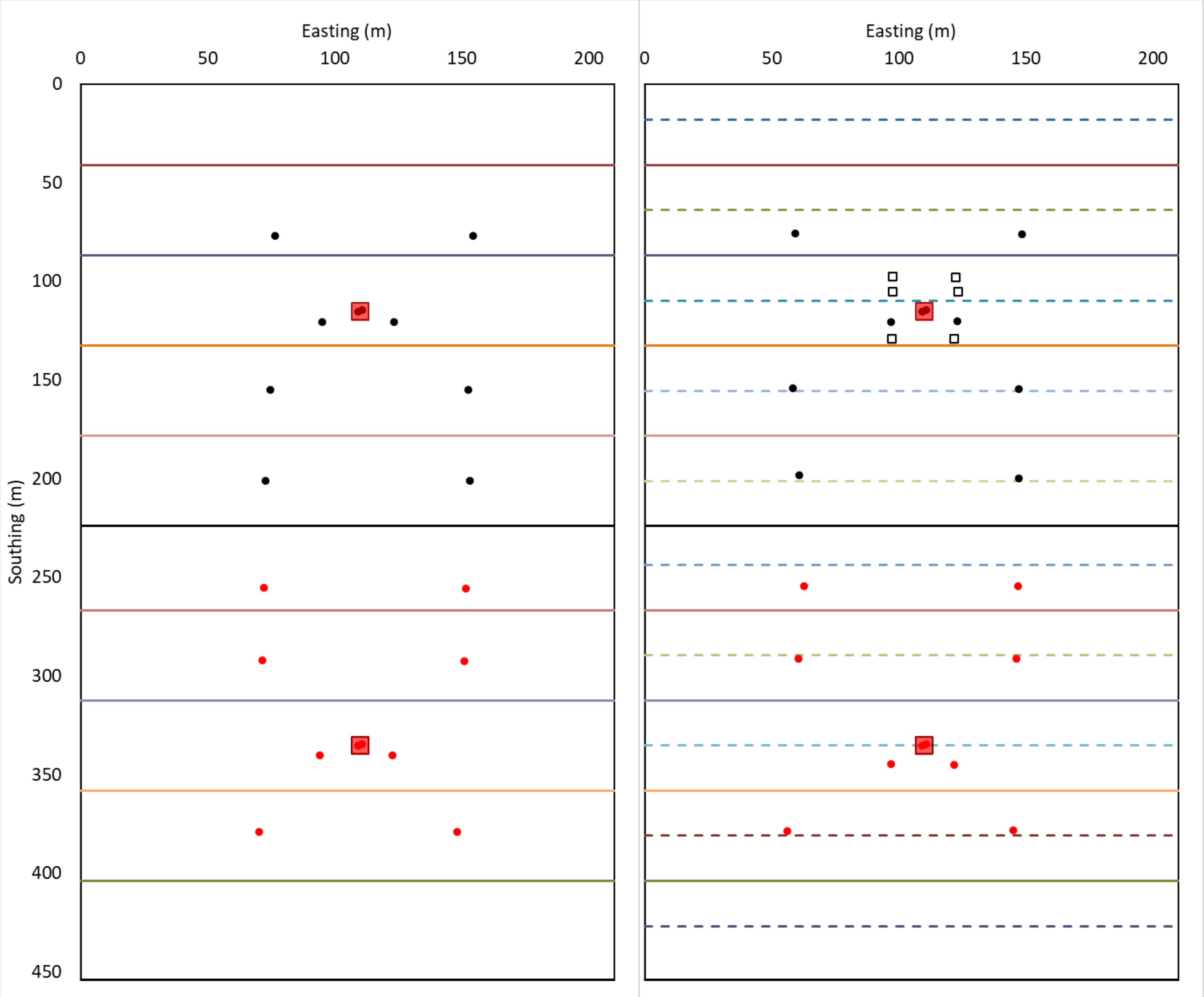
Weighing Lysimeter

- N = 4
- 3 × 3 × 2.3 m deep
- Accuracy: 0.05 mm
- Centered in 4.4 ha field
- Full and deficit irrigated, and dryland production

Water balance
Asset locations

- 4 weighing lysimeters (red boxes)
- 40 neutron probe access tubes
- ET = $I + P + \Delta S + F + R$ for both lysimeter and neutron probe





Evett, et al. (2022). Methods for downhole soil water sensor calibration—Complications of bulk density and water content variations. Vadose Zone Journal, e20235. https://doi.org/10.1002/vzj2.20235

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- Search by author on “Evett”

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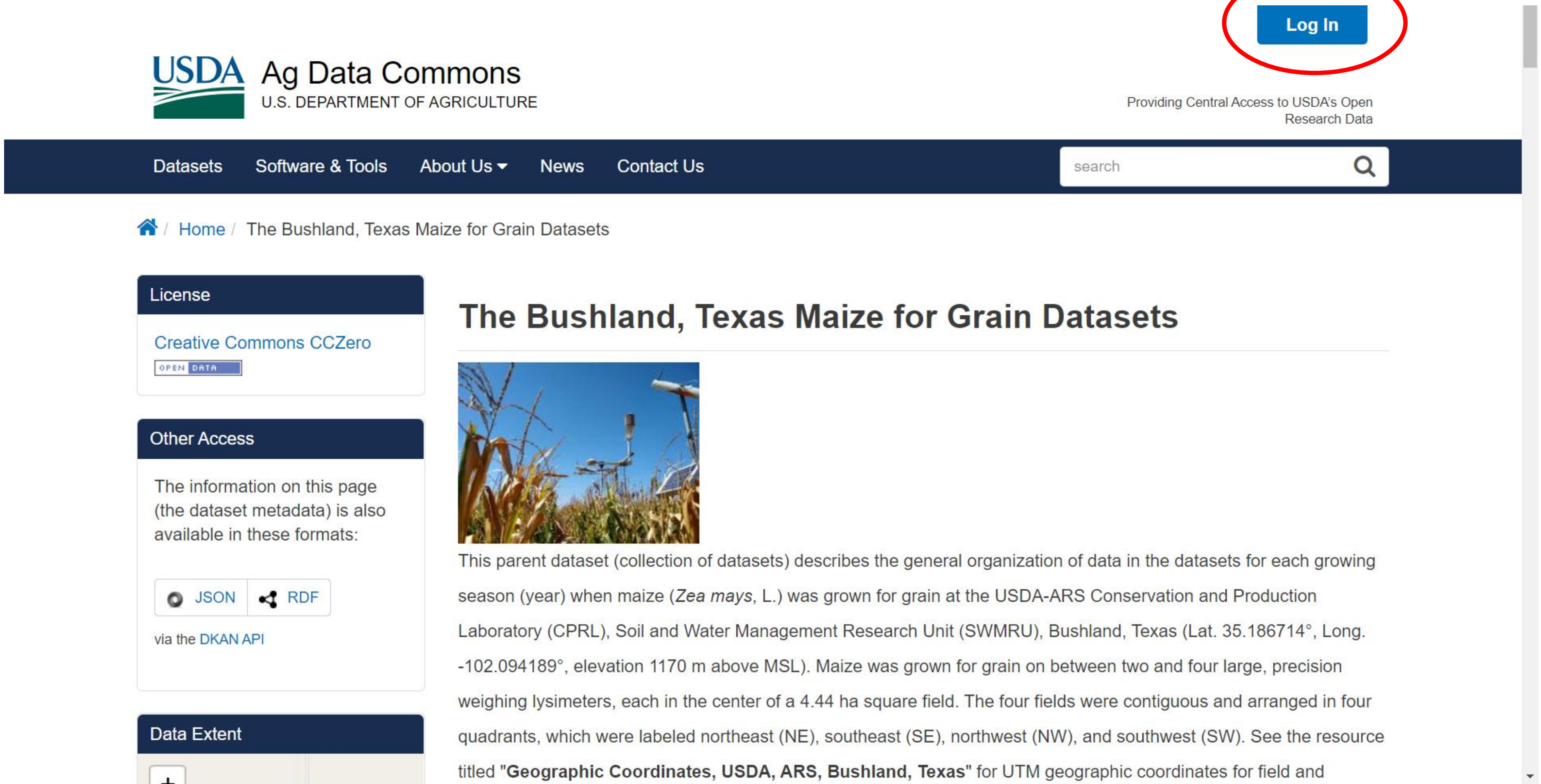


Data available today

- Alfalfa, 1996-1999, as a reference evapotranspiration “tall” crop
  - Evett, Steven R.; Copeland, Karen S.; Ruthardt, Brice B.; Marek, Gary W.; Colaizzi, Paul D.; Howell, Terry A., Sr.; Brauer, David K. (2022). The Bushland, Texas, Alfalfa Datasets. USDA ARS NAL Ag Data Commons. https://doi.org/10.15482/USDA.ADC/1526356
- Maize for grain, 1989, 1990, 1994, 2013, 2016, 2018
  - Evett, Steven R.; Copeland, Karen S.; Ruthardt, Brice B.; Marek, Gary W.; Colaizzi, Paul D.; Howell, Terry A., Sr.; Brauer, David K. (2022). The Bushland, Texas Maize for Grain Datasets. USDA ARS NAL Ag Data Commons. https://doi.org/10.15482/USDA.ADC/1526317
- Sunflower, 2009, 2011
  - Evett, Steven R.; Copeland, Karen S.; Ruthardt, Brice B.; Marek, Gary W.; Colaizzi, Paul D.; Howell, Terry A., Sr.; Brauer, David K. (2022). The Bushland, Texas Sunflower Datasets. USDA ARS NAL Ag Data Commons. https://doi.org/10.15482/USDA.ADC/1528066
- Winter wheat, 1989-1990, 1991-1992, 1992-1993
  - Evett, Steven R.; Copeland, Karen S.; Ruthardt, Brice B.; Marek, Gary W.; Colaizzi, Paul D.; Howell, Terry A., Sr.; Brauer, David K. (2022). The Bushland, Texas, Winter Wheat Datasets. USDA ARS NAL Ag Data Commons. https://doi.org/10.15482/USDA.ADC/1527912

Data availability upcoming

- Soybean, 1995, 2003, 2004, 2010, 2019 - **Submitted**
  - Mix of varieties/genetics, sprinkler or SDI, one dryland year
  - Often as a short season catch crop after cotton failure
- Cotton, 2000, 2001, 2002, 2004, 2008, 2010, 2012, 2020
  - Mix of varieties/genetics, sprinkler irrigated, subsurface drip irrigated (SDI), dryland
- Sorghum, 1987, 1988, 1991, 1993, 1997, 1998, 1999, 2004, 2005, 2006, 2007, 2014, 2015,
  - Mix of varieties/genetics, sprinkler or SDI, some dryland, some for forage
  - Sometimes as a short season catch crop after cotton failure
- Maize for forage, 2006, 2007

Bushland Metadata

- Geographic Coordinates of Experimental Assets
  - https://data.nal.usda.gov/dataset/bushland-texas-maize-grain-datasets/resource/0d9f9b90-a2e5-47c6-bad6-2c9083c82604
- Conventions
  - https://data.nal.usda.gov/dataset/bushland-texas-maize-grain-datasets/resource/30bb4f0a-030c-4dda-bfae-892f8a9423d4
- Symbols and Abbreviations
  - https://data.nal.usda.gov/dataset/bushland-texas-maize-grain-datasets/resource/81987778-bbeb-4075-b334-aca8b9a098ce
- Soil Properties by depth and horizon
  - https://data.nal.usda.gov/dataset/bushland-texas-alfalfa-datasets/resource/ed05ea2c-8d62-4d4f-a0df-738da82c20af

Bushland Crop Specific Data Files

- Weighing Lysimeter Data (5- and 15-min, 365 d, n = 4, initial QA/QC)
  - Radiation balance, microclimate, canopy & soil temperatures, soil heat flux, etc.
- Water Balance Data – Evapotranspiration, Irrigation, Precipitation, Dew/frost (15-min, 365 d, n = 4, final QA/QC)
  - Final quality control. Marek et al. (2014), https://dx.doi.org/10.13031/trans.57.10433
- Growth and Yield Data (periodic, n = 24)
- Agronomic Calendars (daily record of operations/incidents)
- Supporting references – Specific to each crop

Bushland General Data Files

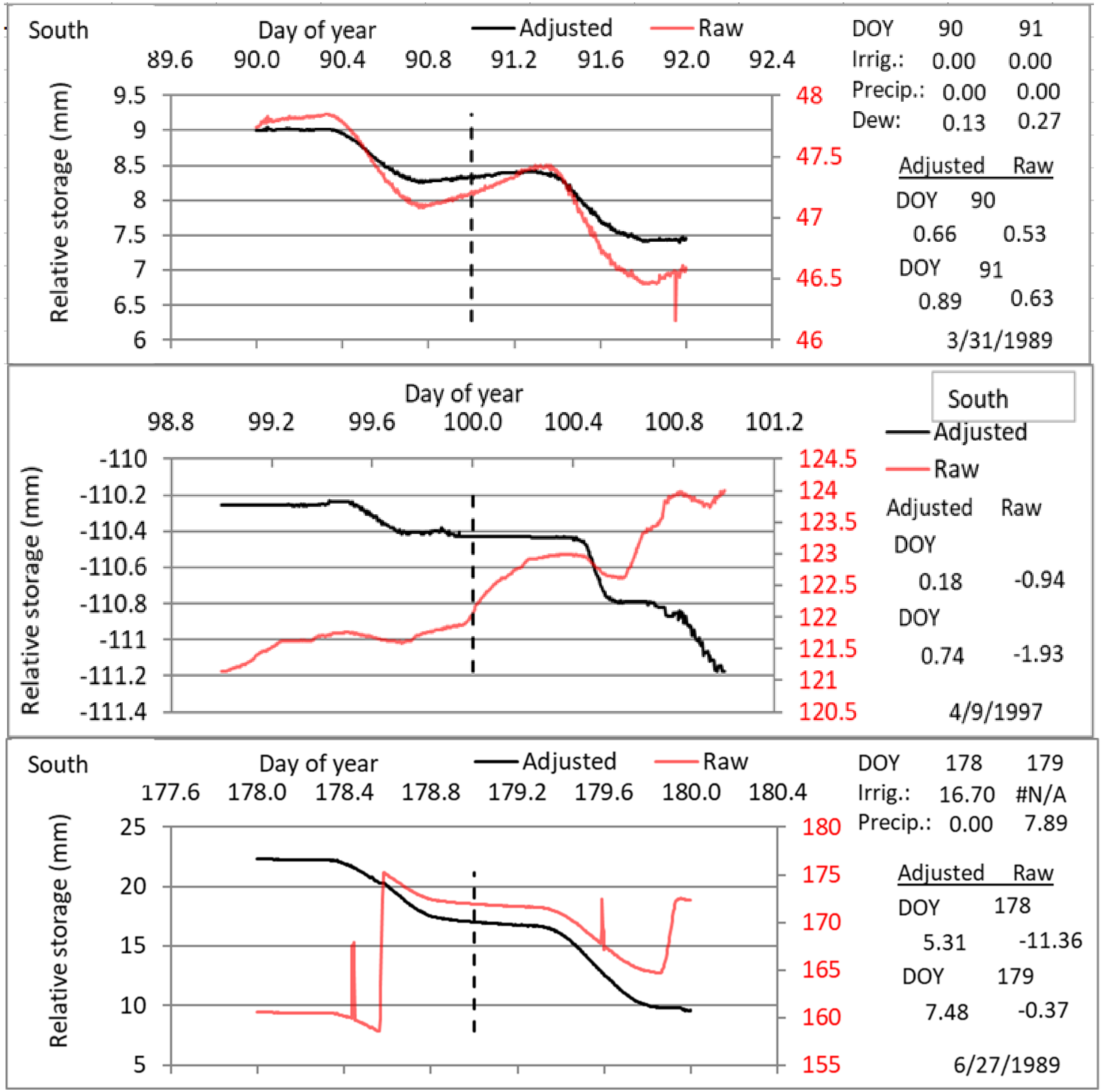
- Standard Quality Controlled Research Weather Data (15-min, 365 d)
  - https://doi.org/10.15482/USDA.ADC/1526433
  - Solar irradiance; wind speed; air pressure, temperature and humidity; precipitation
    - Evett, S.R., Gary W. Marek, Karen S. Copeland and Paul D. Colaizzi. 2018. Quality Management for Research Weather Data: USDA-ARS, Bushland, TX. Agrosyst. Geosci. Environ. 1:180036 (2018). https://doi.org/10.2134/age2018.09.0036
- Soil Water Content Data (periodic neutron probe to 2.3 m, n = 40)
  - https://doi.org/10.15482/USDA.ADC/1526332
    - Evett, S.R., G.W. Marek, P.D. Colaizzi, K.S. Copeland, B.B. Ruthardt. (2022). Methods for downhole soil water sensor calibration—Complications of bulk density and water content variations. Vadose Zone J. 2022;e20235. https://doi.org/10.1002/vzj2.20235
    - Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.). (2008). Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. https://www.iaea.org/publications/7801/field-estimation-of-soil-water-content)

All data are machine readable

- Data in columnar format – typically one is a time stamp
- One header row followed by data rows (no blank lines)
- Comma separated headers and data in CSV files
- Data dictionary for each data tab – defines each header and gives type of data, format, null value, etc. for each header
- Metadata files describe experimental environment, GPS coordinates, conventions, soil properties, etc.
- Files in Excel or CSV format
- File, data tab, and data dictionary names are unique across the datasets

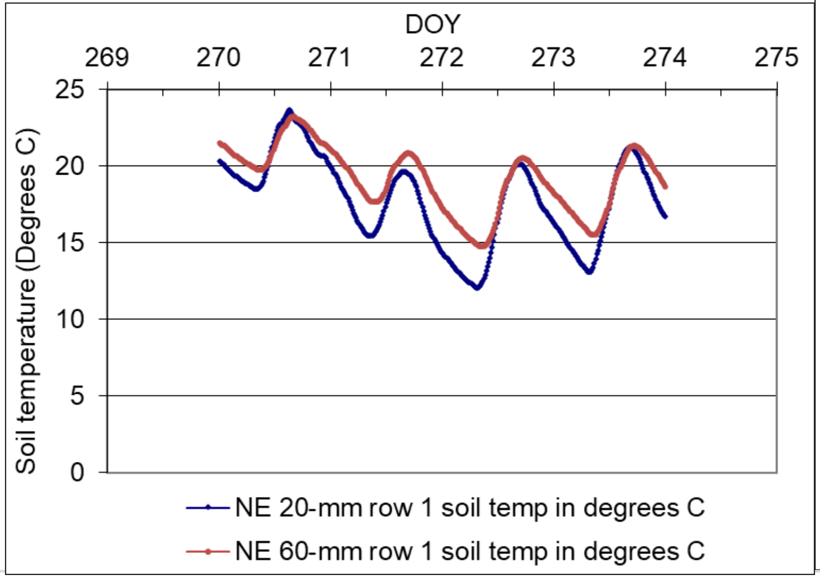
Analysis

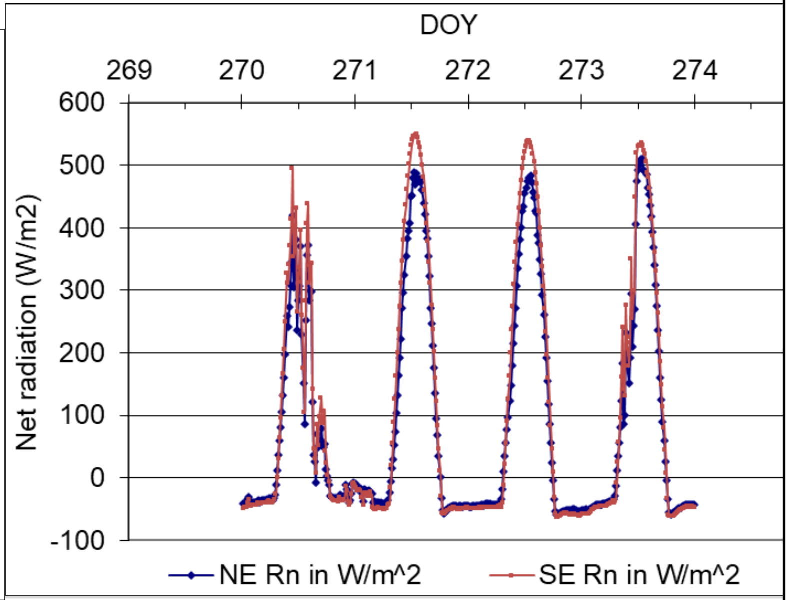
- Dew fall up to 20% of ET
- Most common in winter and spring
- Other corrections:
  - Precipitation
  - Irrigation
  - Drainage
  - Activity on lysimeter
  - etc.

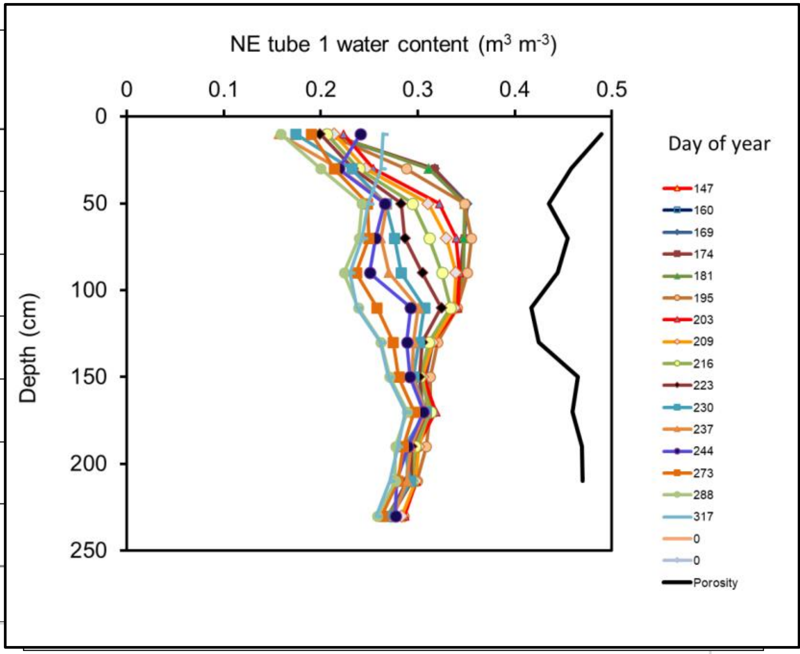


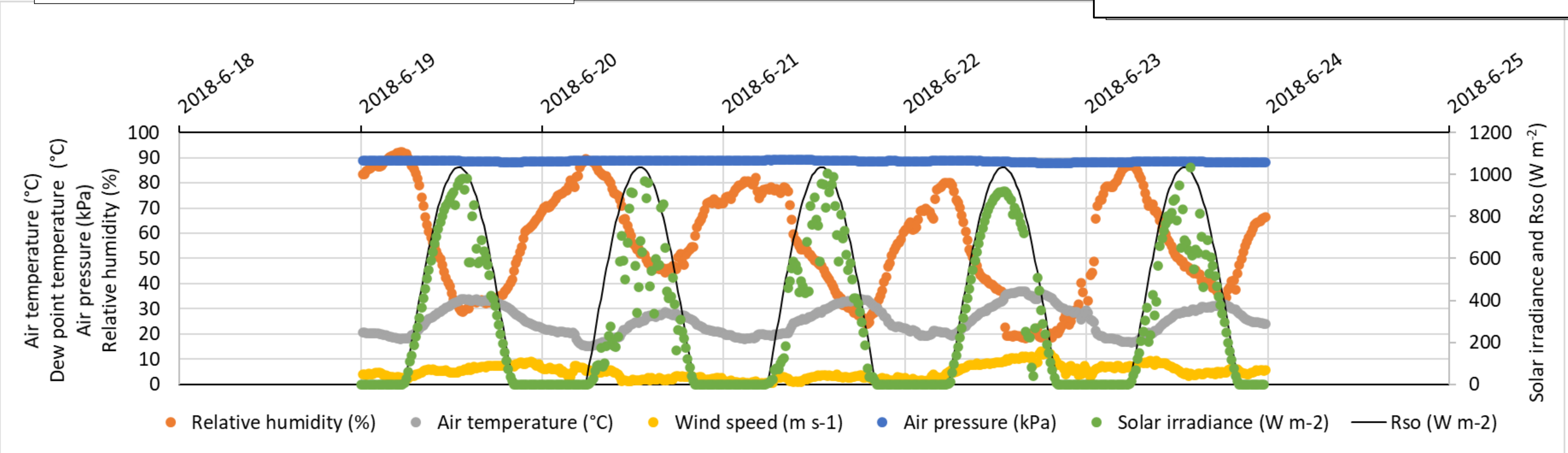
Marek et al. (2014), https://dx.doi.org/10.13031/trans.57.10433

Data Visualization









Some Dataset Uses

- AgMIP maize modeling team comparing 41 models
- AgMIP winter wheat modeling team
- OPENET https://openetdata.org/ satellite based ET estimation
- Crop coefficients for irrigation scheduling
  - Evett, et al. (2020). https://doi.org/10.13031/trans.13920
  - Howell, et al. (2006). https://doi.org/10.1061/40856(200)291
  - Marek, et al. (2020). https://doi.org/10.13031/trans.13924
- Improving SWAT irrigation algorithms
  - Chen, et al. (2019). https://doi.org/10.1016/j.envsoft.2019.04.001
  - Marek, et al. (2016). http://dx.DOI.10.13031/trans.59.10926

Water Security, Precision Agriculture & Sustainability in the Face of Climate Change

- Establishing **water security** is key to sustainability
- In a water scarce nation, **virtual water trading** is immensely important
- **High value crops are key** to establishing a positive virtual water trading context
- Precision irrigation **decreases the virtual water content** of high value crops and products such as **meat, eggs, and milk**
- Precision irrigation **cost can be justified by profitability** of high value crops and products
- Establishment of **precision irrigation manufacturing** in-country is key

Some recent key references:

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Thank you – Questions?

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The author and his sisters cleaning the dairy barn after morning milking, circa 1962. In the right background is a stack of alfalfa bales, preferred dairy forage.

The author's grandfather Orth, who dug irrigation canals and turned the desert green in the Magic Valley region of Southern Idaho beginning in 1910.

The family farm with a corn crop in the 1960s.

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