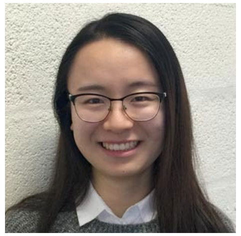
Microtensiometer – a tool for optimizing water management in fruit & nut crops

Michael Santiago
(→ FloraPulse Co)



Siyu Zhu

Rui Gao

Wei-Han Chen

Prof. Fengqi You

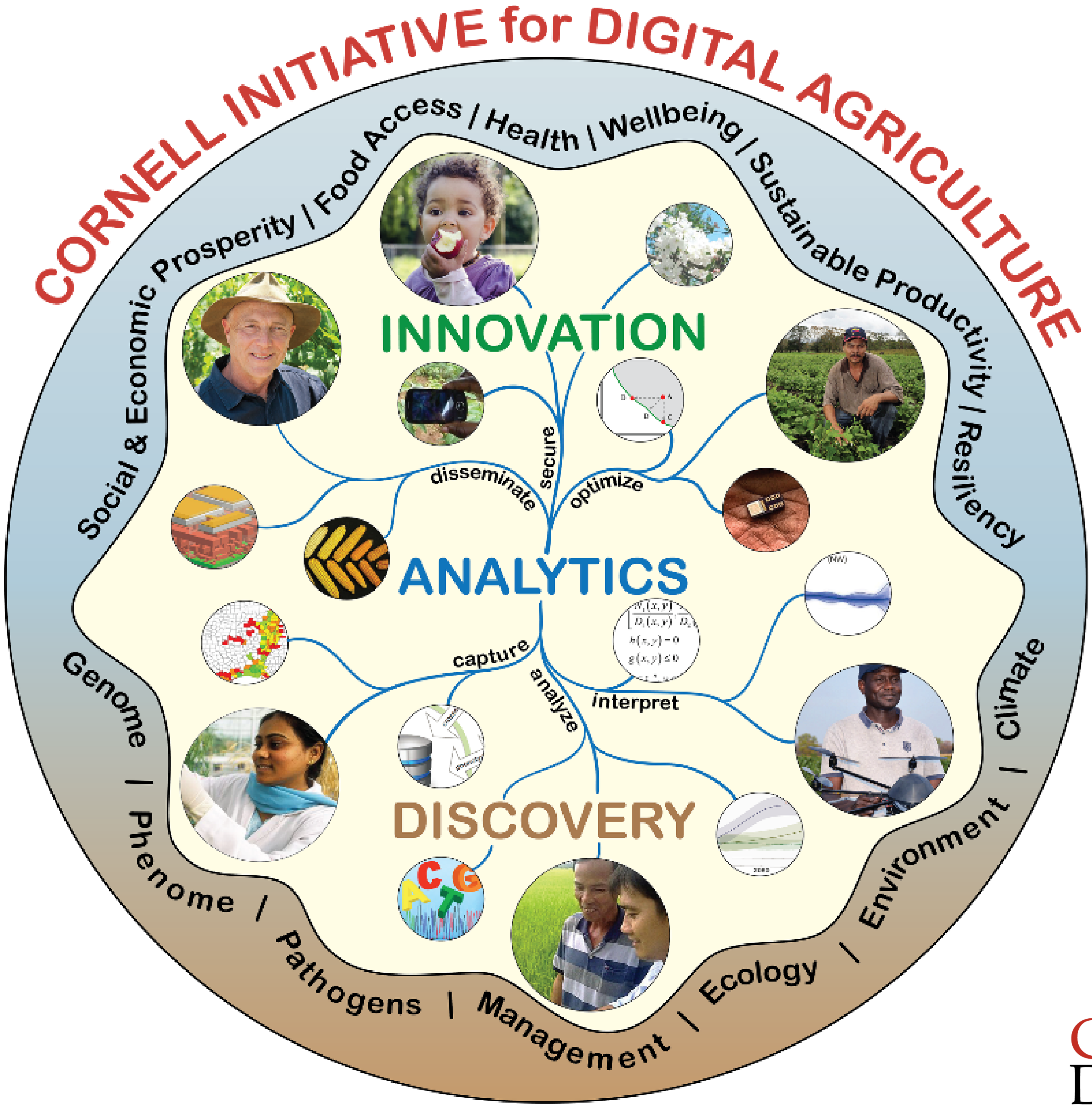
Prof. Alan Lakso

Prof. Lailiang Cheng

Prof. Ken Shackel
(UC Davis)

Abraham Stroock

Chemical and Biomolecular Engineering, Cornell University



Cornell Initiative for Digital Agriculture

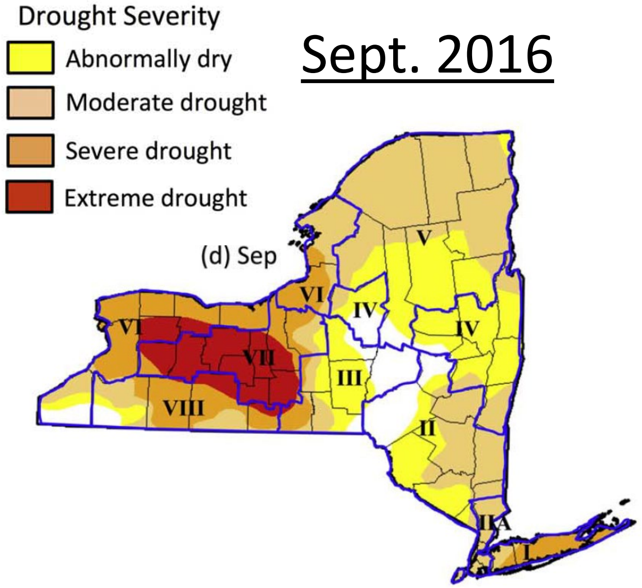
Challenge – Water Management

(http://www.optimumcim.com)

Irrigation accounts for ~70% of human use of fresh water.

Deficit irrigation -> ~40% water savings (+ improved quality, disease management)

(United Nations, 2012; Fereres and Soriano, 2007)



(a) Rainfed crop yield loss

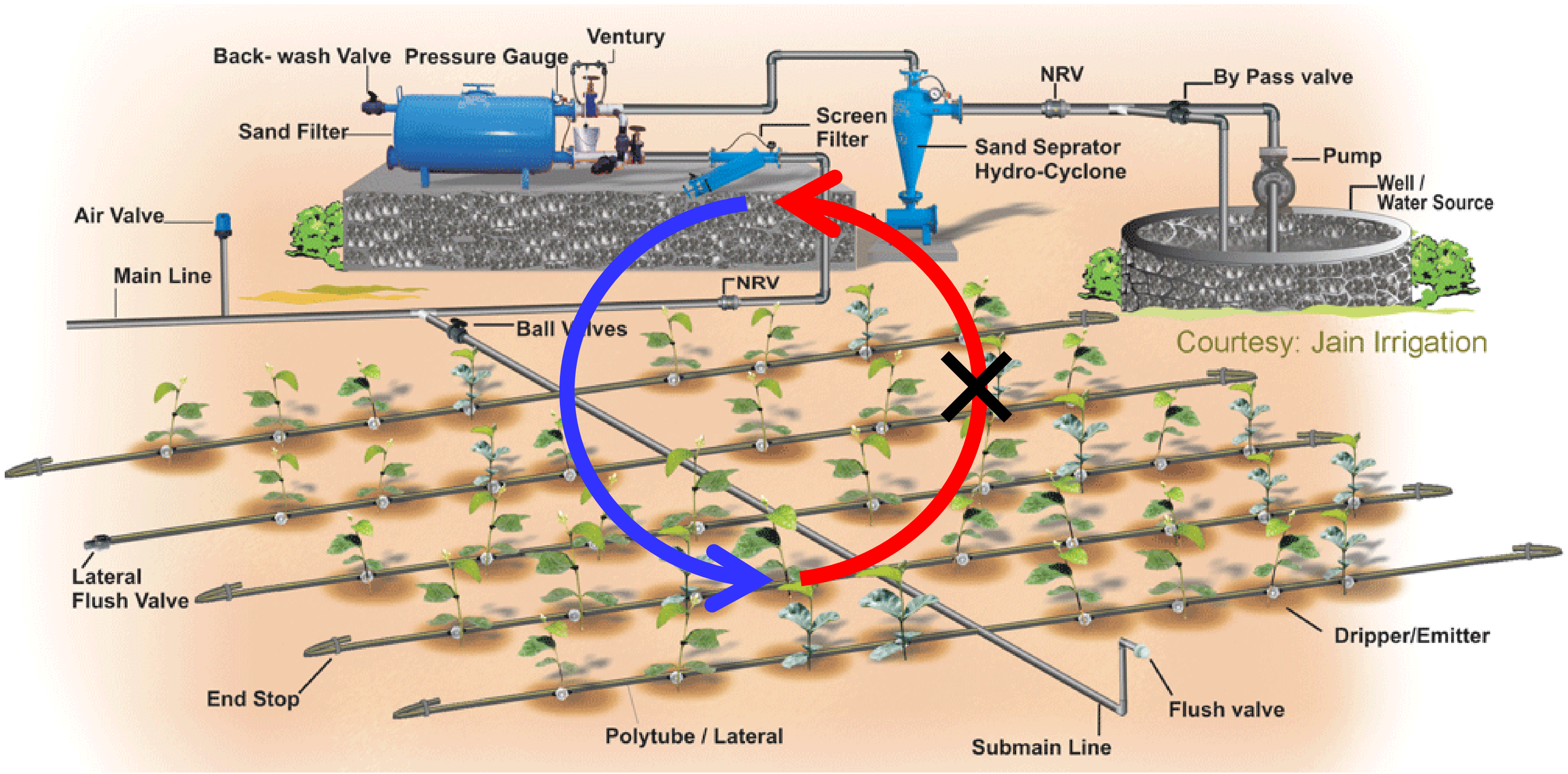
Region	Fruit% loss	# fruit farms
I	13%	2
II	20%	5
III	75%	4
IV	79%	5
V	30%	4
VI	33%	43
VII	69%	14
VIII	60%	2
Mean% loss	47%	
Total # farms		79

(b) Irrigated crop yield loss

Region	Fruit% loss
I	0%
II	4%
III	14%
IV	13%
V	4%
VI	14%
VII	15%
VIII	25%
Mean% loss	11%
Total # farms	

(Sweet et al., Ag Forest Meteor, 2017)

Operational Challenge - An Open Loop

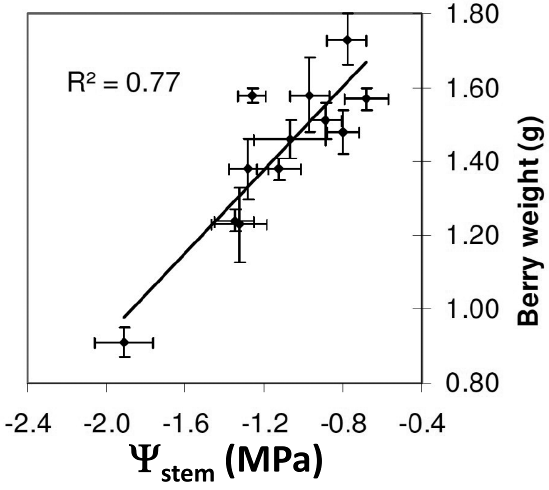


Most irrigation is still run open loop.

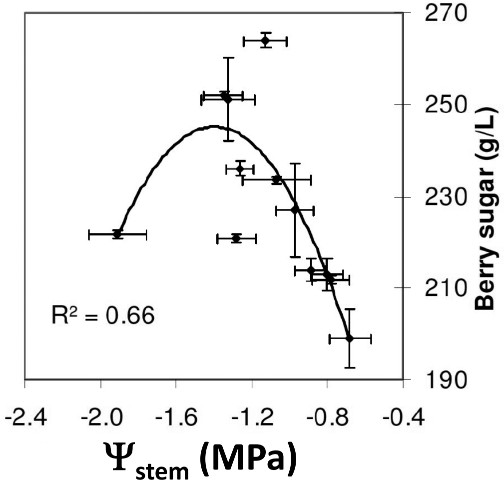
We lack appropriate measurement tools...and cloud-based systems.

What to measure? – Stem Water Potential (Ψ)

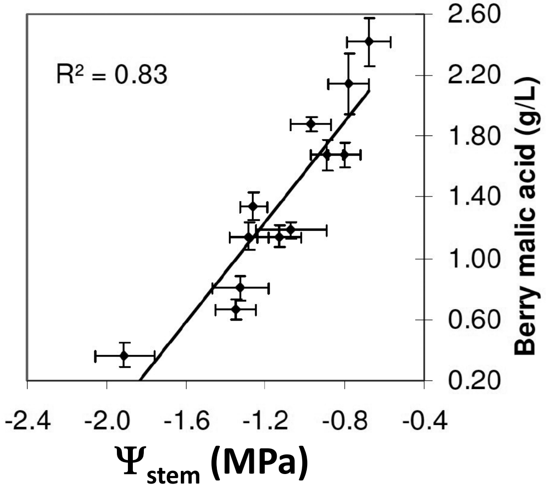
Growth

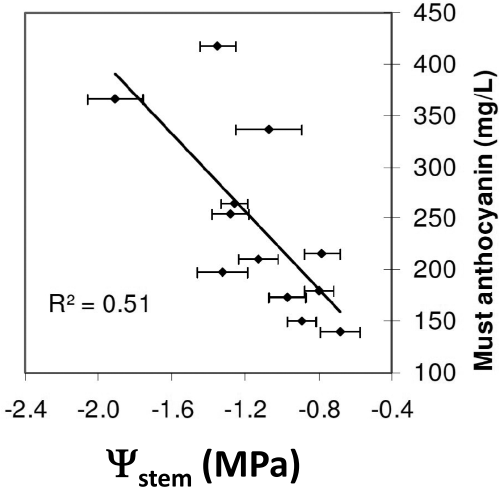


Sugars



Flavors





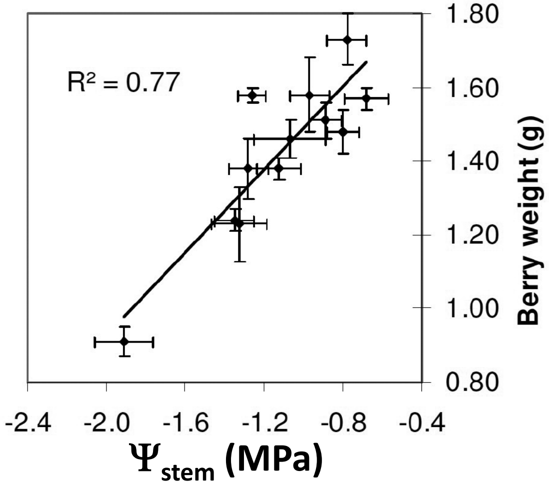
(Van Leeuwen et al, 2009)

"50% of vintage quality is defined by water stress…"

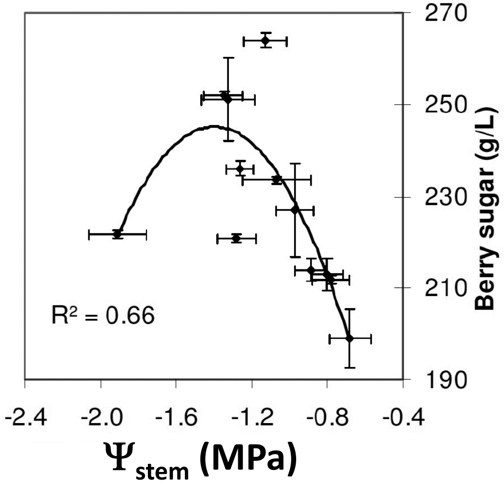
(Cees Van Leeuwen, Chateaux Cheval Blanc, Bordeaux)

What to measure? – Stem Water Potential (Ψ_{stem})

Growth



Sugars



State-of-the-art Ψ-meter

Schölander Pressure Chamber

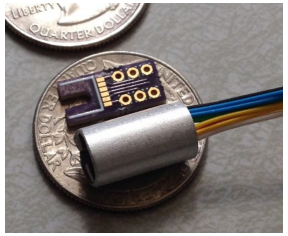
Ψ-meter – can do we do better?

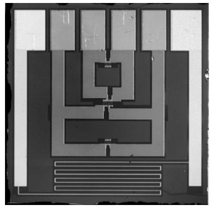
State-of-the-art Ψ-meter

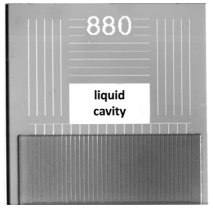
(pressure chamber)

(Scholander et al., Science, 1965)

μTensiometer (MEMS)





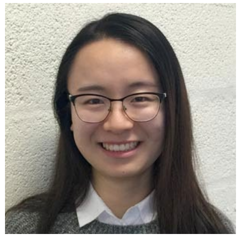


- continuous stem water potential
- wired or wireless data logging
- stable operation across physiological range (Ψ = 0 to -2 MPa)

Prof. Alan Lakso

Vinay Pagay

Michael Santiago



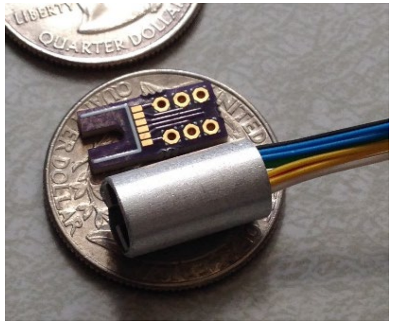
Siyu Zhu

Winston Black

(Pagay et al., LoC, 2014)

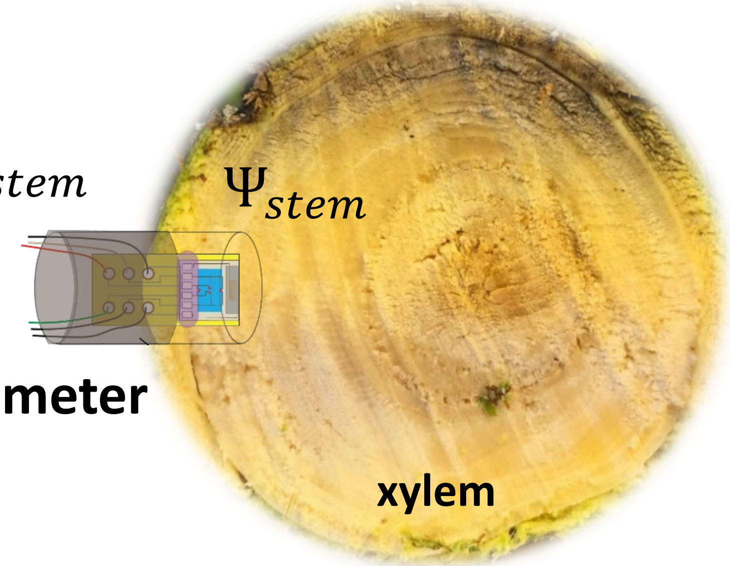
(Santiago et al., in prep, 2018)

MEMS Stress Meter – μTensiometer



stem (trunk)

$\Delta V \propto \Psi_{stem}$



μTensiometer

(equilibrium device ↔ tissue)

<u>Grape</u>
(Matchbook Wines; Zamora, CA)

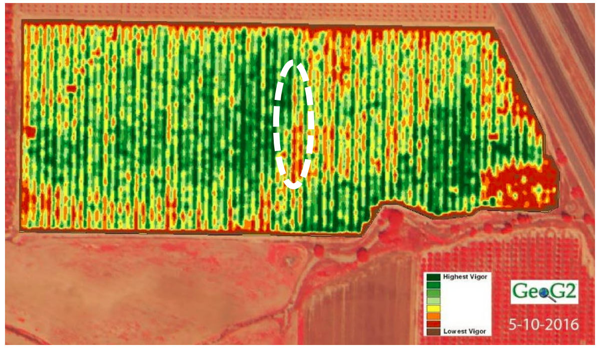
<u>Almond</u>
(Done-Again Farm; Arbuckle, CA)

<u>Apple</u>
(Cornell Orchards; Ithaca, NY)

<u>Corn</u>
(Musgrave Farms; Auburn, NY)

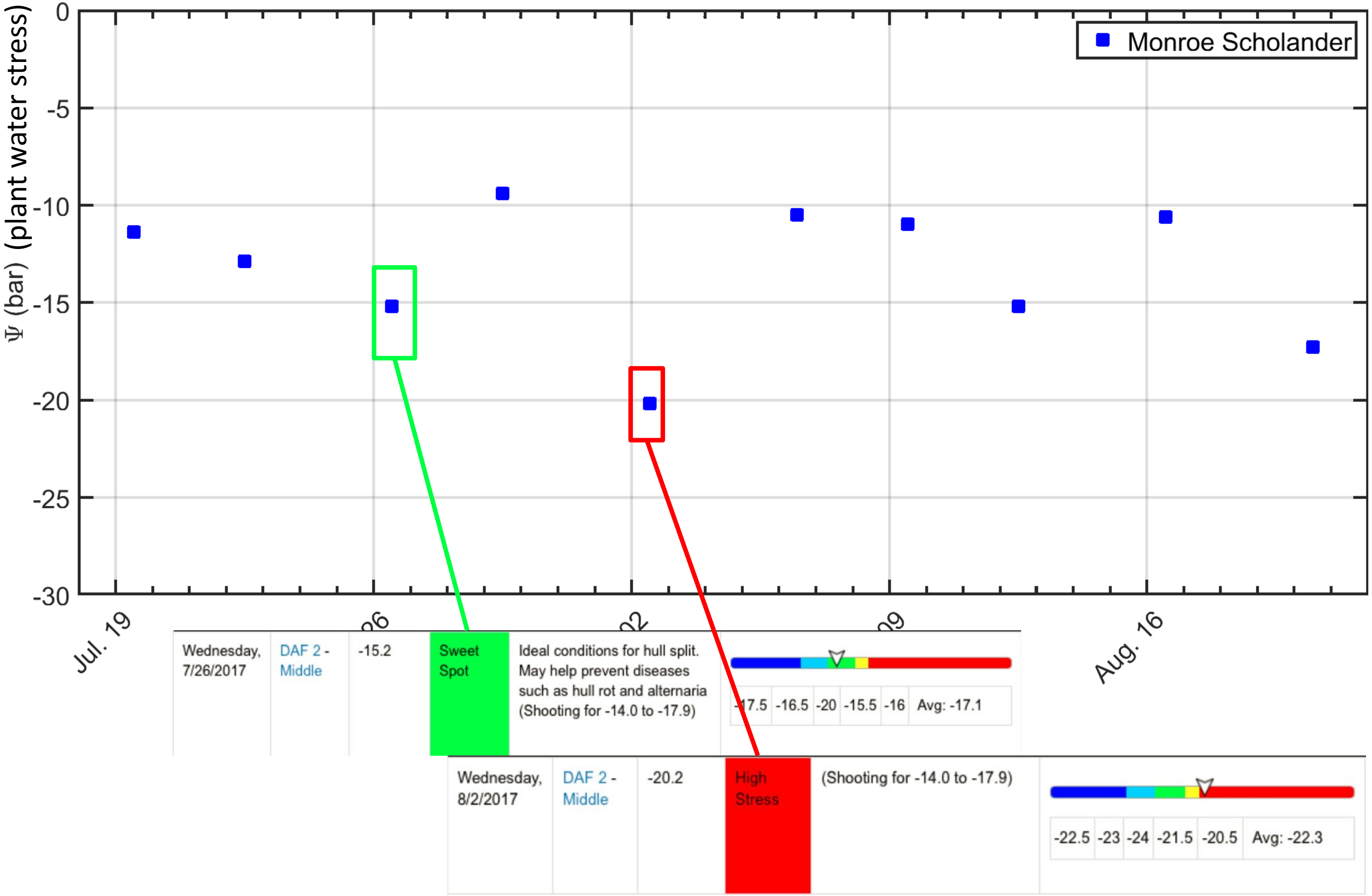
In the field

Done-Again Farm, Arbuckle, CA



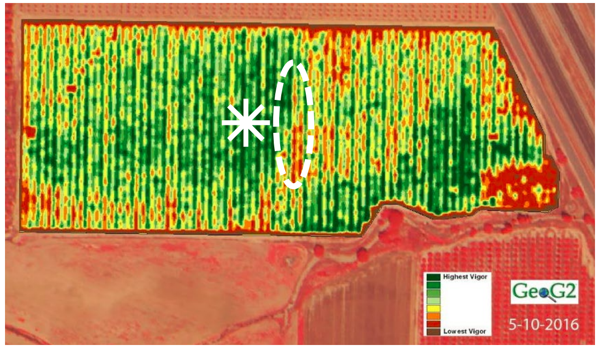
Schölander Bomb

almond – summer 2017

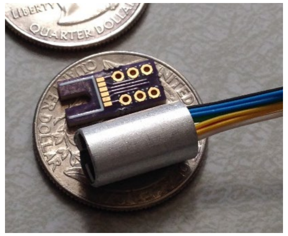


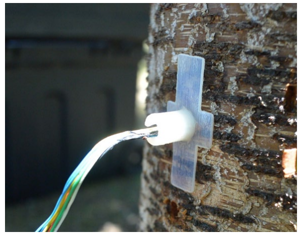
In the field - The Pulse of Trees

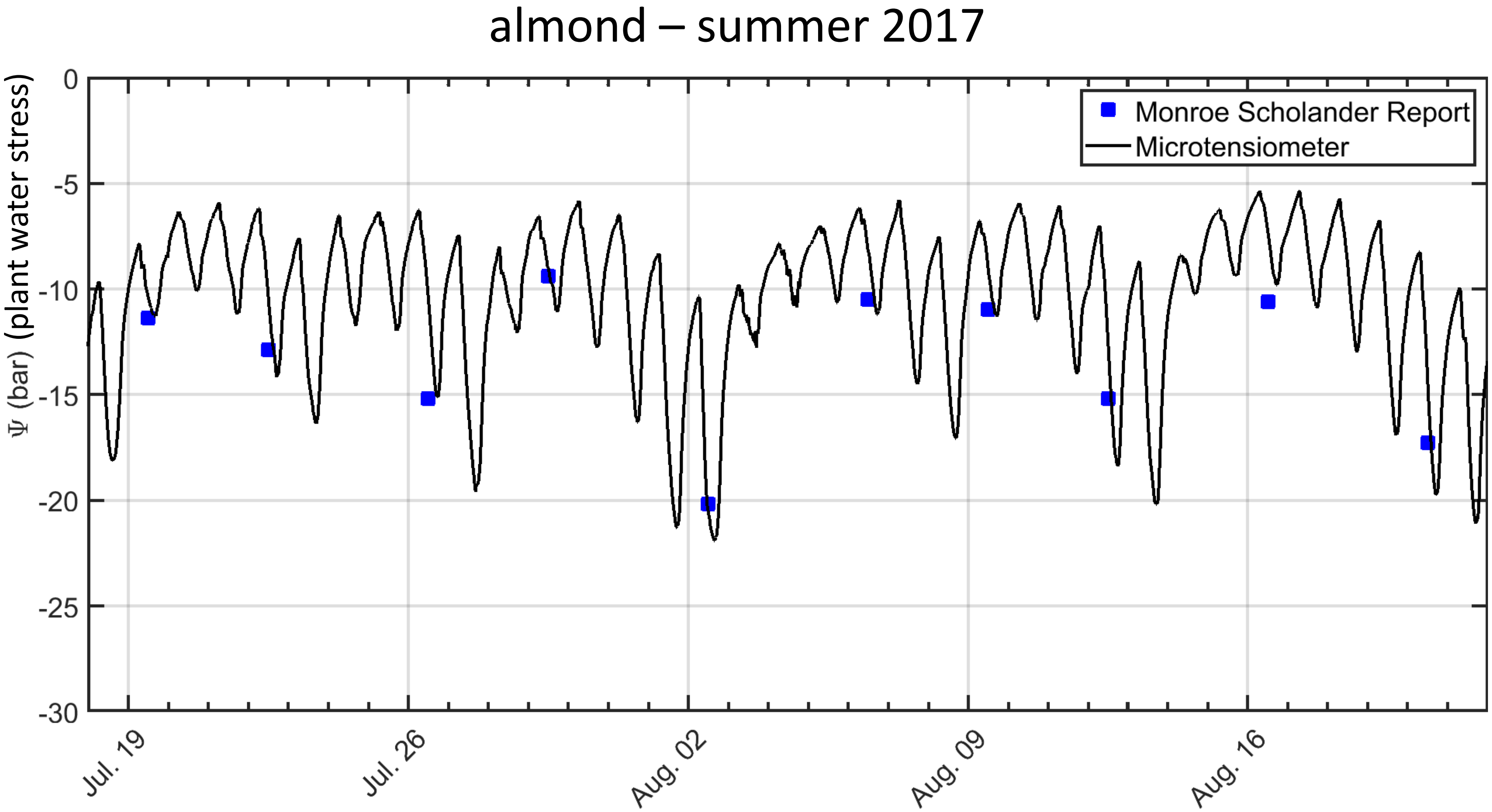
Done-Again Farm, Arbuckle, CA



microTensiometer





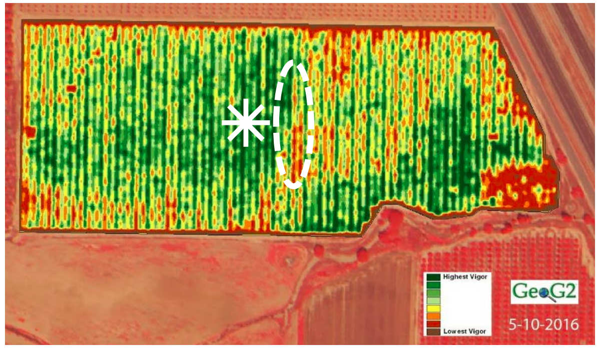


Michael Santiago

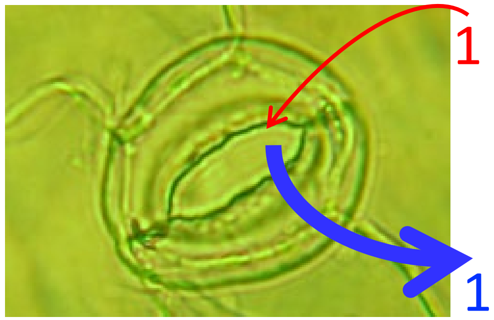
FloraPulse

In the field - The Pulse of Trees

Done-Again Farm, Arbuckle, CA



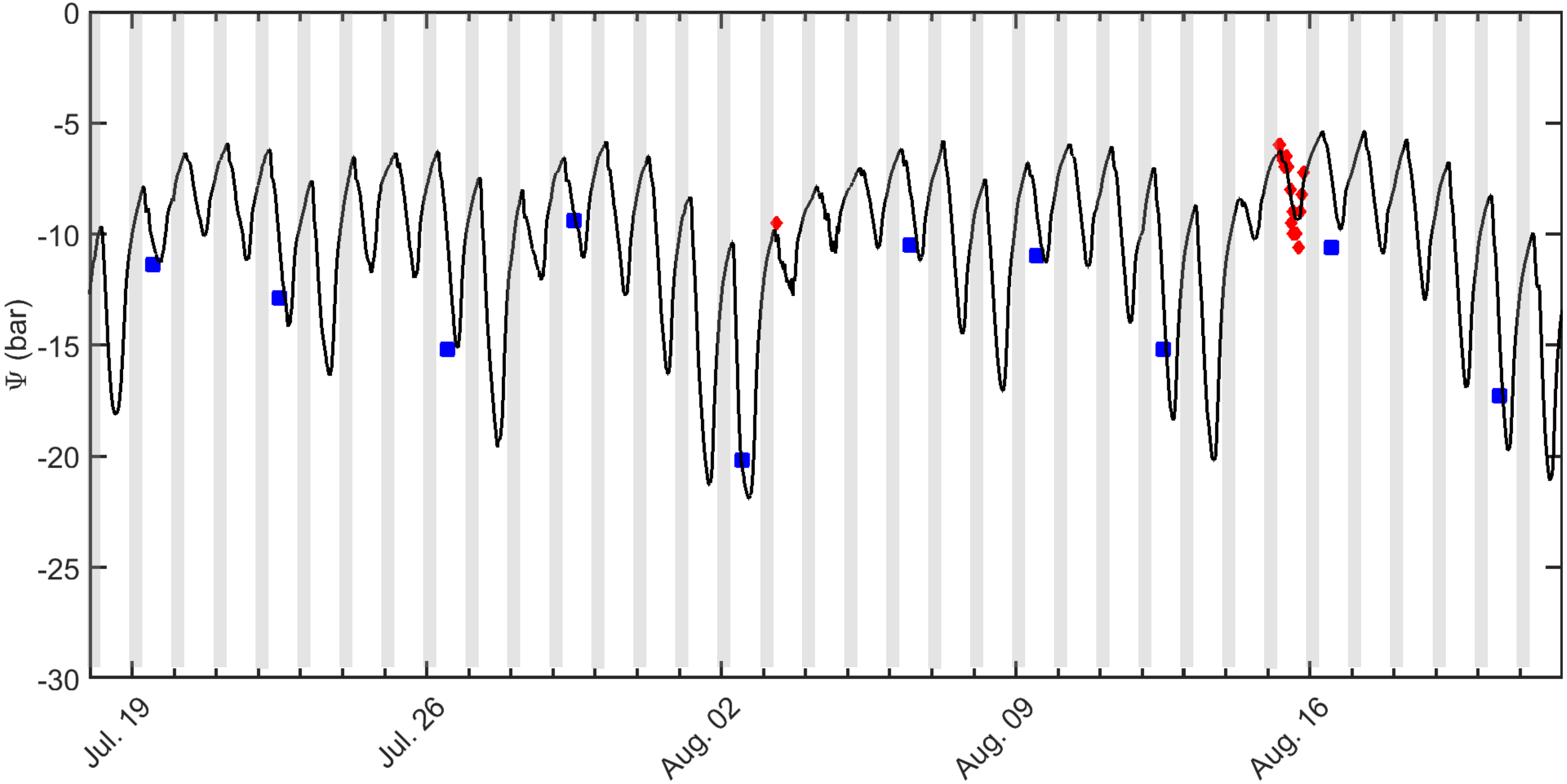
stomata



1 CO_2

100's H_2

almond – summer 2017

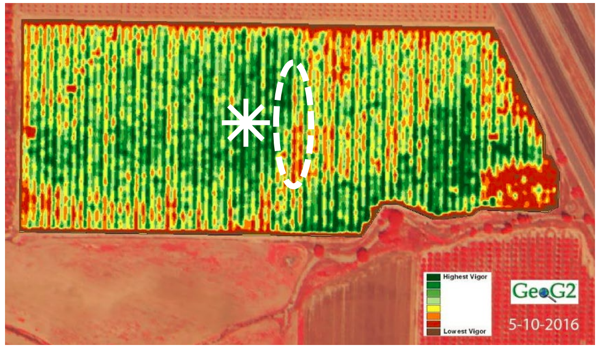


night: $\Psi_{\text{stem}} \rightarrow \Psi_{\text{soil}}$

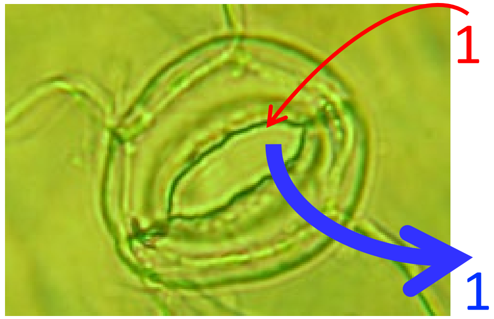
day: $\Psi_{\text{stem}} \rightarrow \Psi_{\text{atm}}$

In the field - The Pulse of Trees

Done-Again Farm, Arbuckle, CA



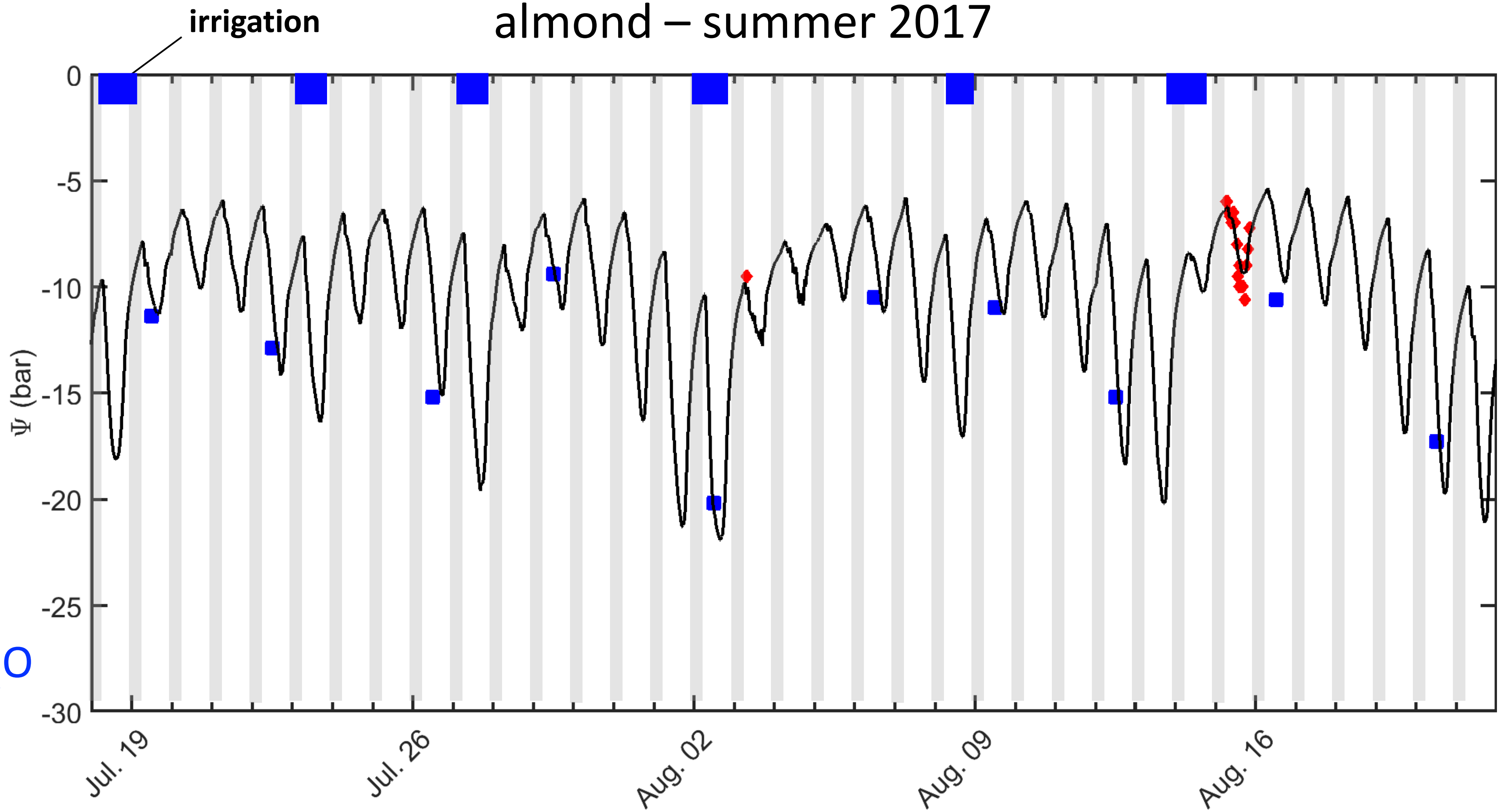
stomata



1 CO_2

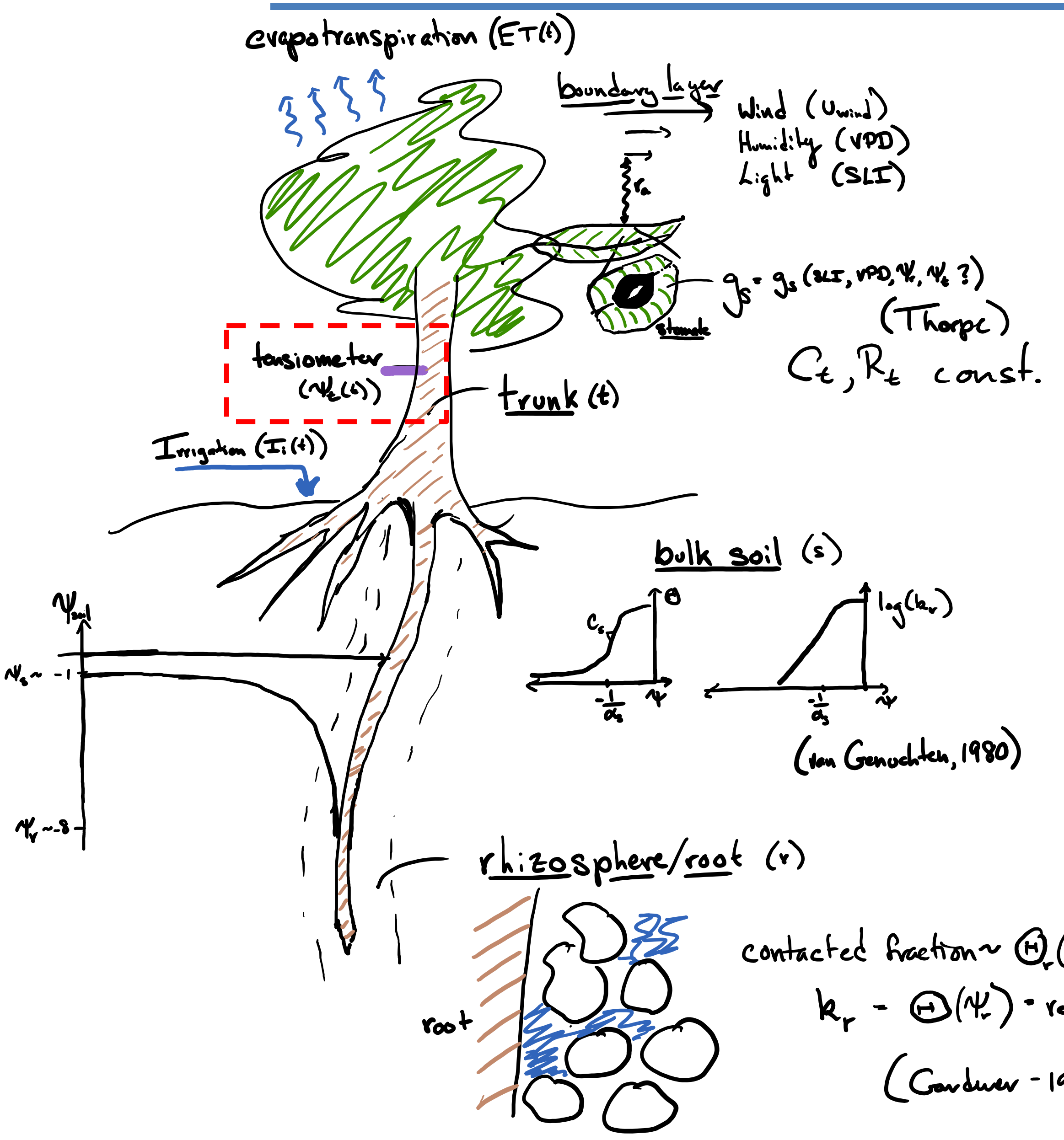
100's H_2O

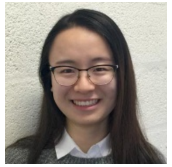
irrigation (Jake Spooner):



<u>Questions</u>: properties of soil, roots, trunk, stomates, canopy,…?

In the field - The Pulse of Trees



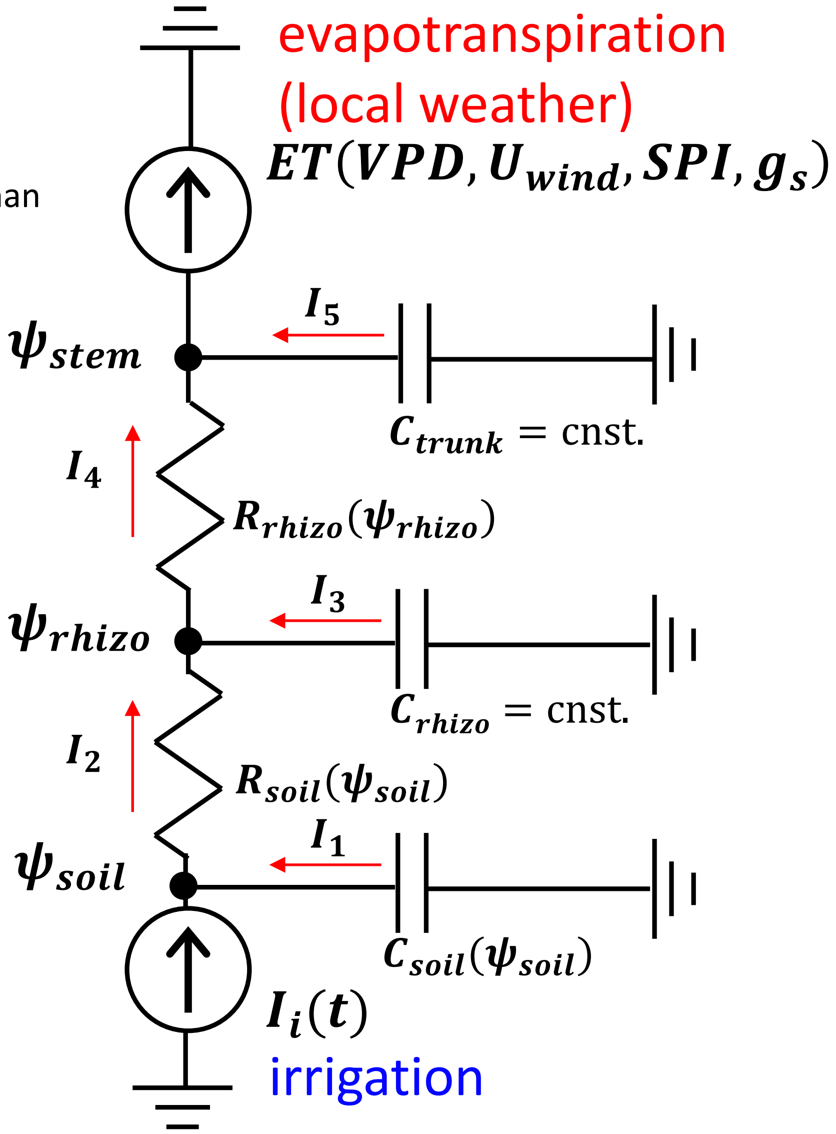


Siyu Zhu

Kathryn Haldeman

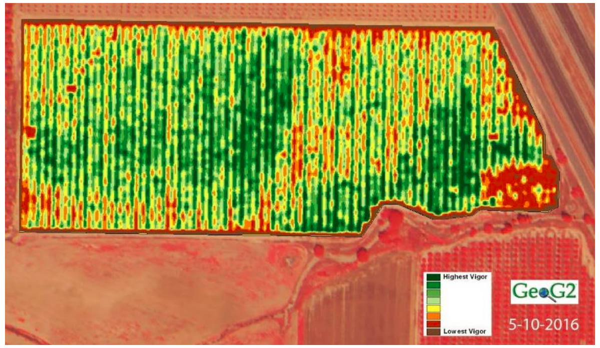
?

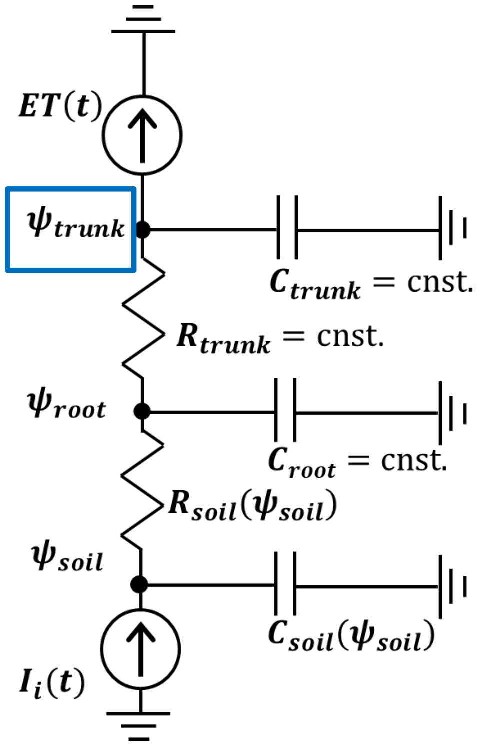
=

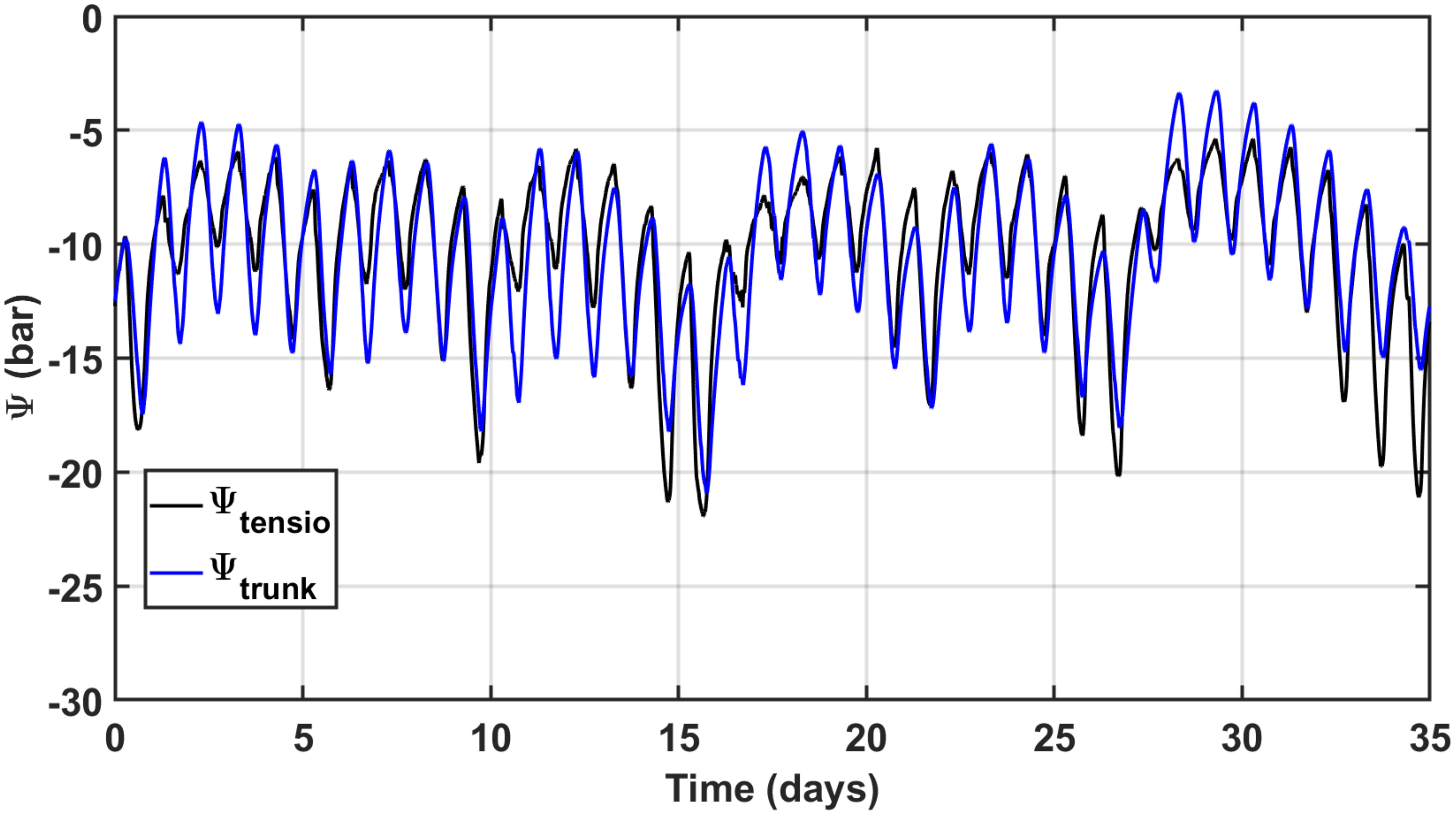


In the field - The Pulse of Trees

Done-Again Farm, Arbuckle, CA

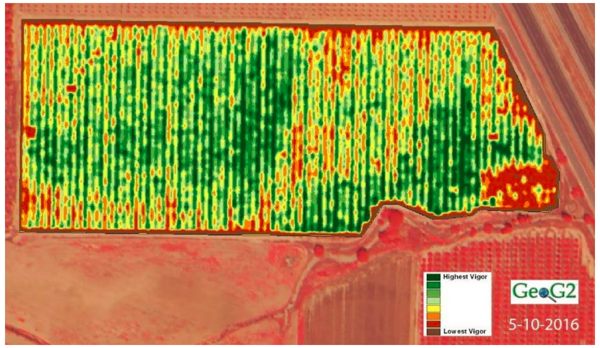


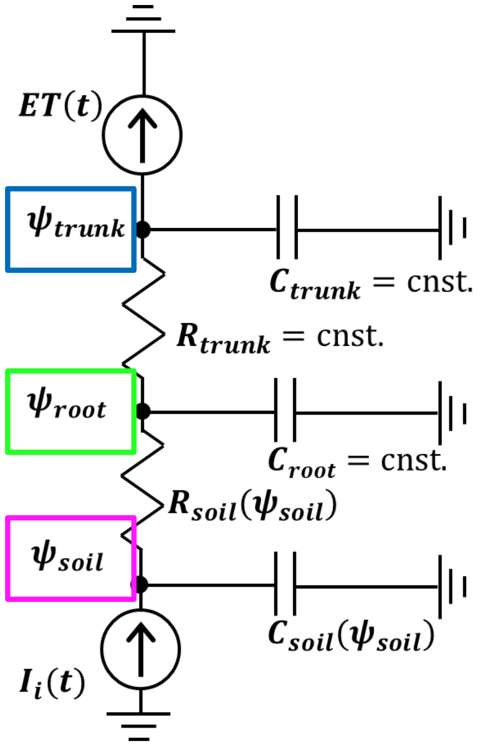




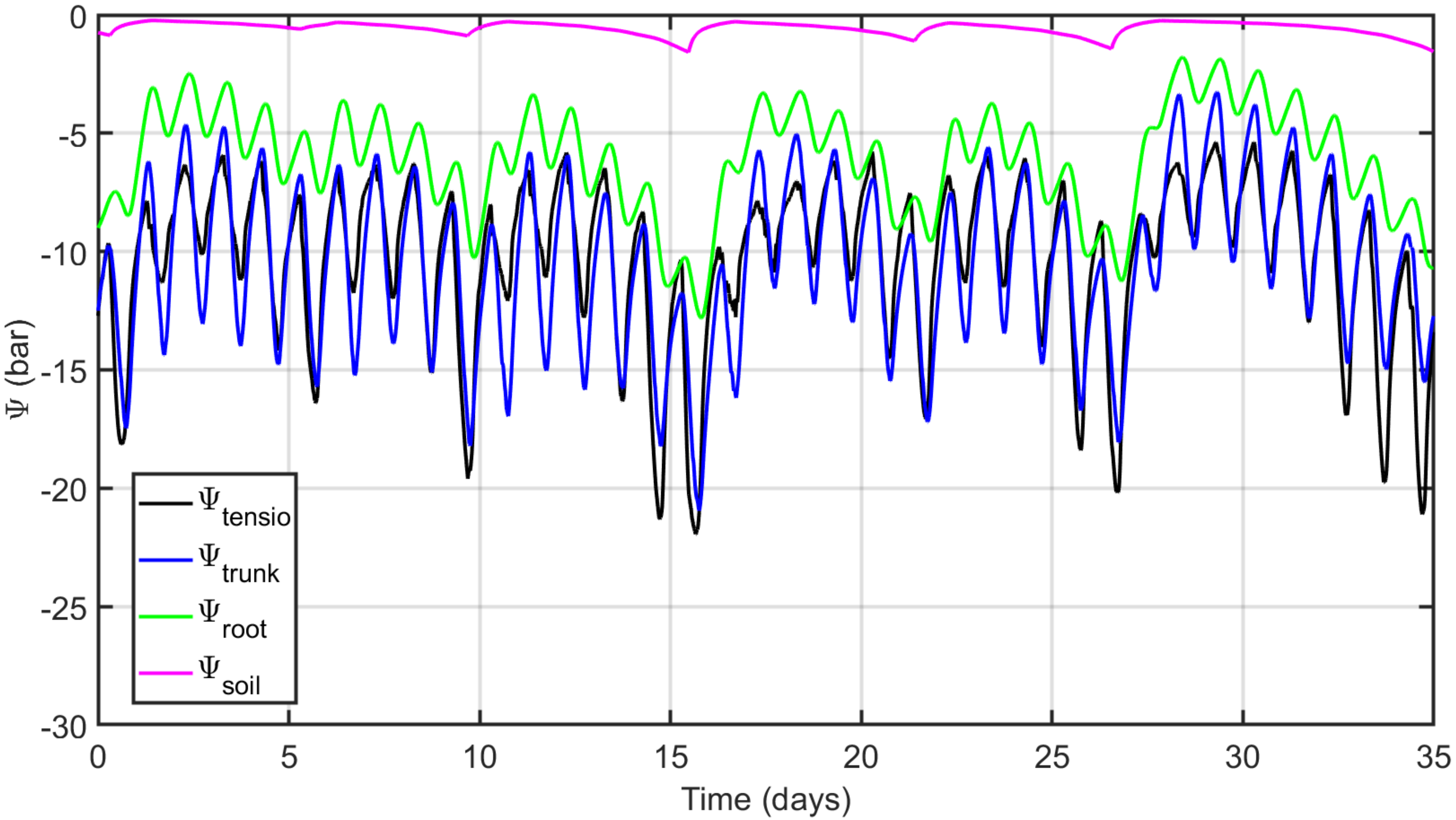
In the field - The Pulse of Trees & Soil

Done-Again Farm, Arbuckle, CA





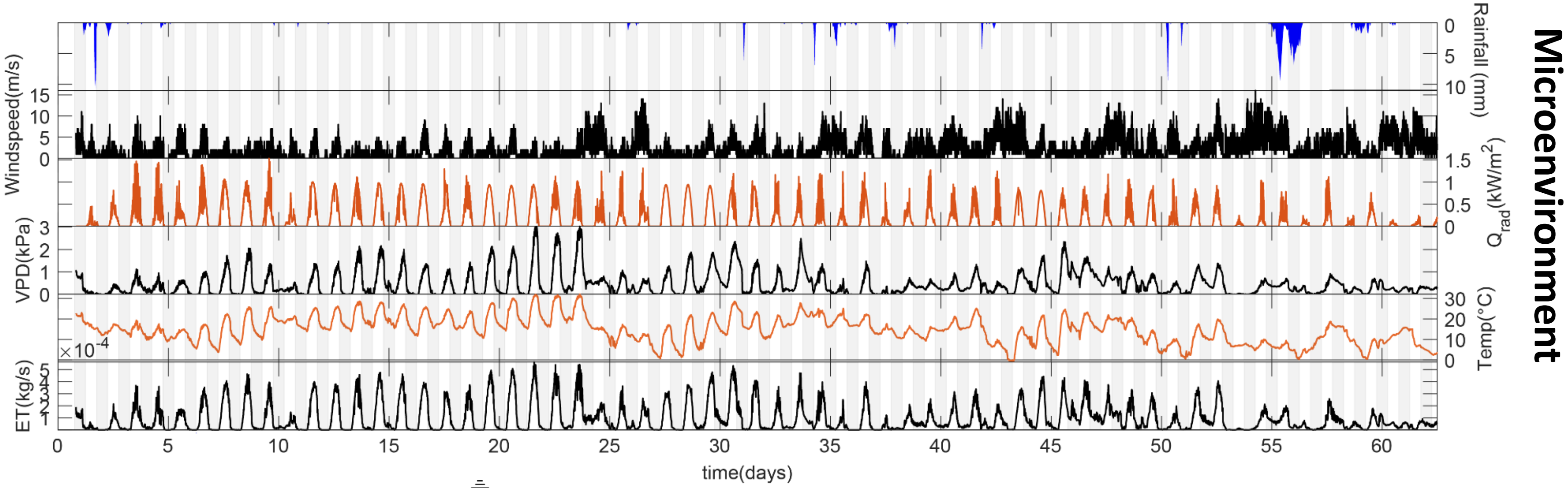
"sandy loam": $\frac{1}{\alpha} = 0.01\ (\text{bar}); \quad n = 2$

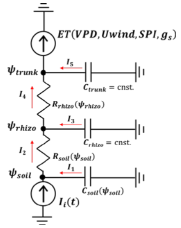


The Pulse of Trees – New York

<u>Apple</u> - Cornell Orchards; Ithaca, NY

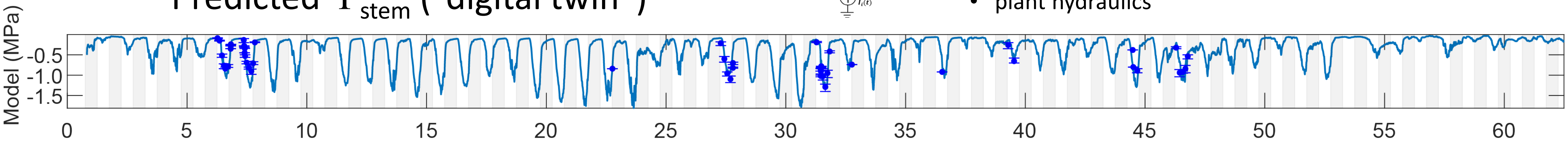
Summer-Fall 2017



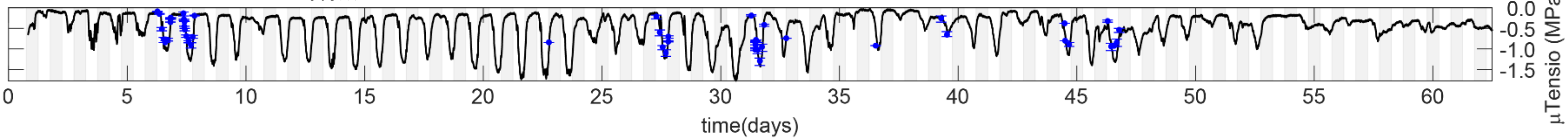


- atmospheric boundary layer
- canopy aerodynamics
- stomatal regulation
- root structure
- soil/rhizosphere hydraulics
- plant hydraulics

Predicted Ψ_{stem} ("digital twin")



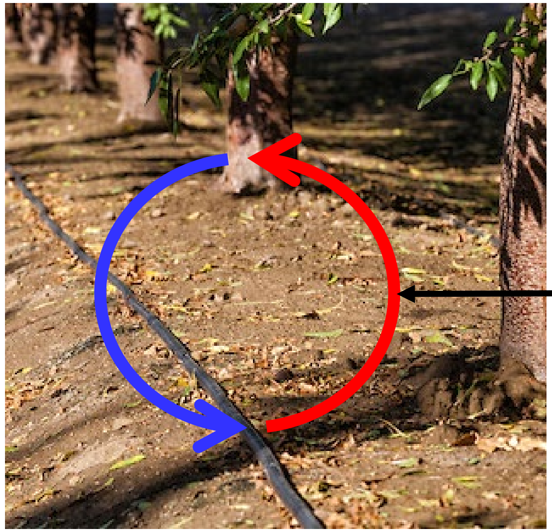
Measured Ψ_{stem} (μTensiometer)



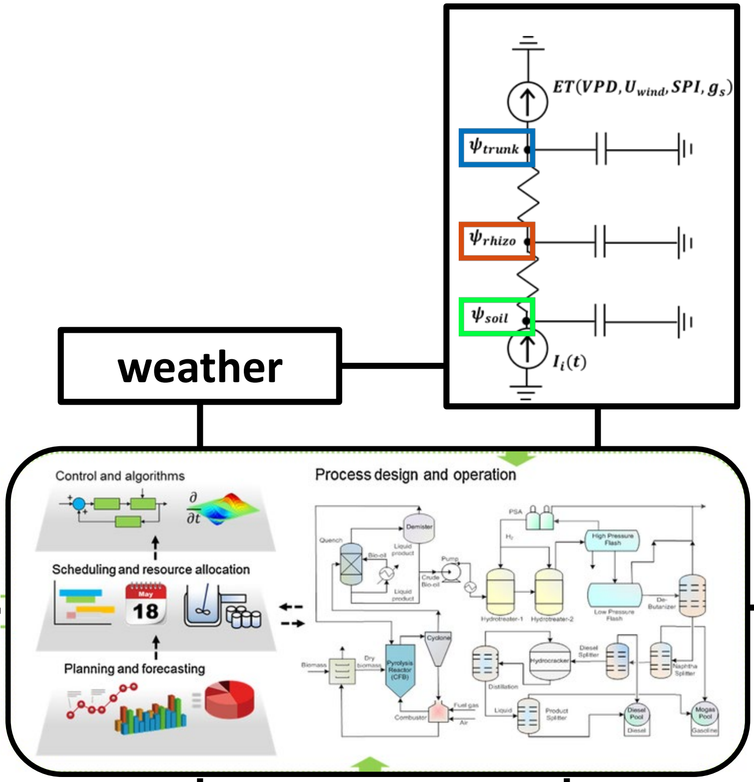
Next steps – Closing the Loop on Irrigation

Prof. Fengqi You

Wei-Han Chen



process model

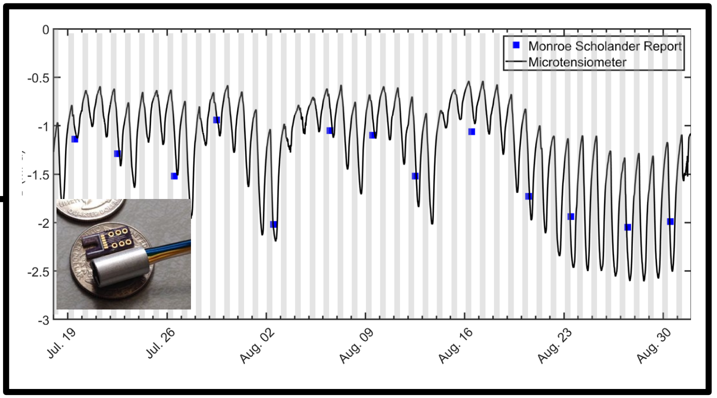


weather

economics

environment

process measurements

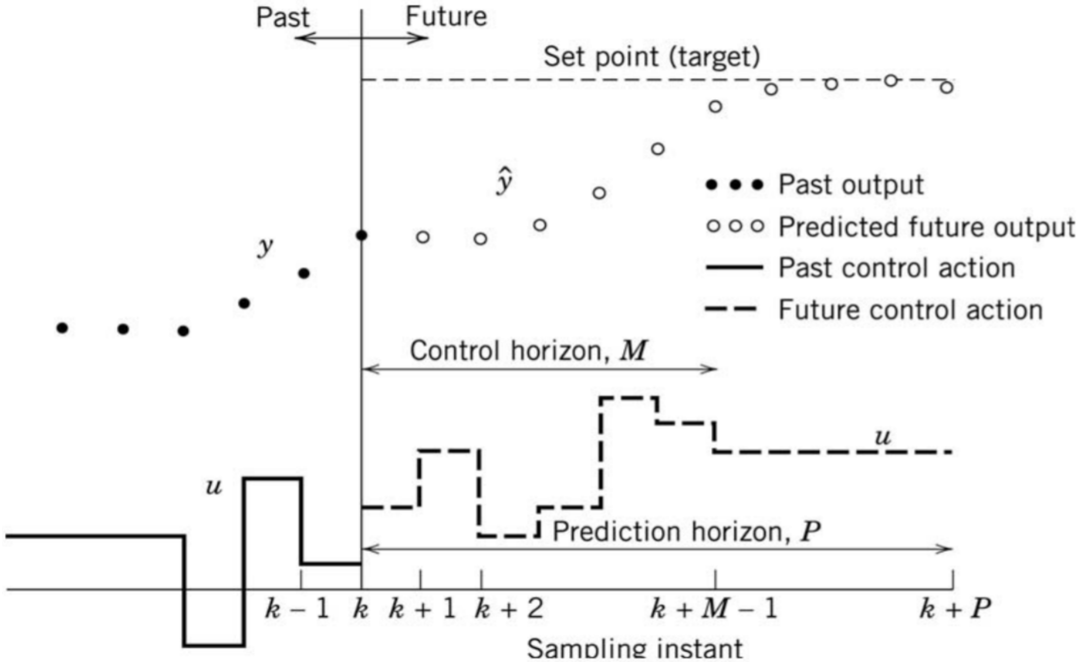


→ Process Optimized Water Management

(Sheng et al., arXiv, 2018)

Next steps – Closing the Loop on Irrigation

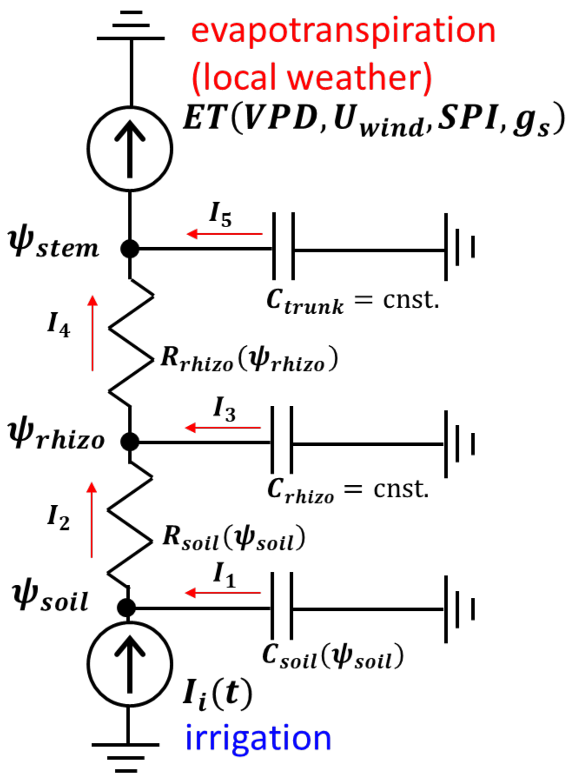
- Closed-Loop Control
  - **ON-OFF control**: once water potential is below the threshold, some water will be supplied
  - **Model Predictive Control (MPC)**: the overall trajectory is optimized in the prediction horizon by considering disturbances



(Sheng et al., arXiv, 2018)

Next steps – Closing the Loop on Irrigation

Non-linear, continuous model



Linearized discrete-time state space model

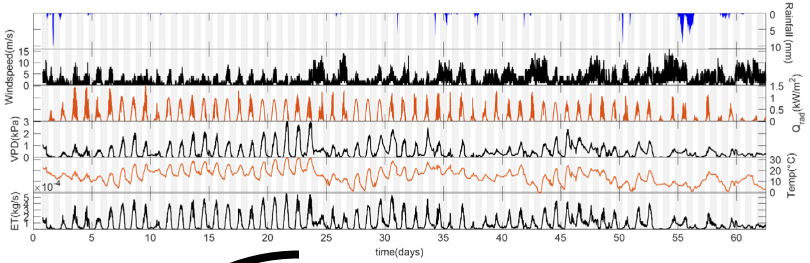
$$\boldsymbol{x} = \boldsymbol{A}_d \boldsymbol{x}_0 + \boldsymbol{B}_{u,d} \boldsymbol{u} + \boldsymbol{B}_v \boldsymbol{v} + \boldsymbol{C}_d$$

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_H \end{bmatrix}, \boldsymbol{A}_d = \begin{bmatrix} A_d \\ A_d^2 \\ \vdots \\ A_d^H \end{bmatrix}, \boldsymbol{B}_{u,d} = \begin{bmatrix} B_{u,d} & 0 & \cdots & 0 \\ A_d B_{u,d} & B_{u,d} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A_d^{H-1} B_{u,d} & A_d^{H-2} B_{u,d} & \cdots & B_{u,d} \end{bmatrix}$$

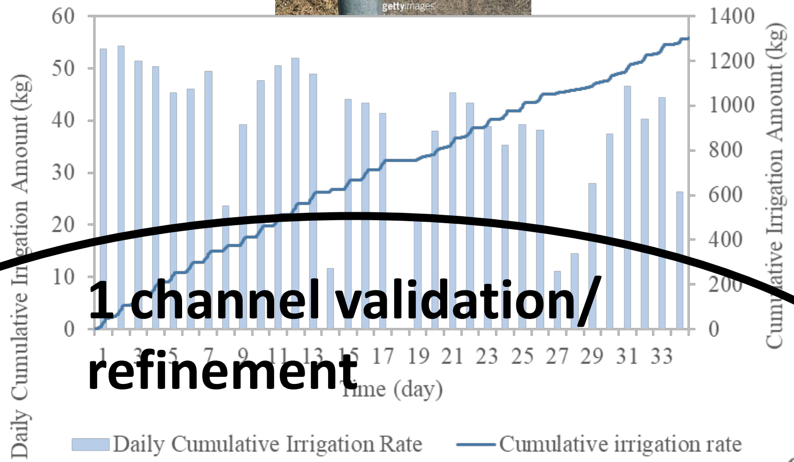
Optimization problem at each step can be solved by ‘cvx’ package in MATLAB

$$\begin{aligned} \min \ & J = \sum_{i=0}^{H-1} u_i + \rho \varepsilon^2 \\ \text{s.t.} \ & \boldsymbol{x} = \boldsymbol{A}_d \boldsymbol{x}_0 + \boldsymbol{B}_{u,d} \boldsymbol{u} + \boldsymbol{B}_v \boldsymbol{v} + \boldsymbol{C}_d \\ & \boldsymbol{x} \geq x_{\min} - \varepsilon \\ & 0 \leq \boldsymbol{u} \leq u_{\max} \\ & \varepsilon \geq 0 \end{aligned}$$

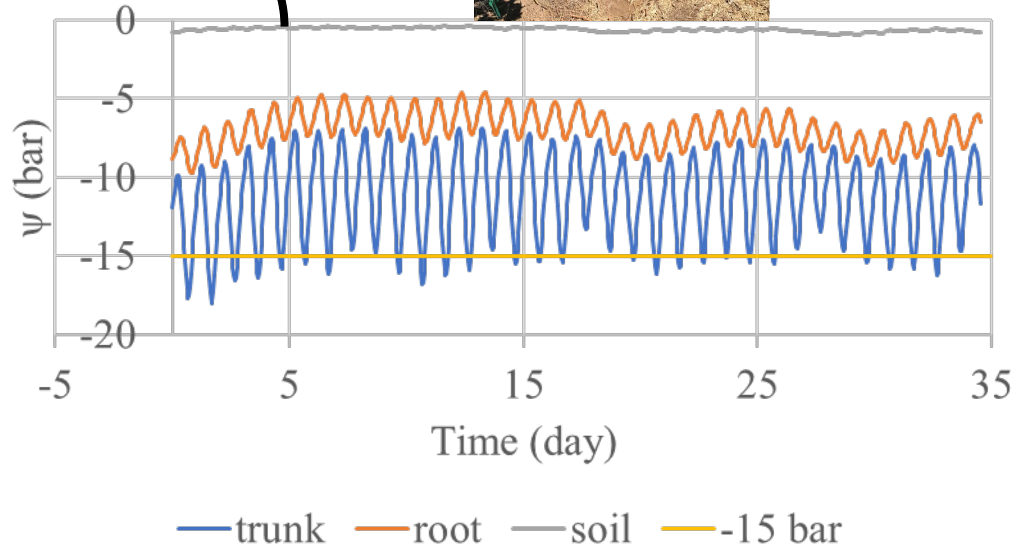
Next steps – Closing the Loop on Irrigation



5 channels of weather data



1 channel validation/ refinement

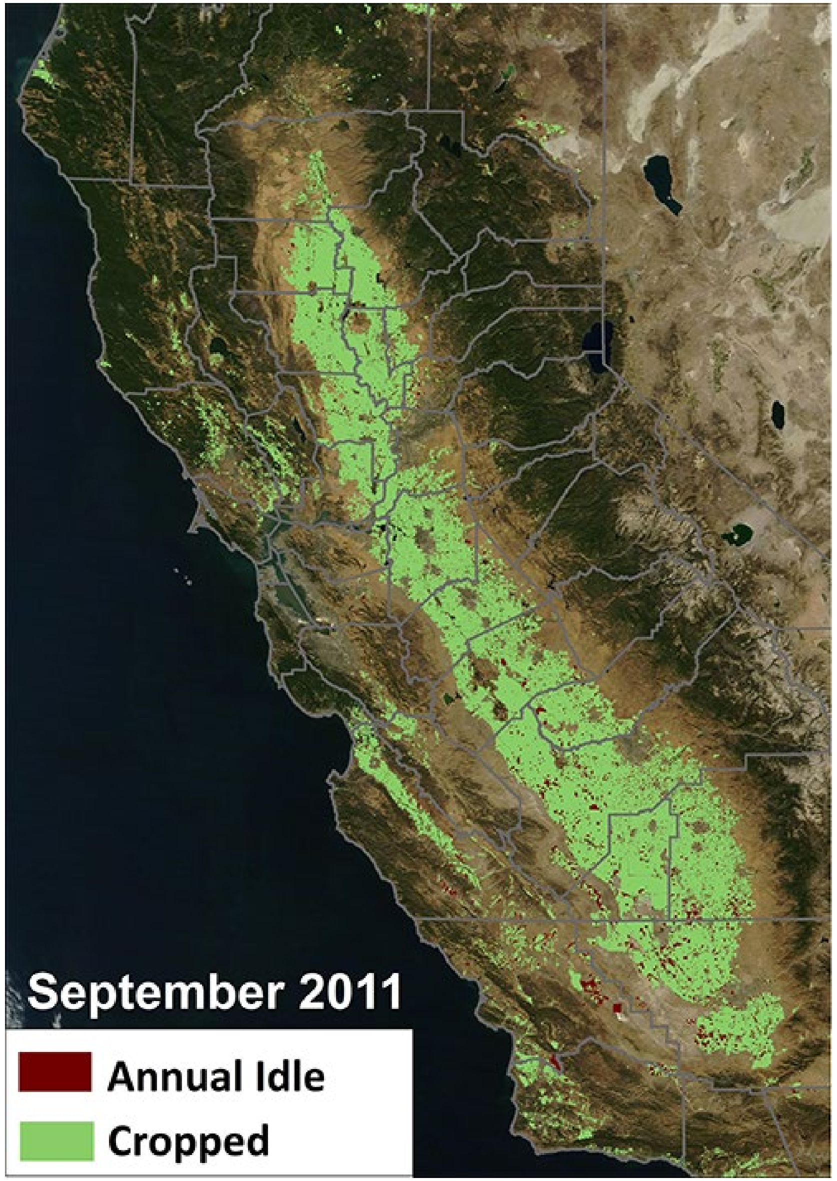


Azure

MPC optimization

1 channel of irrigation control

Next steps – Scale



California irrigated acres: ~5 million

California specialty crops:

grape: 800,000 acres

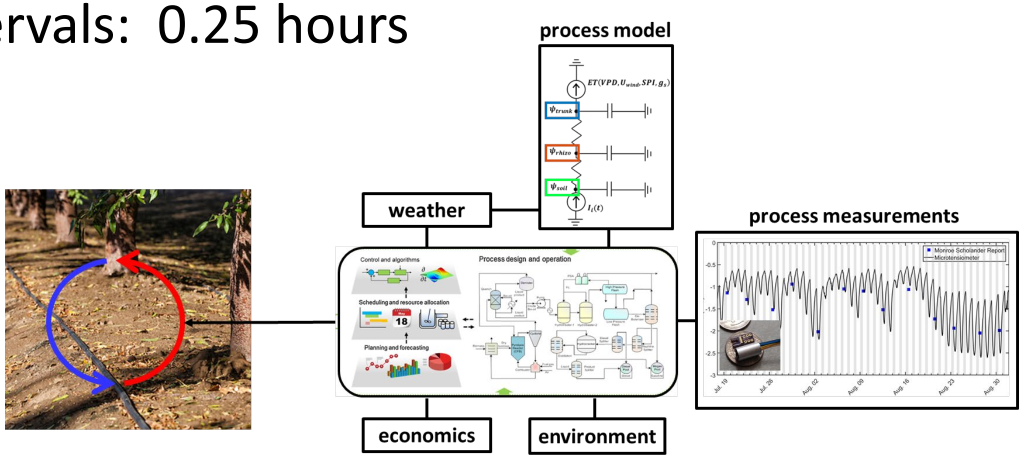
nuts: 1,300,000 acres

Independent irrigation control blocks: ~20,000

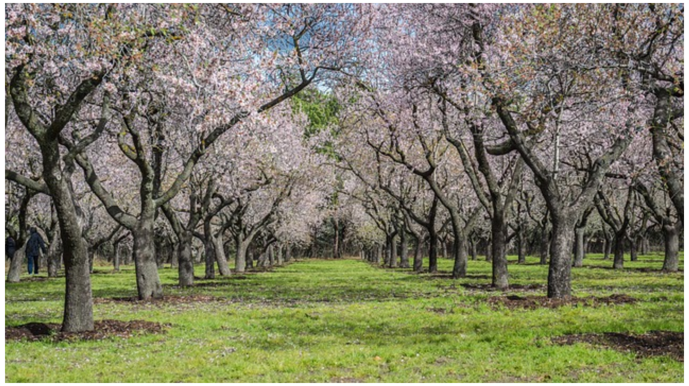
Channels of data: 6+ (could include manual farmer inputs)

Computational channels: 1 per block

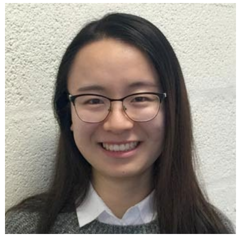
Time intervals: 0.25 hours



Thank you – Questions?



Michael Santiago
(→ FloraPulse Co)



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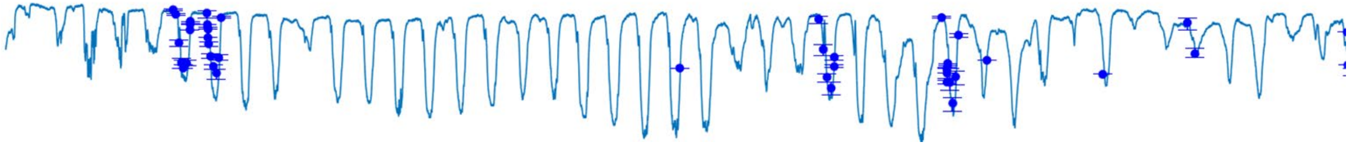
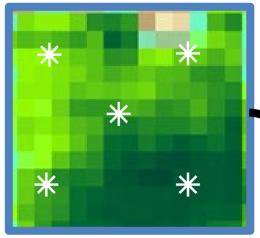


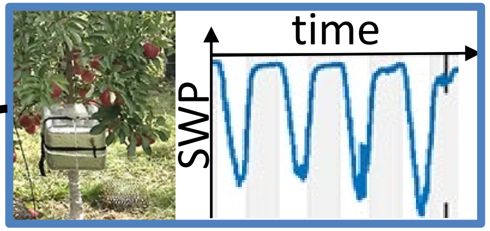
Abe Stroock – abe.stroock@cornell.edu

Directions – Physiologically-Informed Decision Support

remote



ground-based



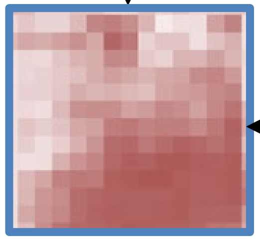
(Cornell/USDA/UC Davis/WSU)

analytics
- distributed SPAC model
- parameter optimization (hybrid data/mechanism)

stress physiology
(apple, grape, almond)
- growth, yield, quality
- **optimal** stress & **timing**

forecasts
- meteorology + climate
- water & crop pricing

"digital twin"



e.g., stress map (hourly, 30 m)

decision support tools
- real-time stress **maps**
- stress **forecasting**
- soil mapping
- irrigation design

socio-economic anal.
- ROI/cost-benefit analysis
- barriers for adoption
- regulatory drivers

auto. management
- model **predictive control**
- **failure detection**