Soil water sensor technologies: Measurement principles and use in evaluating crop water status

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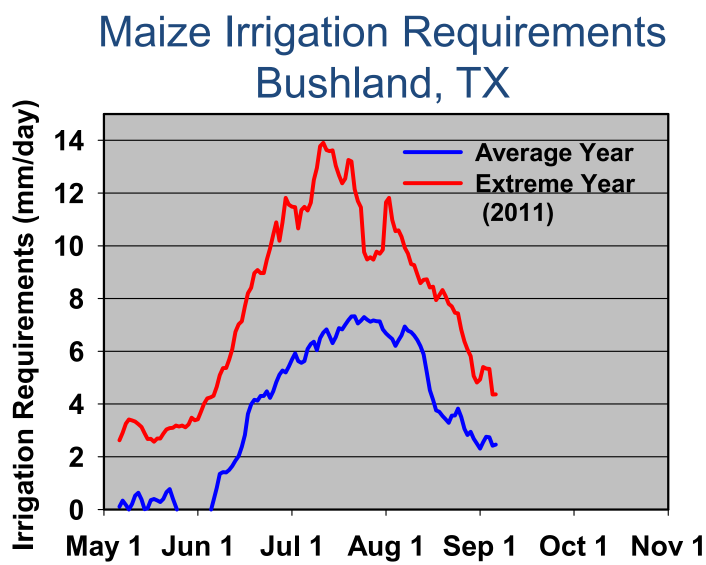
Soil Water Sensors & Irrigation

- Sensor examples based on work in southern US Great Plains - large scale agricultural production but not so intensively managed
- **Sensor performance and problems are similar for small scale intensively managed crops**



- Extreme year to year variability in irrigation requirements
- Overestimation of crop water requirements (reduced risk at expense of inefficient water use and faster aquifer depletion)
- **Need to better assess crop water status – sensor technologies is one way**

Soil Water Sensor Method for Irrigation

Measure a surrogate soil property strongly influenced by soil water

Schedule irrigation based on attainment of a threshold water content measurement below which crop water stress has significant yield / economic impact

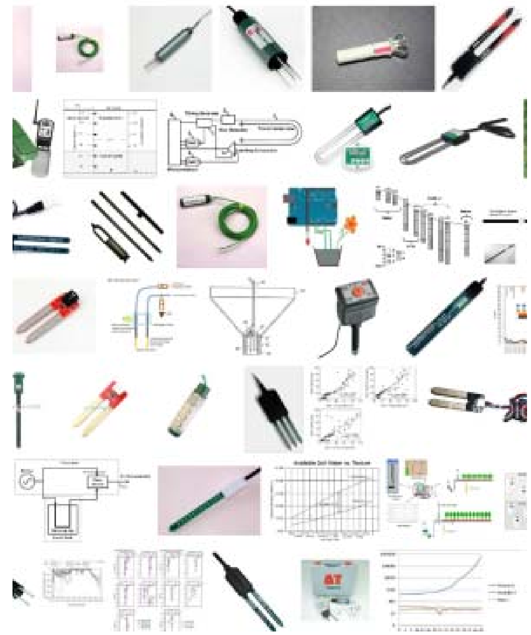
Assumes that irrigator has:

- Control over timing of irrigation withdrawals
- Sufficient irrigation capacity to be flexible

Not as straightforward as it seems!

Soil water sensors

- Vast array of water sensors that respond differently across soils, field and irrigated conditions
- All sensors are not created equal
- Water contents measured by sensors may not represent the field scale
- Manufacturer's often misrepresent the capability and accuracy of sensor
- Development of accurate and affordable sensors is difficult and a work in progress



The Problem - Deciding when to Irrigate

- July 3 – Soil water sensors show that there is enough water in profile so that irrigation can be delayed for at least 3 days.

- **Are the water sensors accurate?**
- **Are they representative of the entire field?**
- **Do you have enough confidence in your sensors to follow the recommendation?**

Outline

- Sensor technologies – focus on EM sensors
- Volume of soil sensed by EM sensors
- Sources of imprecision and inaccuracies
- Irrigation scheduling using EM soil sensors

Soil Water Sensors

- Neutron Probe – Counts of slow neutrons
  - Standard method to which all others are compared
  - Still invaluable in research
  - Use in irrigation management is hampered due to regulatory burdens and labor requirements
  - Automation is not feasible

Soil Water Potential Sensors

- Tensiometers
  - Sensitive to small changes in soil water
  - Useful in sandy soils & shallow rooted crops
  - Restricted range in water contents < 0.8 bar
  - Not suitable for determining water use and application depths

- Granular matrix sensors (e.g. ***WaterMark***)
  - Resistance measurement more related to water potential rather than soil water
  - Sensitive to temperature and conductivity
  - Range in water contents < 2 bars
  - Uncertainty combining two or more measurement depths to schedule irrigation

Electromagnetic (EM) Soil Water Sensors

Measurement of **soil (dielectric) permittivity** at a high AC frequency (50 MHz – 2000 MHz)

Material	Relative Permittivity
Air	1
Ice	3.2
Silica sand	2.7
Clay	3 - 6
Organic Matter	2 - 5
Liquid Water	**80**

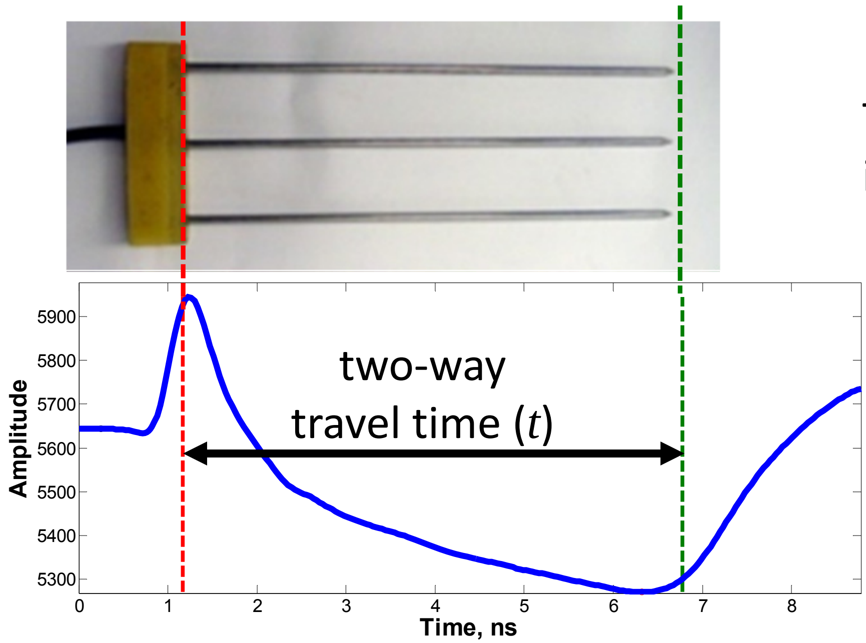
Soil (relative) permittivity ε_a is largely a function of the amount of *water* in the soil

All sensors measure a surrogate property that is then related to permittivity and/or water content through a calibration.

Electromagnetic Soil Water Sensors

Time Domain Methods

Time Domain Reflectometry (TDR) and Time Domain Transmission (TDT) - travel time of a broadband step pulse along a transmission line



Travel time, t, increases with increasing soil water content

$$\varepsilon_a \approx \left(\frac{c \cdot t}{2L}\right)^2$$

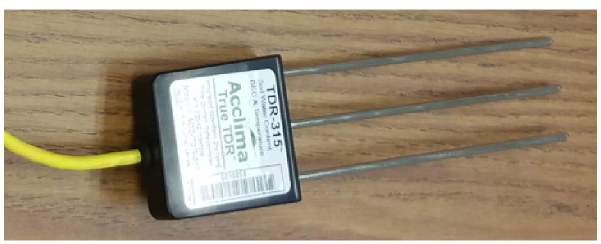
Travel time, t, also increases slightly with increasing conductive losses.

Electromagnetic Soil Water Sensors

Time Domain Methods

- **Conventional TD**R – use of coaxial cables & multiplexers - impractical for irrigation management

- ***Acclima TDT Moisture Sensor*** – all electronics in probe head; digital implementation of waveform analysis

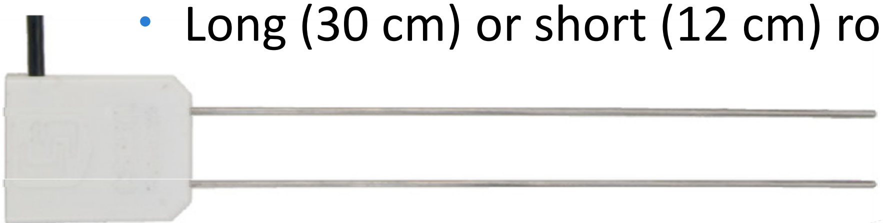


- ***Acclima TDR-315 Sensor*** – all electronics in probe head; digital implementation of waveform analysis

Electromagnetic Soil Water Sensors

Water Content Reflectometry - Quasi-TDR Methods

- Similar to TDR but assesses travel time differently using an oscillation period; results in larger errors associated with conductive losses (compared with conventional TDR)
- ***Campbell Scientific CS650/CS655***
  - Long (30 cm) or short (12 cm) rod lengths



- ***IMKO TRIME-PICO 64***
  - Coated (16 cm probe)
- ***Spectrum FieldScout TDR 300***
- ***ESI Gro-Point*** Moisture Sensor (TDT)

Electromagnetic Soil Water Sensors

Capacitance and frequency domain methods

Measurement of: resonant frequency of an oscillator; Charge /discharge time of capacitor (soil) to evaluate the phase shift – Many Variations!

- Low frequency measurement (< 200 MHz)
- Measures capacitance C_m

$$C_m \approx g_m \varepsilon_0 \varepsilon_a$$

- Geometric factor g_m is unknown and may change with soil water content
- Sensitive to electrical conductivity - causes current leakage / errors
- Probes coated with insulation to reduce effects of conductivity

Electromagnetic Soil Water Sensors

Capacitance and frequency domain methods

- Capacitance probes
  - ***Decagon ECH$_2$O*** Family

- Frequency Domain / Impedance probes
  - ***Dynamax ML2x ThetaProbe***

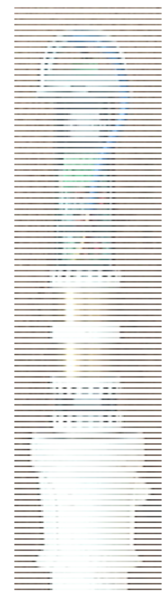
  - ***Hydra Probe***

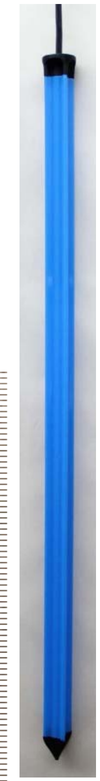
Electromagnetic Soil Water Sensors

Down-hole Configurations

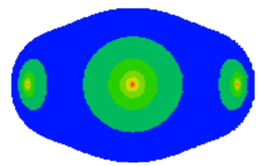
- Installation with minimal site disturbance
- Can provide measurements throughout the root zone
- Less sensitive to soil water – **measurements must subtract the influence of the access tube**

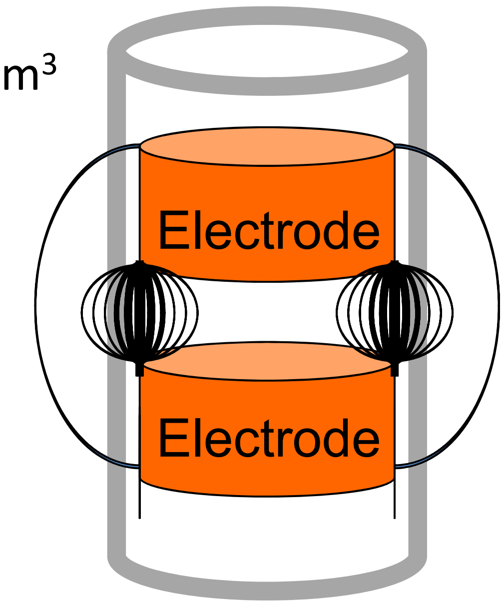
- **Quasi travel-time based**
  - ***ESI Gro-Point Profiling Probe*** (TDT)
  - ***IMKO Trime T3***
- **Frequency domain / capacitance based**
  - ***AquaSPY***
  - ***Sentek EnviroSCAN***
  - ***Delta-T PR2***



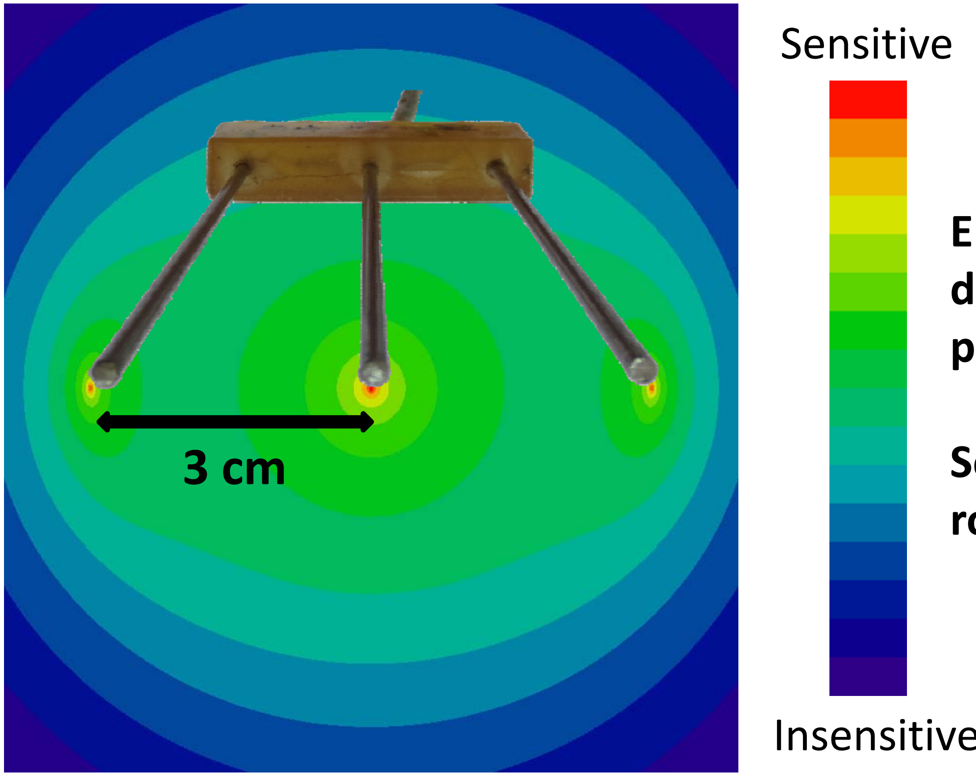


Volume of Soil Sensed at each measurement depth (90% EM field)

- Neutron probe — **14,000 – 65,000** cm^3
- TDR (20 cm long)  — **360** cm^3
- ***Decagon 5TE***  — **60** cm^3
- Ring capacitor (***Sentek EnviroSCAN***) — **600** cm^3
  - Less than 3 cm from sidewall
  - Half of capacitance is probe body / air (Schwank et al., 2006)



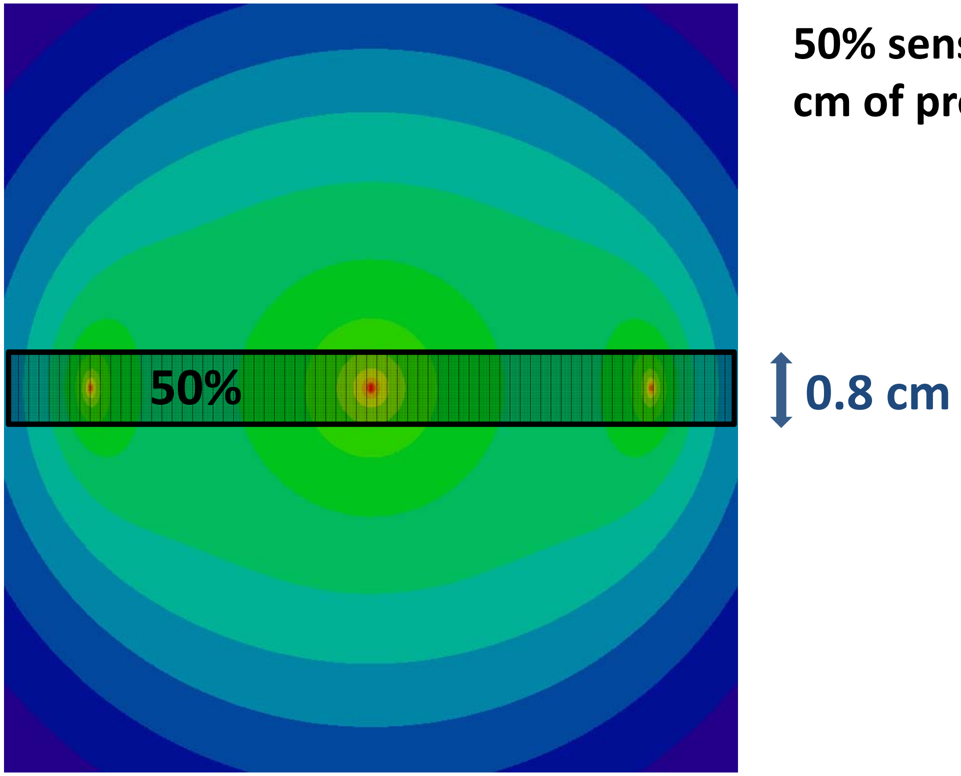
Sensing Volume – TDR Probe



Electric field density distribution for a three-wire probe (log scale)

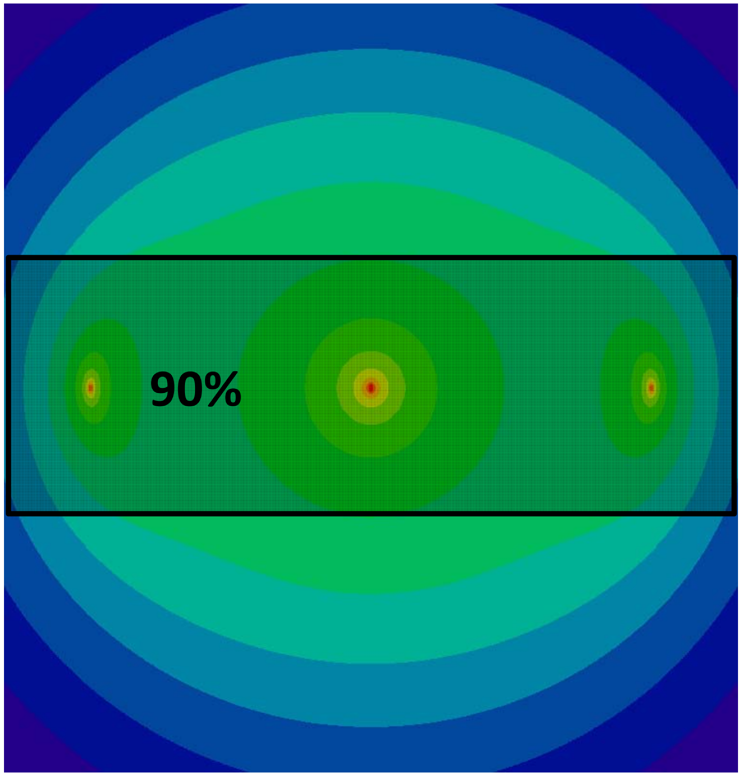
Sensing volume depends on rod spacing and diameter

Sensing Volume – TDR Probe



50% sensing volume is within 0.4 cm of probe

Sensing Volume – TDR Probe



90% sensing volume is within 1.4 cm of probe

2.8 cm

Many manufacturer's inflate reported sensing volume by evaluating EM field to 99%

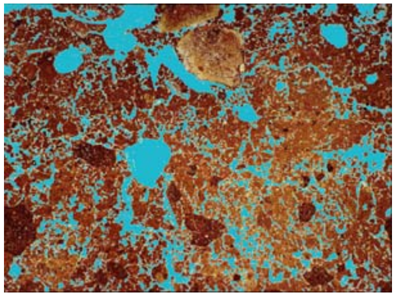
Decagon 5TE

- Measured 90% = 60 cm^3
- Reported = 715 cm^3

In soils, deviations in soil water content at large distances (> 6 cm) are usually far below the resolution of the sensor!!

Sources of Imprecision/Inaccuracy

Soil salinity – bulk electrical conductivity (EC_a)



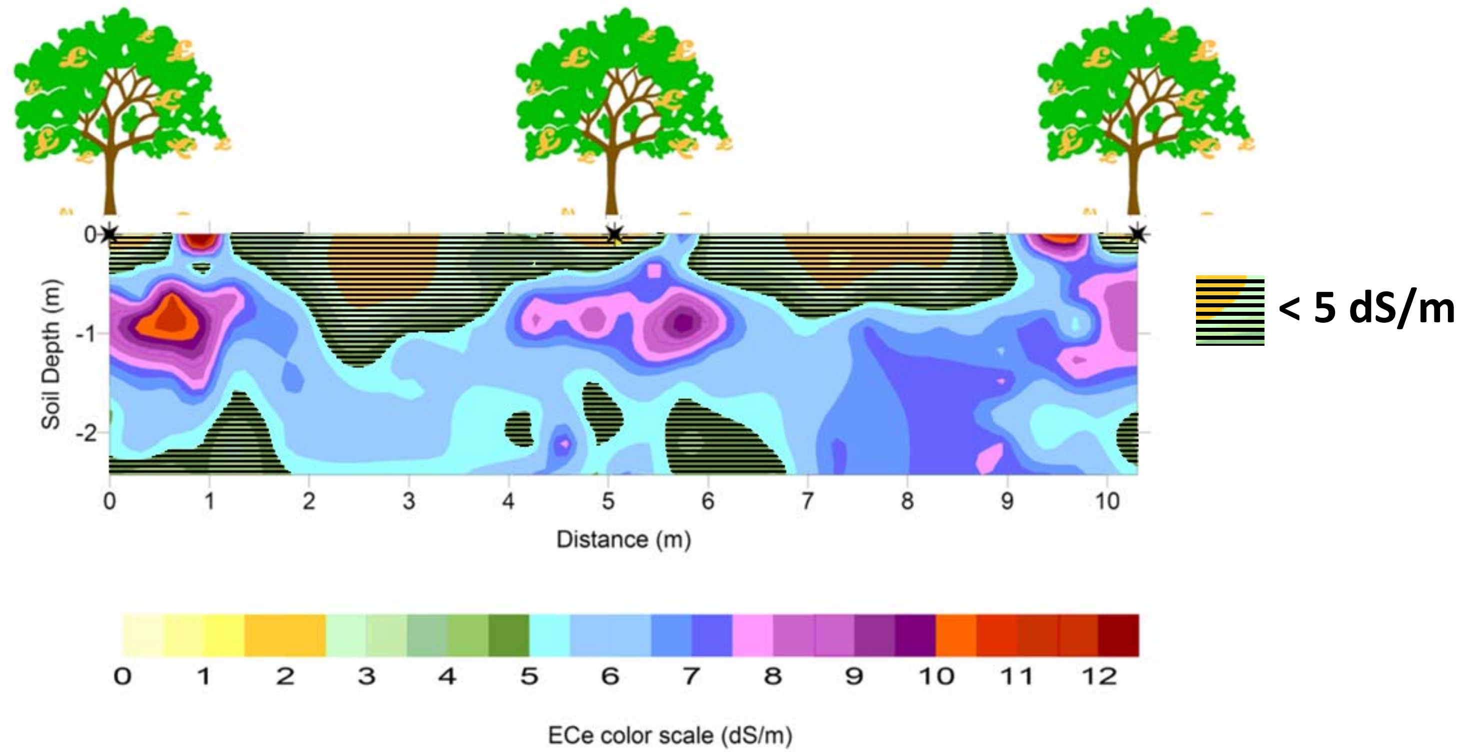
- Sensors respond to bulk electrical conductivity not solution EC
- Bulk electrical conductivity increases with increasing
  - Water content
  - Solution EC
  - Clay content
  - Bulk density
  - Temperature

- TDR and TDT Technology
  - Signal loss is problematic at EC_a > 2 dS/m (slightly saline soils) and water content measurements become impossible above 4 to 8 dS/m
  - Use shorter probes to reduce attenuation
- Frequency domain / capacitance methods
  - Lower frequency measurements ➔ more sensitive to EC

Sources of Imprecision/Inaccuracy

Most sensors begin to be influenced by EC when near saturation and saturated extract is greater than about 2 to 5 dS/m

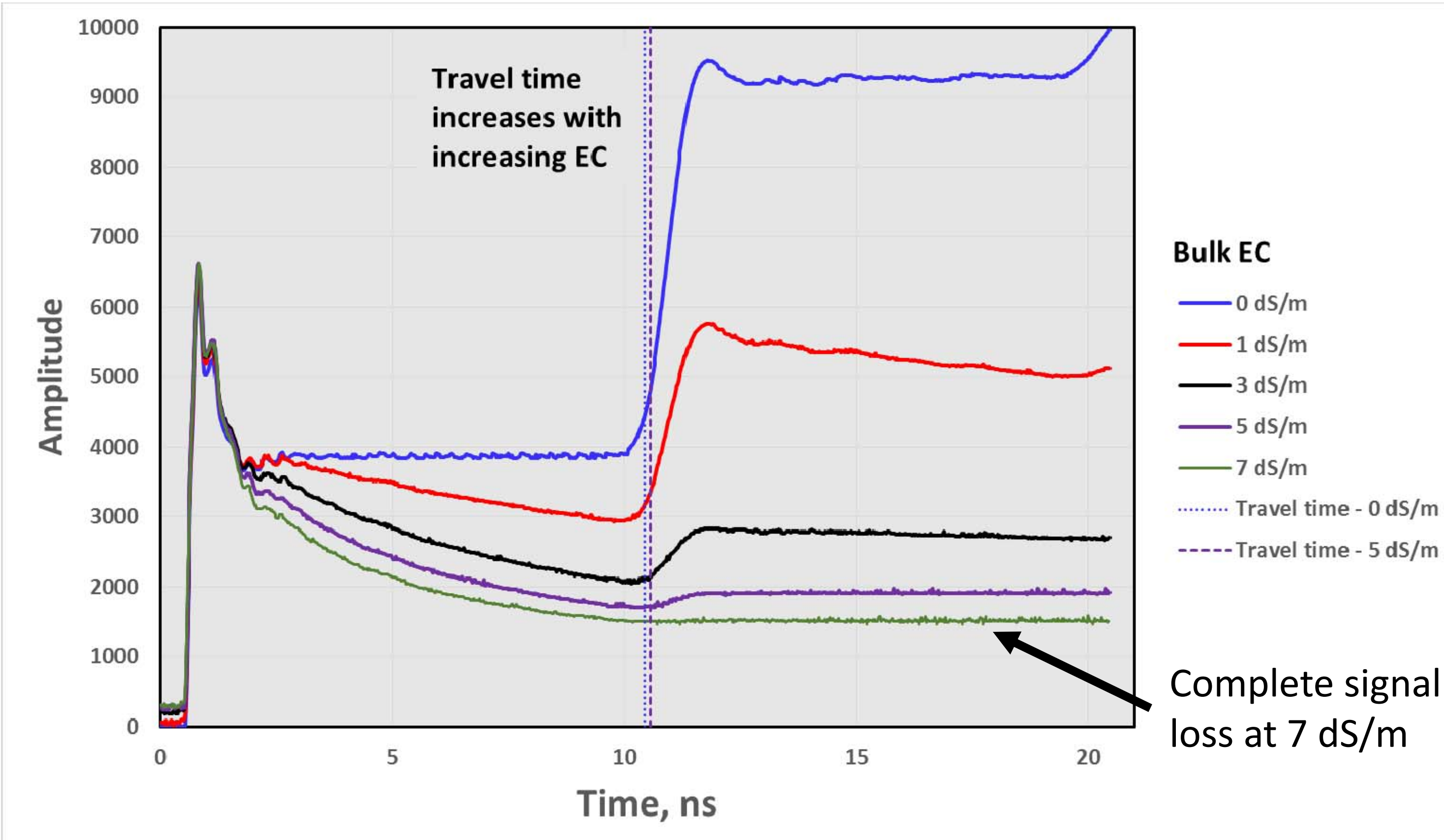
Soil electrical conductivity of the saturated extract in a microspray irrigated almond orchard (Burt et al., 2003)



Sources of Imprecision/Inaccuracy

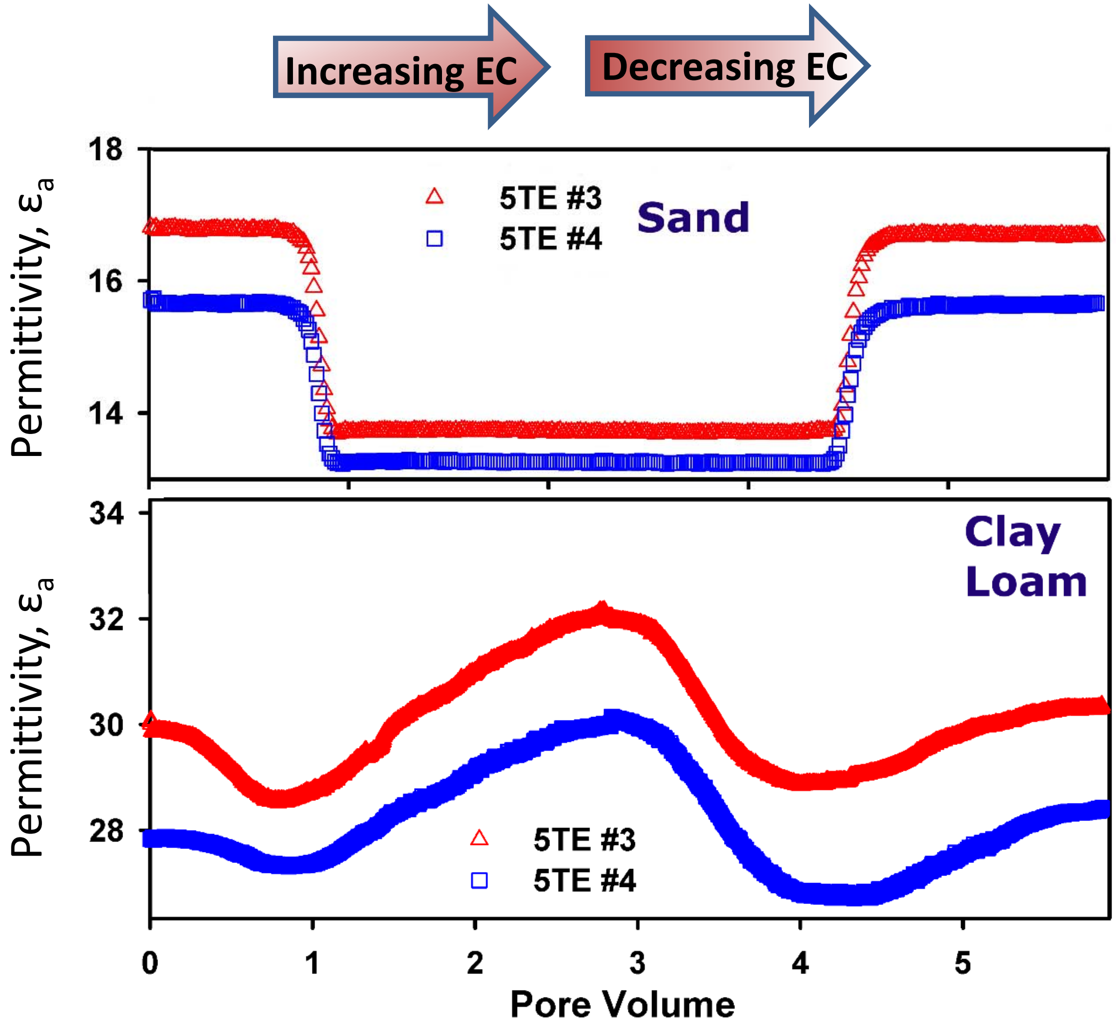
TDR response to bulk electrical conductivity (EC_a)

Directly coupled TDR-315



Sources of Imprecision/Inaccuracy

Decagon 5TE response to (EC_a) at saturation

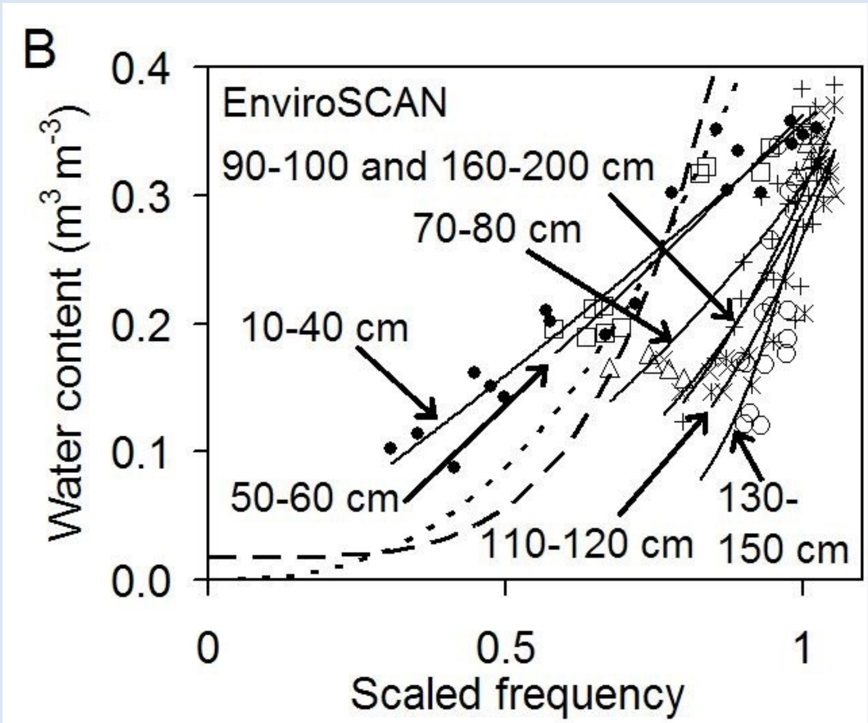


Magnitude and direction of response depends on soil texture

Water content calibration to account for EC_a not trivial

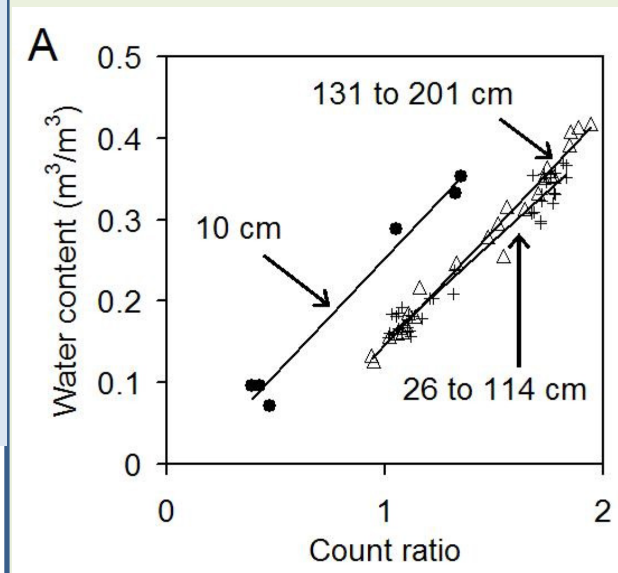
Sources of Imprecision/Inaccuracy

EnviroSCAN response to bulk electrical conductivity (EC_a)



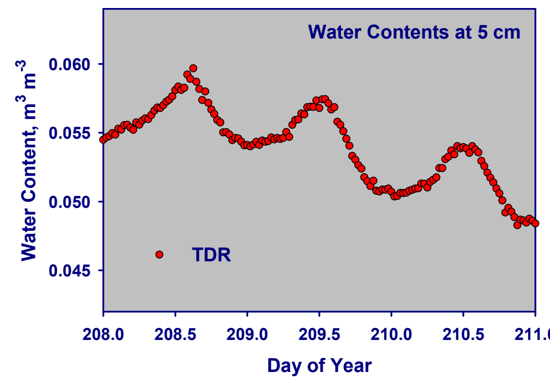
Downhole capacitance sensors affected by increasing bulk electrical conductivity with depth in a drip irrigated field (Mazahrih et al., 2008)

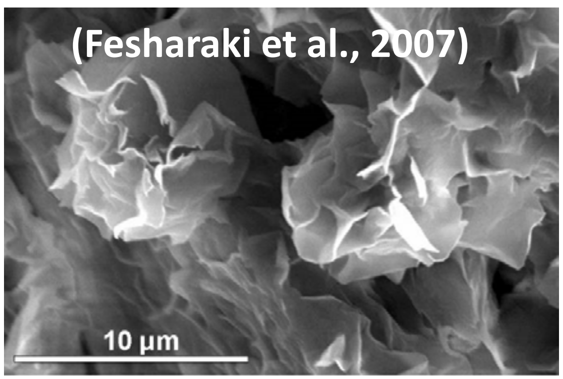
Neutron Moisture Meter



Sources of Imprecision/Inaccuracy

- Temperature
  - Permittivity of water and soil conductivity change with temperature
  - Magnitude can approach daily water use





- Clay content and type of clay
  - Water near clay surfaces has a permittivity that is 5-30% of “free” water
  - Measurement problems in soils with significant amounts of high surface area clays

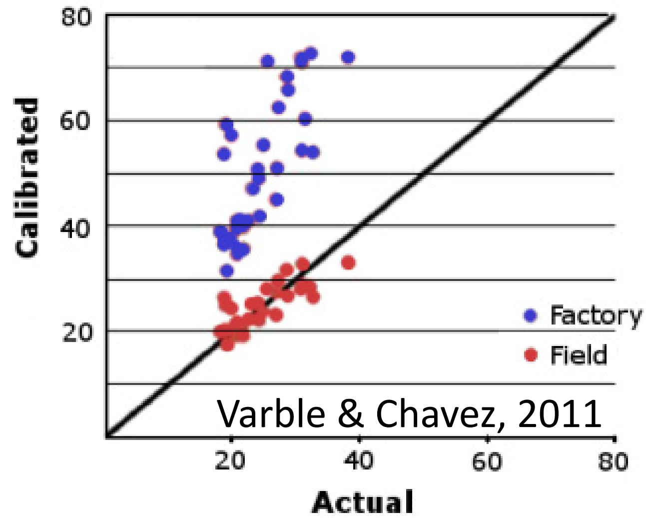
Sources of Imprecision/Inaccuracy

Accuracy in the field

- Field accuracy is typically less than laboratory
  - Uniform, repacked soils
  - Controlled temperature
- Field accuracy is reduced due to
  - Soil variability on large and small spatial and temporal scales; e.g., bulk density, texture, salinity, bulk EC, temperature effects on bulk EC…
  - Sensor installation imperfection

Sources of Imprecision/Inaccuracy

- **Sensor calibration**
  - No "Universal Calibration"
  - Factory calibration – predictions can deviate greatly from actual water contents
  - Soil texture dependent
  - Calibration will likely change with soil depth



  - **Full calibration (soil specific)**
    - Only way to estimate water use by crops using soil water sensors - **for research and crop hybrid development**
    - **Errors: 0.02 – 0.05 m^3/m^3** depending on soil/sensor
    - Impractical for routine use to manage irrigation

Irrigation Scheduling Using Management Allowable Depletion

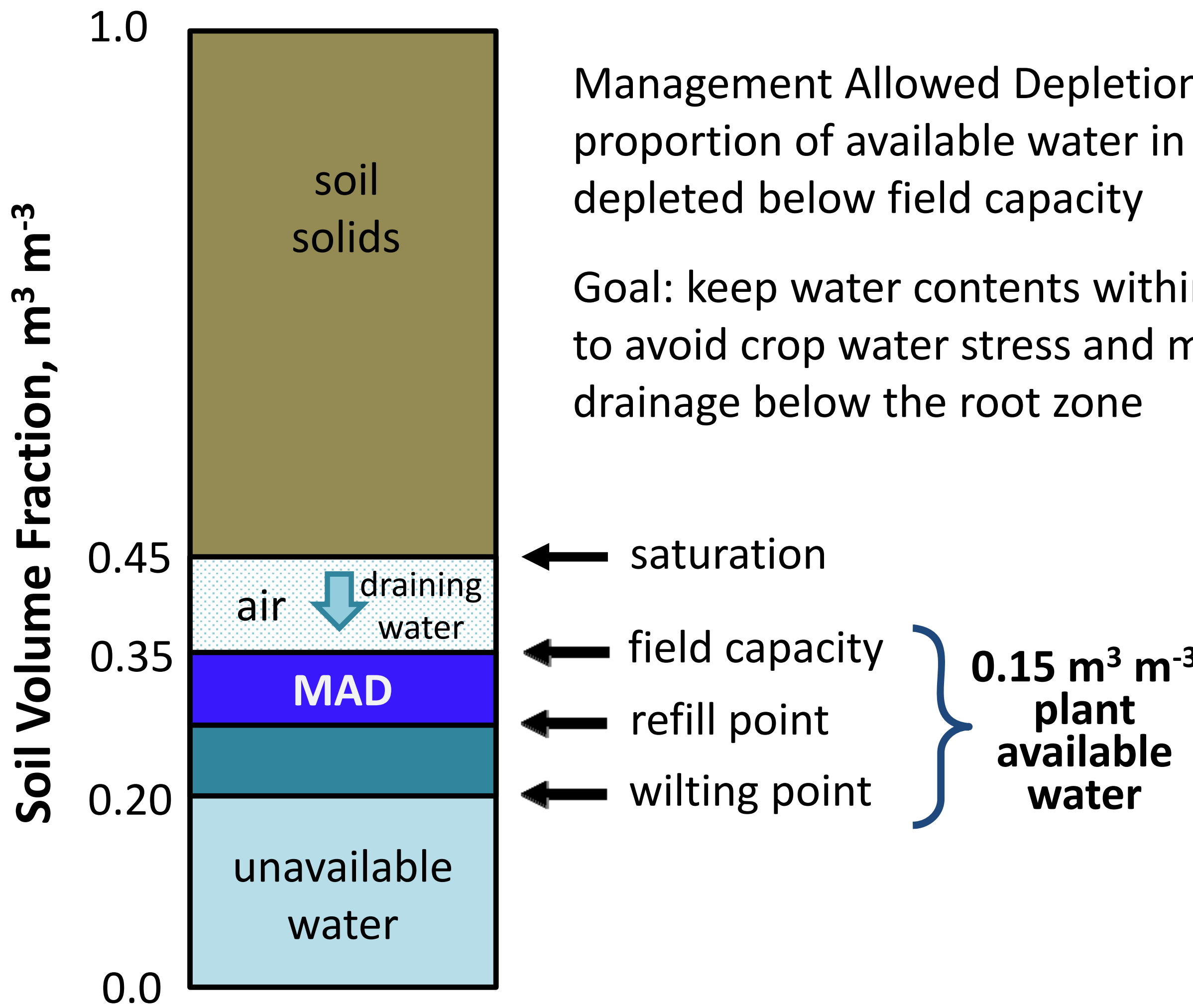
Irrigation Scheduling: Evaluation of sensor readings at field capacity and refill point

- Water depletion ➔ water stress ➔ reduced transpiration ➔ reduced biomass accumulation
- Below the refill point, transpiration declines with decreasing soil water content – nearly linear relationship!!
- **Irrigate when refill point is attained!**

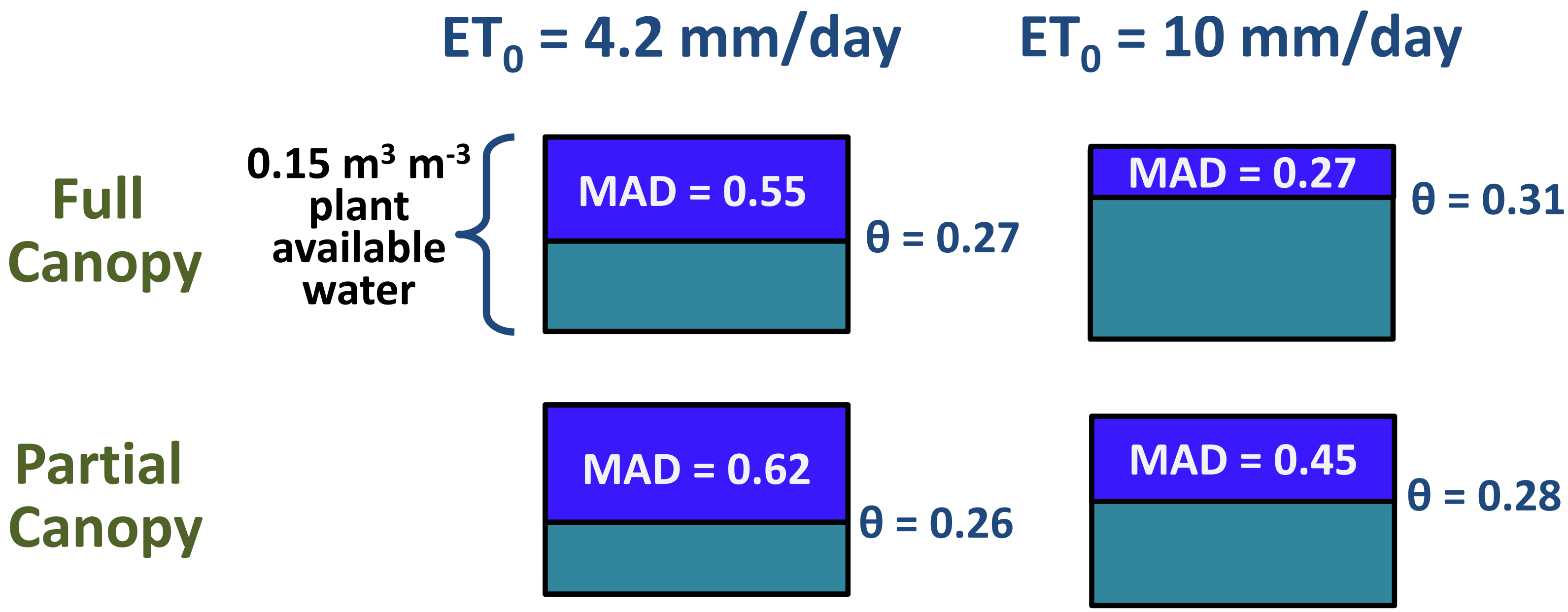
Irrigation Scheduling Using Management Allowable Depletion

Management Allowed Depletion (MAD) – proportion of available water in root zone depleted below field capacity

Goal: keep water contents within this range to avoid crop water stress and minimize drainage below the root zone

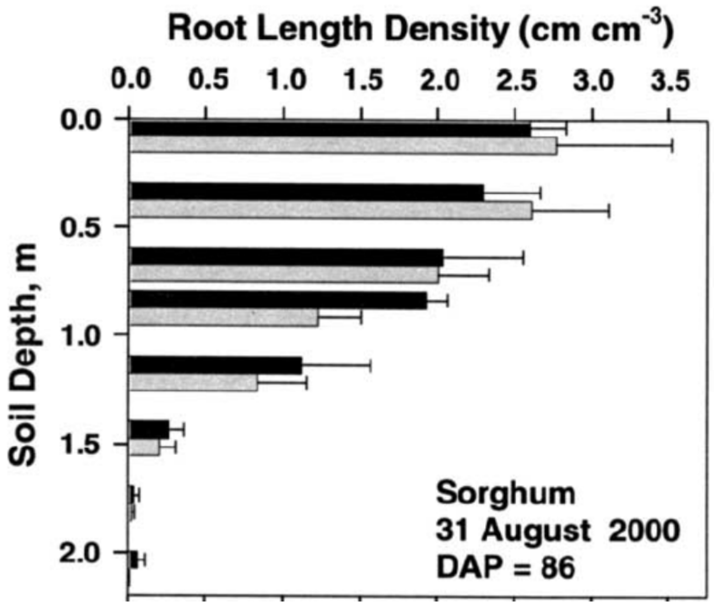


Allowable depletion varies with ET and crop growth stage (FAO-56) - maize



Refill point varies from θ = 0.26 to 0.31 $m^3 m^{-3}$ but for practical purposes managed for conditions of near maximum water stress (e.g. Bushland $0.4 < MAD < 0.3$)

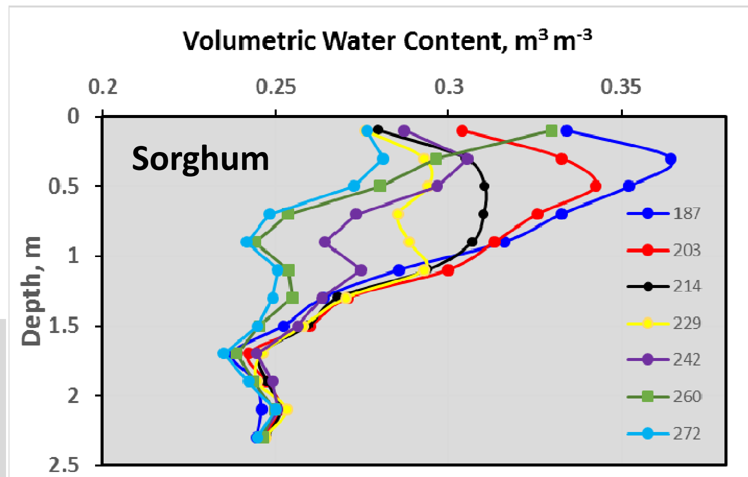
Irrigation Scheduling Using Management Allowable Depletion



Moroke et al., 2005

Assumes water is equally available throughout the entire rooting zone

Decline in root length density with depth means that less water is accessible at deeper depths



Bell, 2013

Typically MAD is evaluated at shallower depths to account for slow root water uptake at deeper depths

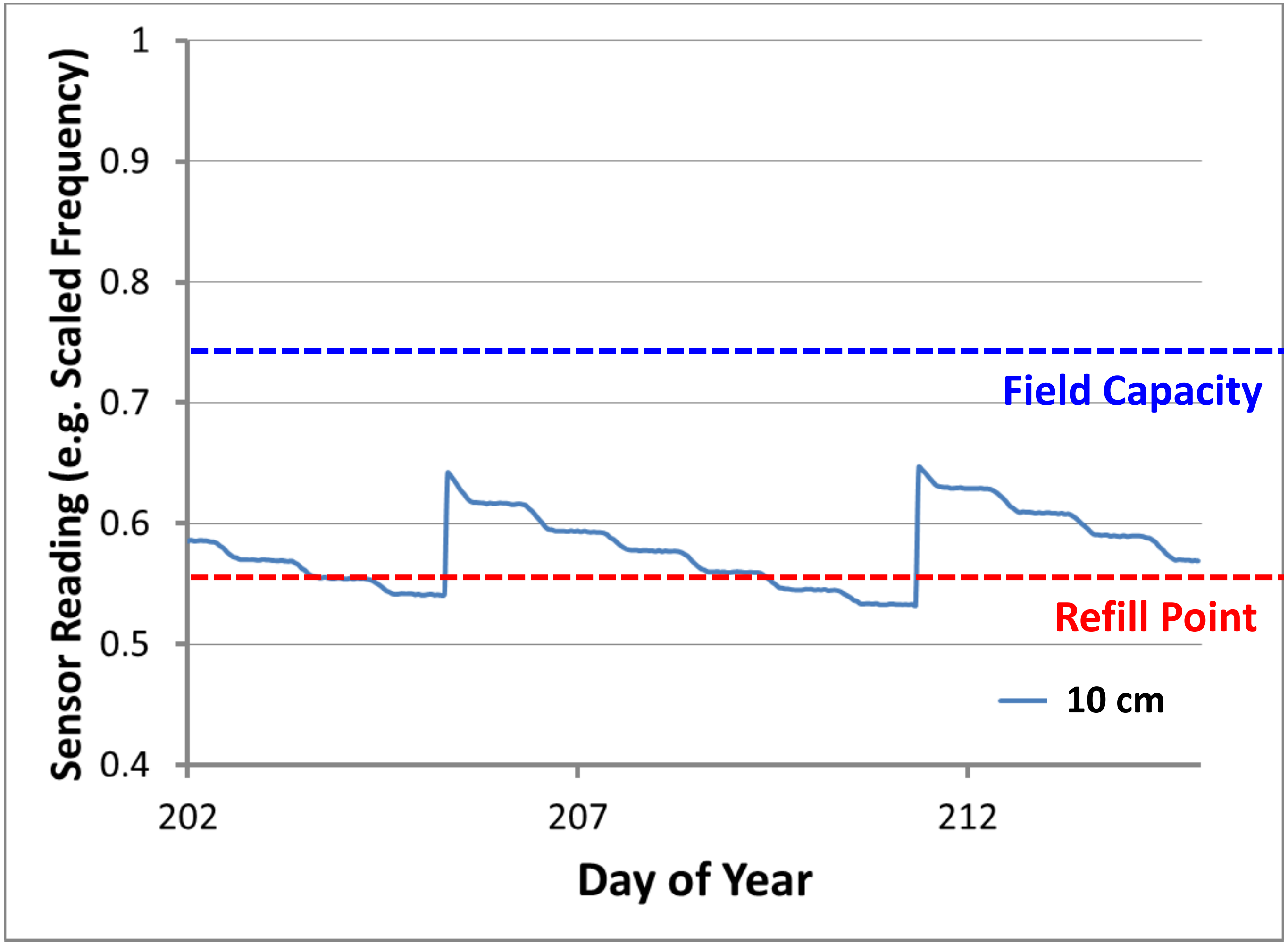
Irrigation Scheduling Using Maximum Allowable Depletion (50% of AWC)

Texture	FC	PWP	AWC	MAD Range	Refill Point
	---------------- $m^3\ m^{-3}$ ----------------				
fine sand	0.10	0.04	0.06	0.03	0.07
loamy sand	0.14	0.06	0.08	0.04	0.10
sandy loam	0.20	0.08	0.12	0.06	0.14
loam	0.27	0.10	0.17	0.085	0.185
silt loam	0.30	0.10	0.2	0.10	0.20
sandy clay loam	0.28	0.13	0.15	0.075	0.205
clay loam	0.33	0.17	0.16	0.08	0.25
clay	0.39	0.24	0.15	0.075	0.315

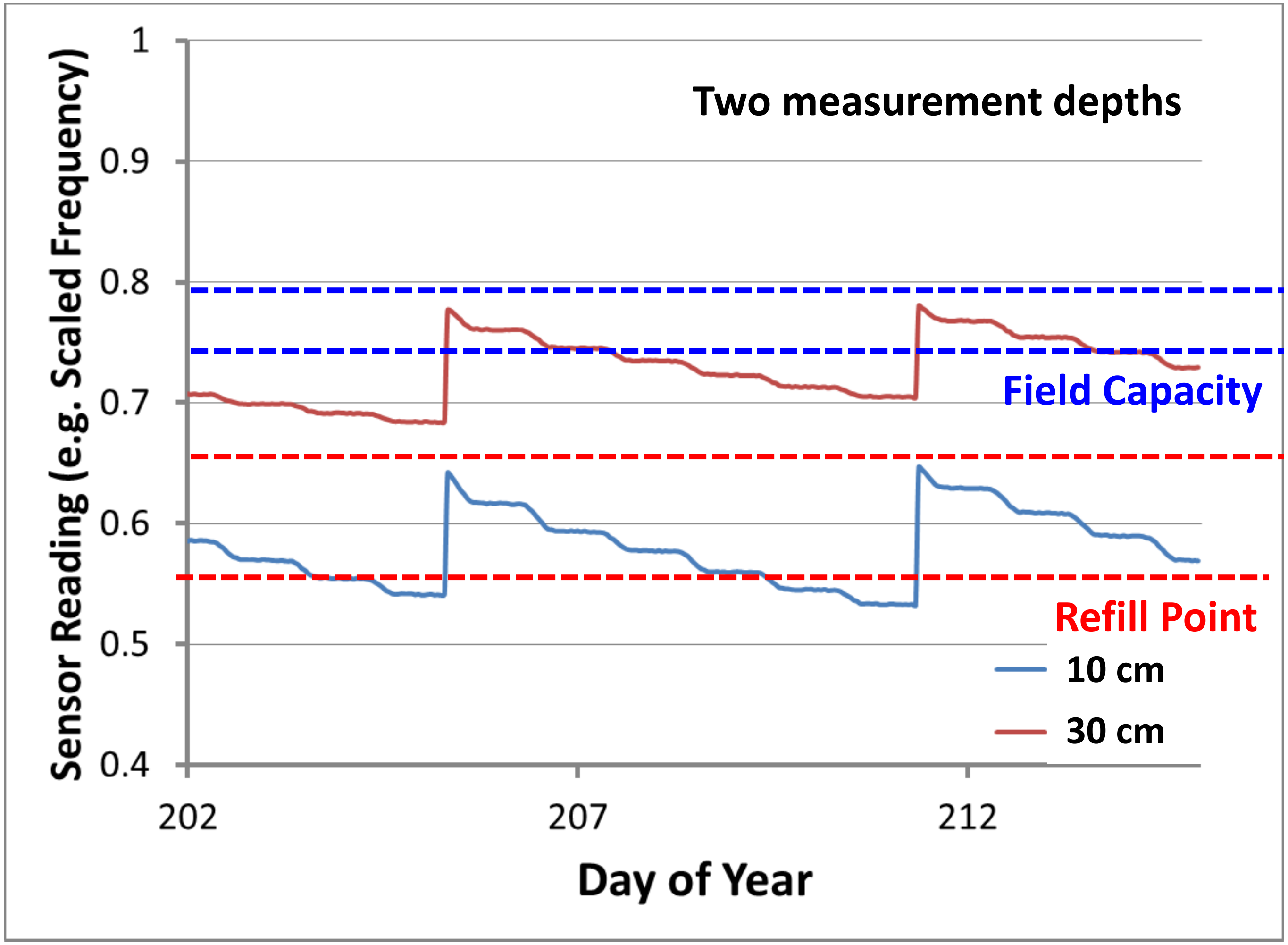
Management range is similar to sensor accuracies in sandy soils!

PWP – permanent wilting point; FC – field capacity; AWC – available water Content; MAD – management allowable depletion.

Using Sensor Output to Identify Field Capacity and Refill Point

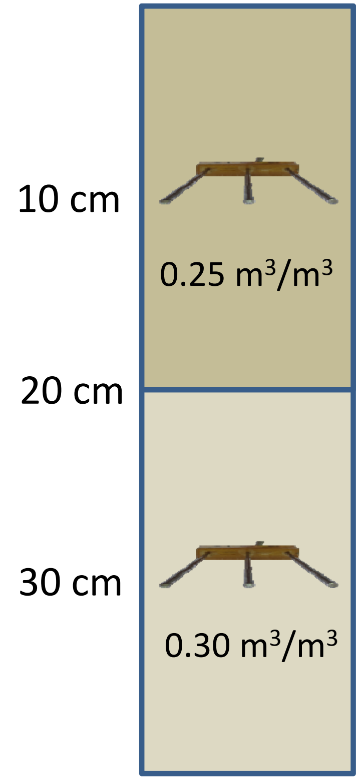


Using Sensor Output to Identify Field Capacity and Refill Point



Combining sensor readings at different depths

- Combining **raw** sensor readings by taking an average value does not give meaningful information (sensor readings are a nonlinear function of water content)
- Need a calibration to convert from sensor reading to water content
  - 0 – 20 cm - clay loam at 0.25 m^3/m^3
  - 20 – 40 cm - clay at 0.30 m^3/m^3
  - Average water content (0 – 40 cm) = 20 x 0.25 + 20 x 0.30 = 11 cm or **0.275 m^3/m^3**
  - **Compare with depth weighted refill point to make irrigation decision**
- **The factory calibration is a good starting point (sometimes)**



Using the Factory Calibration

Likelihood of obtaining accurate measurements at field capacity and refill point (within 0.02 m^3/m^3) at low bulk electrical conductivities

Technology	Sand	Sandy Loam	Silt Loam	Clay Loam	Clay
TDR / TDT					
Quasi-TDR					
Capacitance					

High

Moderate

Low

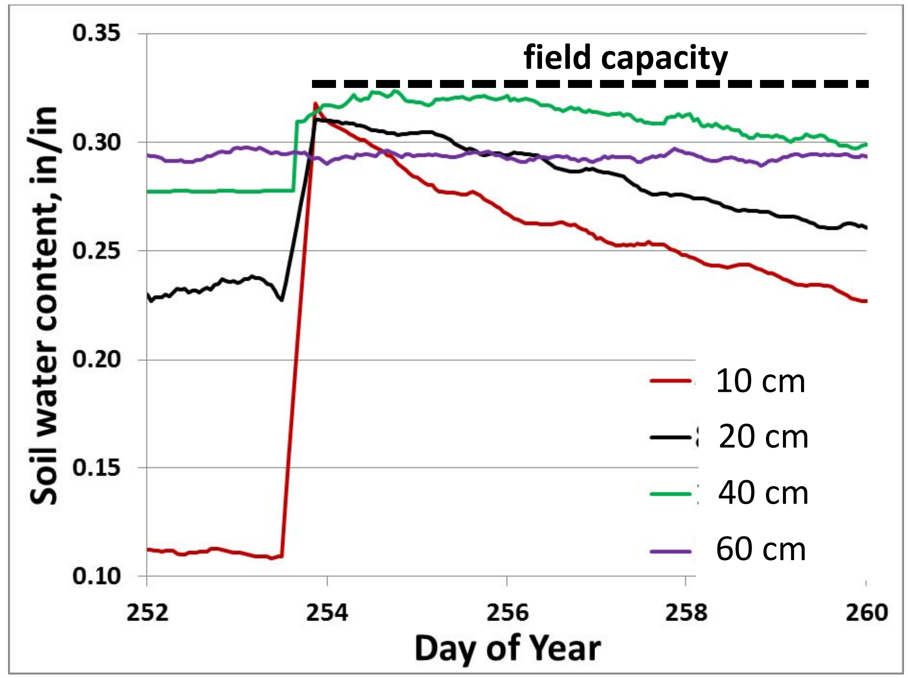
Poor

Forget it!

Evaluation of Field Capacity & Refill Point

- Field capacity - use factory calibration and adjust based on sensor readings one day after soil is thoroughly wetted by a series of heavy rainfall events or irrigations

Grain sorghum, Pullman clay loam, 2010



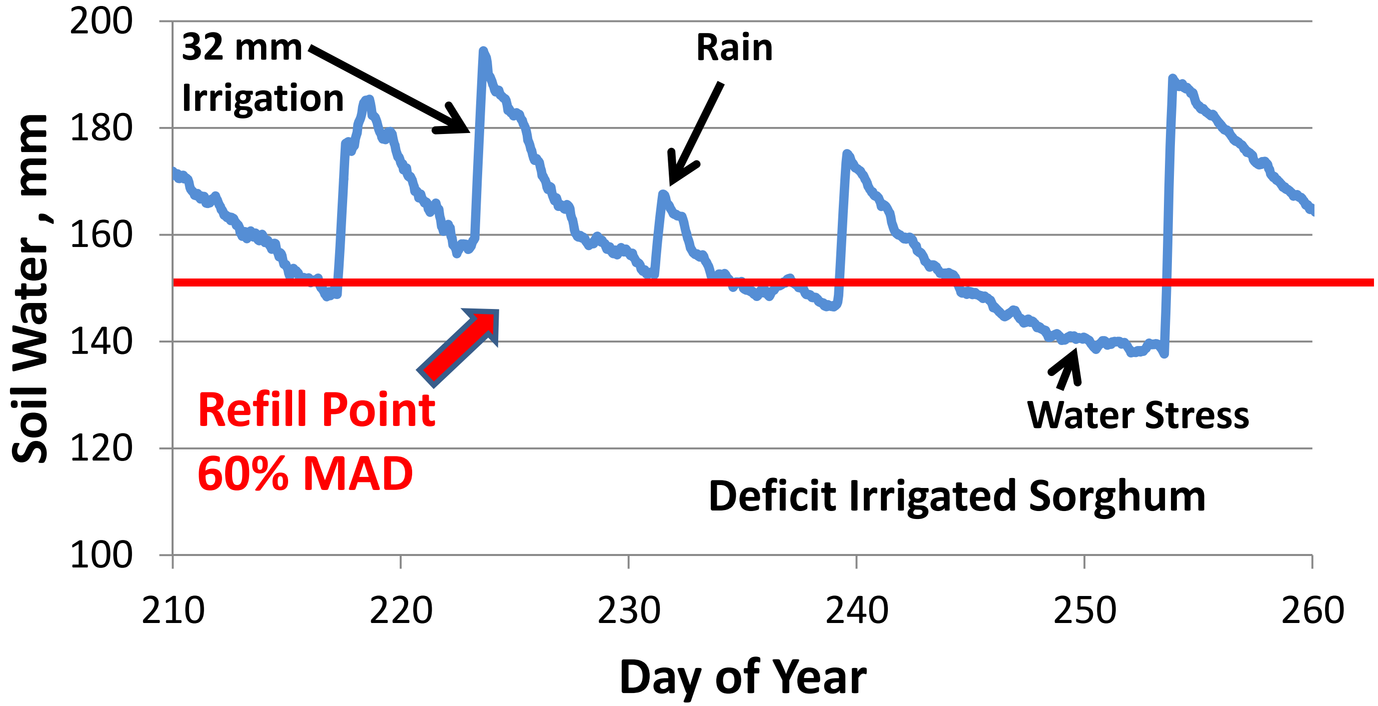
Evaluation of Field Capacity & Refill Point

- Refill Point Estimation
  - Use factory calibration as starting point
  - Observe changes in soil water with time
  - Use signs of crop stress as feedback and adjust refill point upward or downward
  - Will take some trial and error during a season to get it right
- Difficulties in assessing Refill Point
  - Water use patterns not always obvious
    - Diurnal temperature fluctuations
    - Water redistribution
  - Refill point changes throughout the season
    - Sensitivity of crop to deficits
    - Rooting depth changes
  - Weather variations that influence daily crop ET

- Taking gravimetric soil water contents and comparing with sensed measurements can help with interpretation

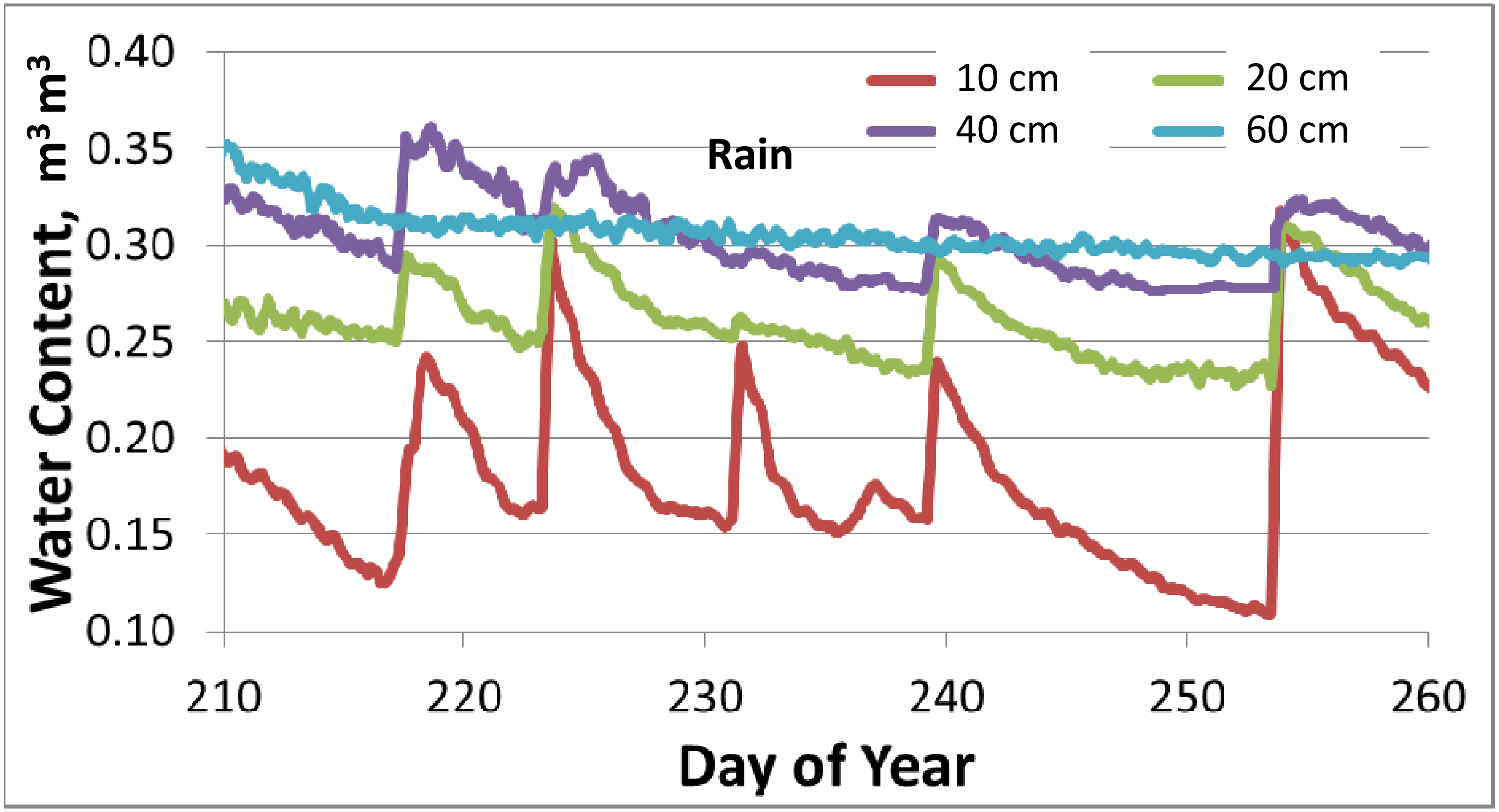
Detection of Irrigation Depth & Water Stress

Fully calibrated sensors at 10, 20, 40, and 60 cm
MESA - Mid Elevation Drops

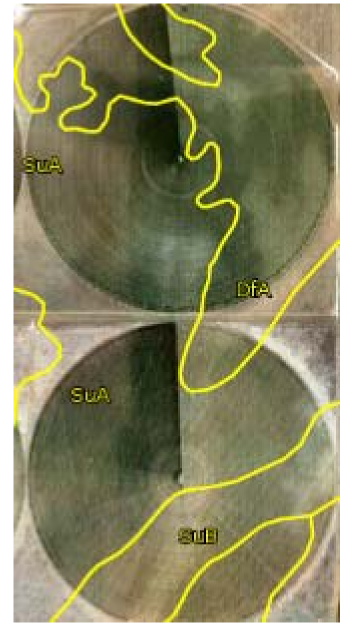


Detection of Wetting Depth

Sensor response can be used to assess how deeply an irrigation wets the profile



Sensor placement

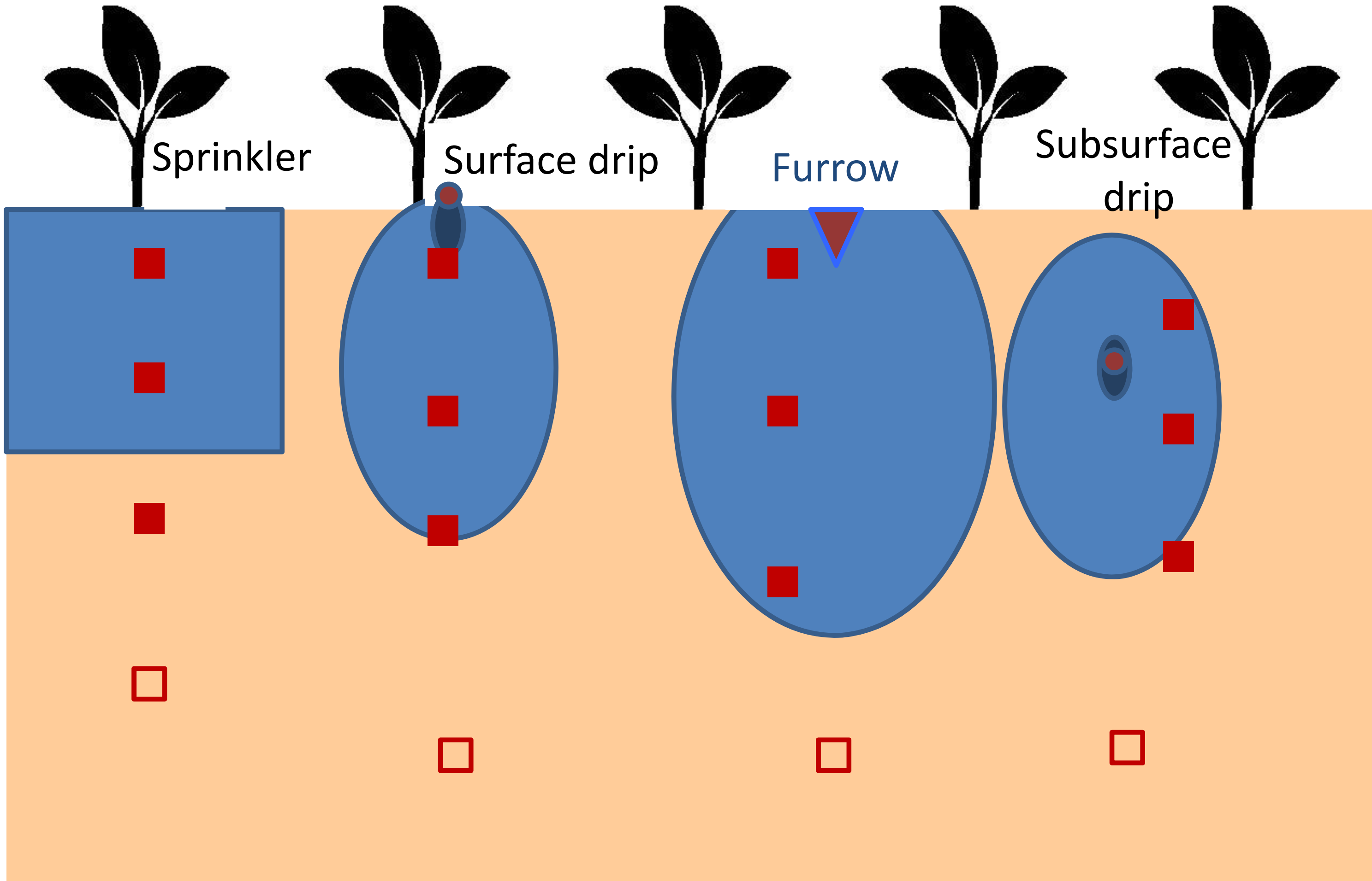


- **Throughout the most active rooting depth of the crop**
- Terrain / Drainage – avoid low areas in field
- Consider soils / soil texture when placing sensors
  - Focus on predominant soil type
- Center pivot
  - Sensor placement in areas in the outer spans

Furrow irrigation
- Between bed and furrow; 1/4 distance from beginning and end of run

Surface & subsurface drip
- Sensor placement is critical (entire soil not wetted)
- Could be problematic - refill point depends on distance from emitter

Sensor placement

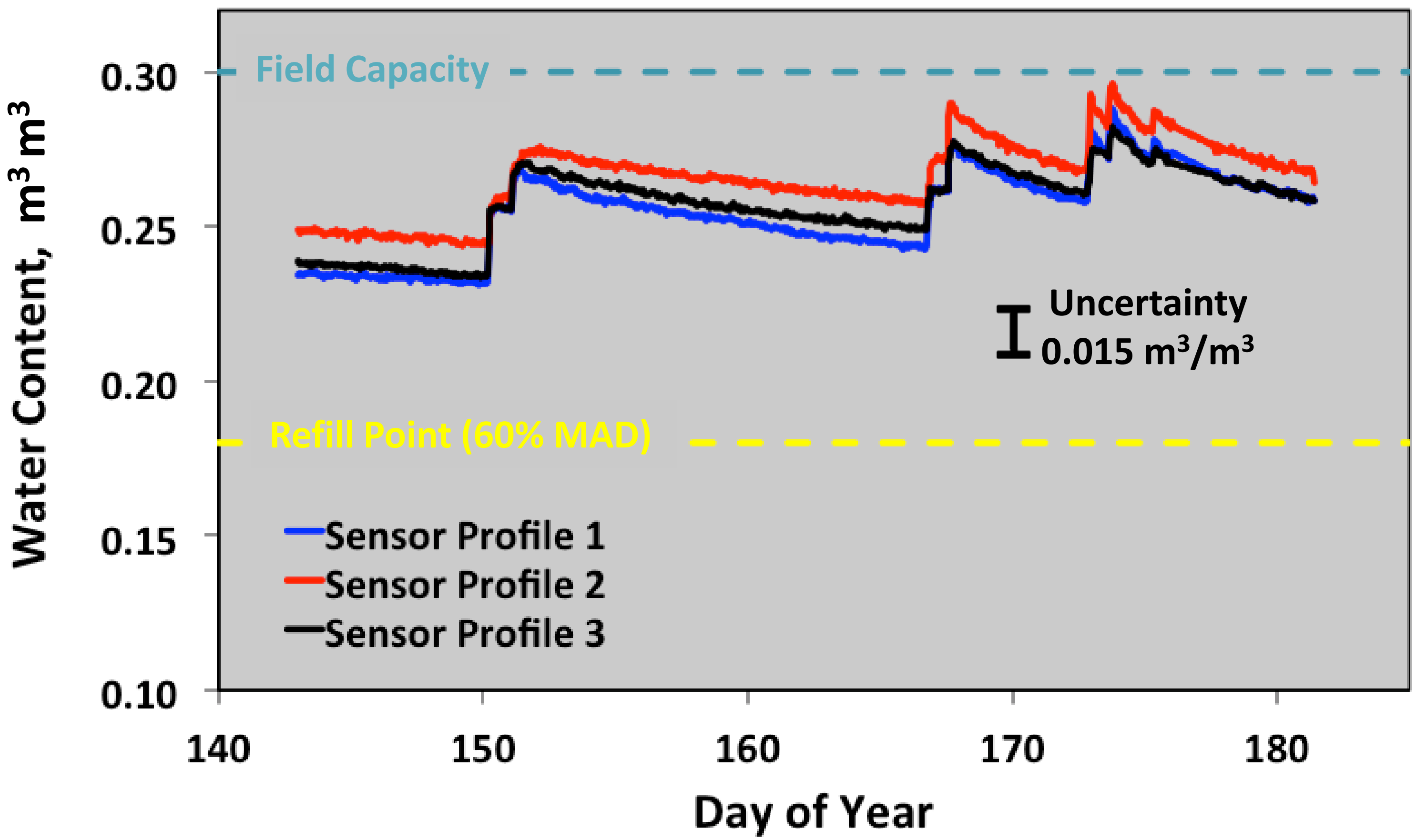


Installation

- Down-hole sensors
  - Avoid slurry installation – if installed using a slurry:
    - Measure water content of slurry not soil
    - Encourages root growth along the length of the access tube
  - Install tube with good soil contact and no large air gaps
- In Soil (single unit) sensors
  - Preferably in undisturbed soil
  - Avoid air gaps
- Flag all sensor locations
- Visually check installation site
  - **Make sure crop density/growth stage around sensors is similar to rest of field**

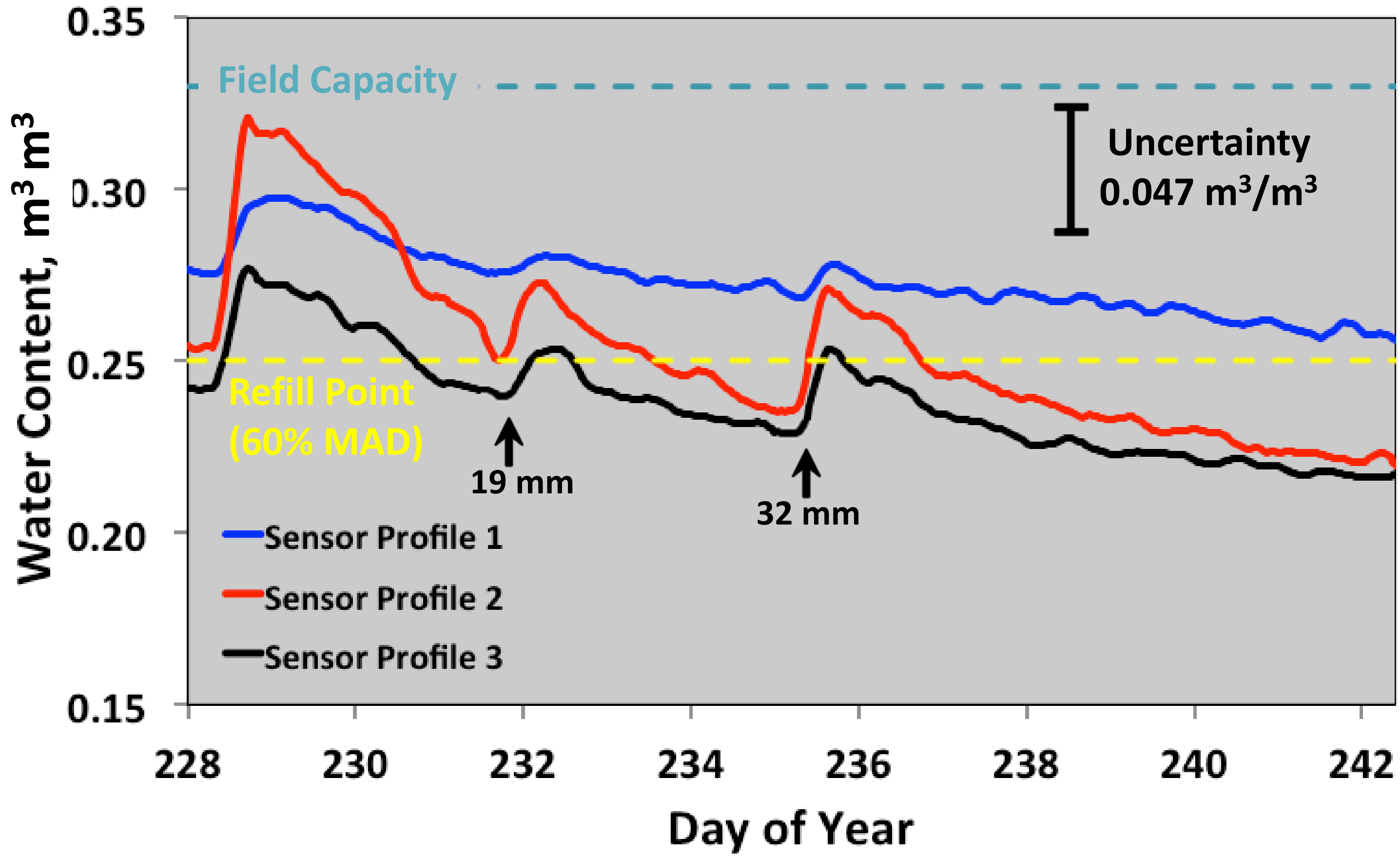
Number of sensor profiles in a uniform field

90 cm profile – grain sorghum in 2006 for a Richfield silt loam (Tribune, KS)

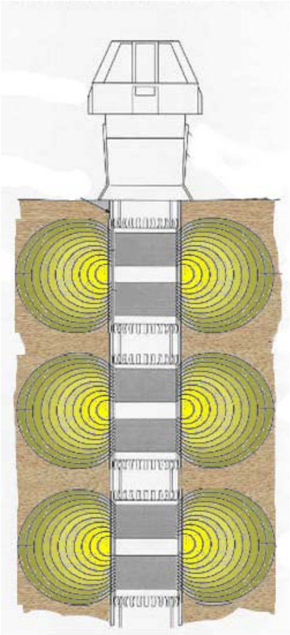


Number of sensor profiles in a uniform field

70 cm profile – deficit irrigated grain sorghum 2011 for a Pullman clay loam in Bushland, TX (Courtesy Jourdan Bell, 2013).



Number of sensor profiles in a uniform field?



Depends on:

- Range in water content from refill point to field capacity
- Sensor technology
    - Capacitance type sensors require more
    - TDR / TDR like measurements < 5?

- **Minimum of 3 for each major soil type – <u>calculate the confidence interval</u>**

- **Less than 3 – uncertainty in determining which sensor is giving spurious readings**

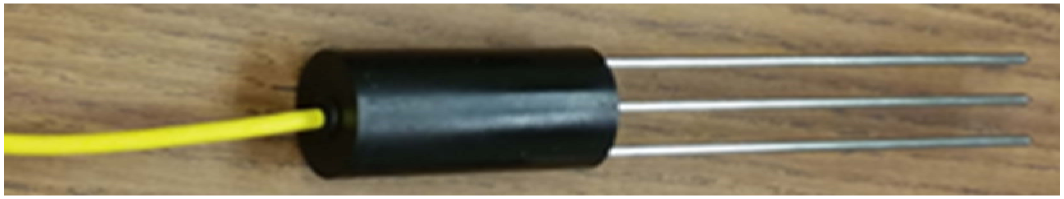
EM down-hole sensors – synopsis

- There is no reliable and accurate down-hole soil water sensor suitable for a wide range of soils except for the neutron probe

Texture	MAD Range (in/in)	Verdict
fine sand	0.03	Maybe useful - Errors could be too large for this narrow range in MAD
loamy sand	0.04	
sandy loam	0.06	Useful – EM down-hole sensors can be used for irrigation scheduling if the EC is low
loam	0.085	
silt loam	0.10	
sandy clay loam	0.075	Maybe useful - Clay in the soil compromises accuracy of EM down-hole sensors; EC must also be minimal
clay loam	0.08	
clay	0.075	

The (Near) Future

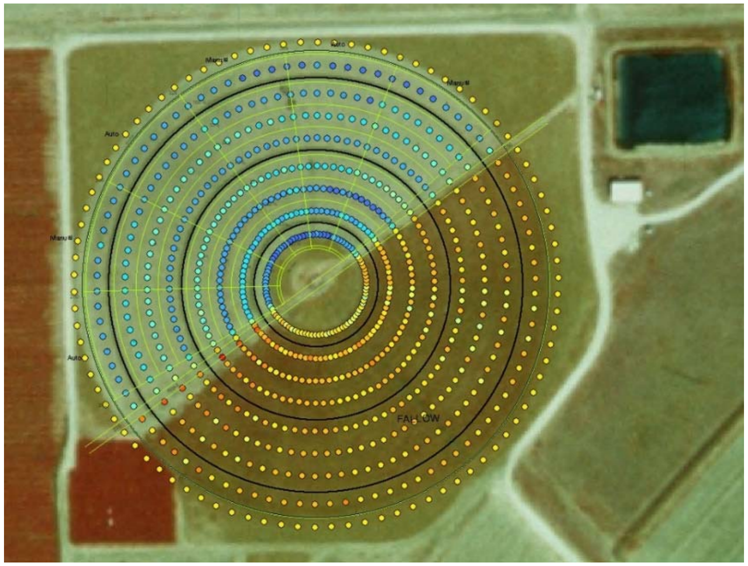
- Improved down-hole water sensors based on TDR technology
- Designs to facilitate easier installation at deeper depths



- Capability for or improvements in wireless data transmission and accessibility from the internet

TDR down-hole prototype
Acclima, Inc.

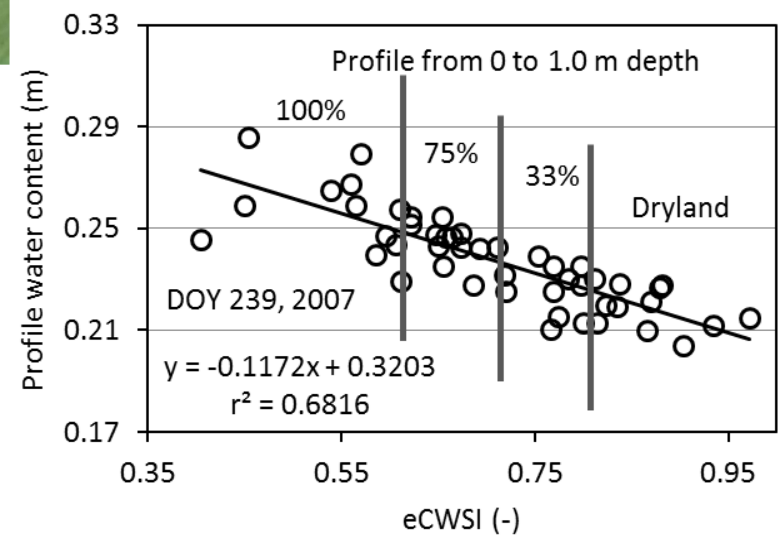
The (Near?) Future



Field Scale Water Content

Combine a few water content measurements with the crop water stress index based on infrared canopy temperature measurements to better predict field soil water content

- Relationship is good for a single point in time and well-watered crops
- Relationship changes during the course of the growing season



Main Points

- No universal calibration
- Interference from bulk electrical conductivity and clay content cause problems especially with capacitance type EM sensors
- Identification of the refill point and field capacity is possible without a full calibration
- Irrigation scheduling based on a refill point will work given the "right" sensor and in certain soils – trial and error will likely be necessary
- If possible, use ET-based scheduling to supplement water content sensor-based determinations
- **Try to avoid using a single technology or method** to schedule irrigation


United States Department of Agriculture
Agricultural Research Service
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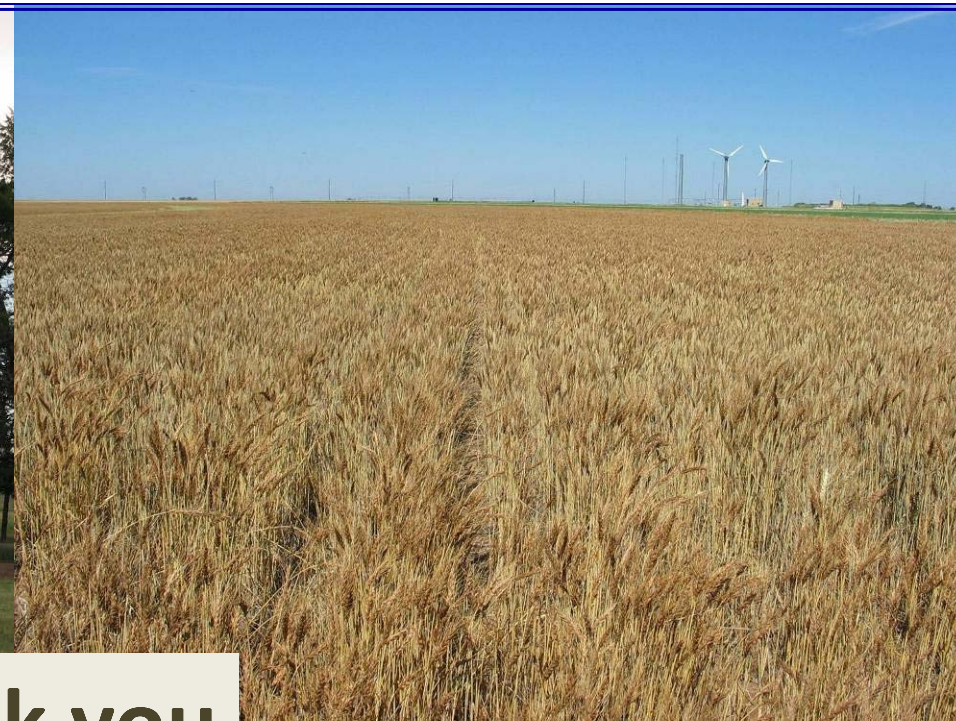
Texas Agricultural Experiment Station
Conservation and
Production Research
Laboratory



Thank you

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Disclaimers and Acknowledgements

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