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

Abraham Stroock
Chemical and Biomolecular Engineering, Cornell University
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)
Most irrigation is still run open loop.

We lack appropriate measurement tools...and cloud-based systems.
What to measure? – **Stem Water Potential** ($\Psi$)

**Growth**

- $R^2 = 0.77$

**Sugars**

- $R^2 = 0.66$

**Flavors**

- $R^2 = 0.83$

- $R^2 = 0.51$

“50% of vintage quality is defined by water stress…”

(Cees Van Leeuwen, Chateaux Cheval Blanc, Bordeaux)
What to measure? – Stem Water Potential ($\Psi_{stem}$)

**State-of-the-art $\Psi$-meter**

**Schölander Pressure Chamber**

**Growth**

$R^2 = 0.77$

**Sugars**

$R^2 = 0.66$
State-of-the-art Ψ-meter
(pressure chamber)

Ψ-meter – can do we do better?

(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)

(Pagay et al., LoC, 2014)

(Santiago et al., in prep, 2018)
MEMS Stress Meter – $\mu$Tensiometer

\[ \Delta V \propto \Psi_{stem} \]

$\Psi_{stem}$ (stem (trunk))

$\mu$Tensiometer

$\Psi_{stem}$ (xylem)

(equilibrium device ↔ tissue)

Grape
(Matchbook Wines; Zamora, CA)

Almond
(Done-Again Farm; Arbuckle, CA)

Apple
(Cornell Orchards; Ithaca, NY)

Corn
(Musgrave Farms; Auburn, NY)
Schöander Bomb

Done-Again Farm, Arbuckle, CA

In the field

almond – summer 2017

$\psi$ (bar) (plant water stress)

<table>
<thead>
<tr>
<th>Date</th>
<th>DAF 2</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wednesday, 7/26/2017</td>
<td>-15.2</td>
<td>Ideal conditions for hull split. May help prevent diseases such as hull rot and alternaria (Shooting for -14.0 to -17.9)</td>
</tr>
<tr>
<td>Wednesday, 8/2/2017</td>
<td>-20.2</td>
<td>High Stress (Shooting for -14.0 to -17.9)</td>
</tr>
</tbody>
</table>

-22.5 -23 -24 -21.5 -20.5 Avg: -22.3
In the field - The Pulse of Trees

almond – summer 2017

microTensiometer

Michael Santiago

FloraPulse
Done-Again Farm, Arbuckle, CA

almond – summer 2017

In the field - The Pulse of Trees

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

day: $\Psi_{stem} \rightarrow \Psi_{atm}$
In the field - The Pulse of Trees

Done-Again Farm, Arbuckle, CA

irrigation (Jake Spooner):

Questions: properties of soil, roots, trunk, stomates, canopy,...?
In the field - The Pulse of Trees

Evapotranspiration (ET(0))

- Wind (U_{wind})
- Humidity (VPD)
- Light (SIL)

Irrigation (ET(0))

- bulk soil (\Theta)

bulk soil (\Theta)

\( \psi_{stem} \)

\( \psi_{rhizo} \)

\( \psi_{soil} \)

\( R_{rhizo}(\psi_{rhizo}) \)

\( R_{soil}(\psi_{soil}) \)

\( I_1 \)

\( I_2 \)

\( I_3 \)

\( I_4 \)

\( I_5 \)

\( I_i(t) \)

\( C_{trunk} = \text{cnst.} \)

\( C_{rhizo} = \text{cnst.} \)

\( C_{soil}(\psi_{soil}) \)

irrigation

evapotranspiration (local weather)

\( ET(VPD, U_{wind}, SPI, g_s) \)

Siyu Zhu  Kathryn Haldeman
Done-Again Farm, Arbuckle, CA

In the field - The Pulse of Trees
Done-Again Farm, Arbuckle, CA

"sandy loam": $\frac{1}{\alpha} = 0.01 \text{ (bar)}; \ n = 2$
The Pulse of Trees – New York

Apple - Cornell Orchards; Ithaca, NY
Summer-Fall 2017

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

Predicted $\Psi_{stem}$ ("digital twin")

Measured $\Psi_{stem}$ ($\mu$Tensiometer)
Next steps – Closing the Loop on Irrigation

Prof. Fengqi You
Wei-Han Chen

→ 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

\[
x = A_d x_0 + B_{u,d} u + B_v v + C_d
\]

\[
x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_H \end{bmatrix}, \quad A_d = \begin{bmatrix} A_d \\ A_d^2 \\ \vdots \\ A_d^H \end{bmatrix}, \quad B_{u,d} = \begin{bmatrix} B_{u,d} & 0 & \cdots & 0 \\ A_d B_{u,d} & B_{u,d} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A_d^{H-1} B_{u,d} & A_d^{H-2} B_{u,d} & \cdots & B_{u,d} \end{bmatrix}
\]

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

\[
\min J = \sum_{i=0}^{H-1} u_i + \rho \varepsilon^2
\]

s.t. \[ x = A_d x_0 + B_{u,d} u + B_v v + C_d \]

\[
x \geq x_{\min} - \varepsilon
\]

\[
0 \leq u \leq u_{\max}
\]

\[
\varepsilon \geq 0
\]
Next steps – Closing the Loop on Irrigation

- 5 channels of weather data
- 1 channel of irrigation control
- Azure
- MPC optimization
- 1 channel validation/refinement
- Graphs showing daily cumulative irrigation amount and rate over time
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)
Siyu Zhu
Rui Gao
Wei-Han Chen

Prof. Fengqi You
Prof. Alan Lakso
Prof. Lailiang Cheng
Prof. Ken Shackel (UC Davis)

Abe Stroock – abe.stroock@cornell.edu
Directions – Physiologically-Informed Decision Support

remote

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

ground-based

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

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

“digital twin”
e.g., stress map (hourly, 30 m)

auto. management
• model predictive control
• failure detection

forecasts
• meteorology + climate
• water & crop pricing

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

(Cornell/USDA/UC Davis/WSU)