Estrés hídrico con énfasis en sequía

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Isabela, Puerto Rico
Agenda

- What is crop water stress?
- What external factors cause crop water stress?
- How do we model crop water stress?
- PR drought of 2015
- How do we avoid crop water stress?
What is crop water stress?

- “Plants experience water stress either when the water supply to their roots becomes limiting or when the transpiration rate becomes intense.”

- “Plant growth under drought is influenced by altered photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism, and hormones.”

- “Water stress is primarily caused by the water deficit, i.e. drought or high soil salinity. In case of high soil salinity and also in other conditions like flooding and low soil temperature, water exists in soil solution but plants cannot uptake it – a situation commonly known as ‘physiological drought’.”

FIGURE 1
Schematic representation of a stoma

Atmosphere

Leaf

- water vapour
- cuticula
- epidermal cells
- mesophyll cells
- intercellular space
Relationship between relative crop yield and relative seasonal crop water requirement applied.
How much money are we talking about?

<table>
<thead>
<tr>
<th>CROP*</th>
<th>Percentage of Crop Water Requirement Applied</th>
<th>$ Lost / Acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gandules</td>
<td>47 32 10 0 12 35 69</td>
<td></td>
</tr>
<tr>
<td>Pepinillo</td>
<td>111 76 25 0 15 56 124</td>
<td></td>
</tr>
<tr>
<td>Repollo</td>
<td>256 174 57 0 21 103 247</td>
<td></td>
</tr>
<tr>
<td>Sandia</td>
<td>293 199 65 0 23 114 277</td>
<td></td>
</tr>
<tr>
<td>Platanos y Guineos, Plantilla</td>
<td>318 216 71 0 24 122 299</td>
<td></td>
</tr>
<tr>
<td>Calabaza</td>
<td>390 265 87 0 27 146 359</td>
<td></td>
</tr>
<tr>
<td>Cebolla</td>
<td>543 369 121 0 34 195 490</td>
<td></td>
</tr>
<tr>
<td>Pimiento</td>
<td>578 393 129 0 36 206 519</td>
<td></td>
</tr>
<tr>
<td>Barenjena</td>
<td>757 514 169 0 44 264 670</td>
<td></td>
</tr>
<tr>
<td>Platanos y Guineos, Reton~o</td>
<td>1,006 684 225 0 76 388 945</td>
<td></td>
</tr>
<tr>
<td>Melon, Cantaloupe y Honeydew</td>
<td>1,027 698 229 0 56 352 899</td>
<td></td>
</tr>
<tr>
<td>Raices y Tuberculos</td>
<td>1,041 707 232 0 57 356 911</td>
<td></td>
</tr>
</tbody>
</table>

*Based model budget data from the Conjunto Tecnológico, UPR Experiment Station*
What external factors cause crop water stress?

- Drought
- Planting at the wrong time of year
- Poor irrigation system design
- Poor irrigation management
- Climate Change
The total changes in precipitation, mean temperature and PET ratio from the first time interval (1960 to 1990) to the last time interval (2071 to 2099) based on the multi-model average of all twelve models.
How do we model crop water stress?
Crop Water Stress Index (CWSI)

\[
CWSI = 1 - \frac{ET_a}{ET_P} = \frac{\gamma \left( 0.81 + \frac{r_s}{r_{ah}} \right) - \gamma^*}{\delta + \gamma \left( 0.81 + \frac{r_s}{r_{ah}} \right)}
\]

\[
\gamma^* = \gamma \left[ 0.81 + \left( \frac{r_s}{r_{ah}} \right)_p \right]
\]

\( ET_a \) = Actual evapotranspiration
\( ET_P \) = Reference evapotranspiration
\( \gamma \) = Psychrometric constant
\( \delta \) = Slope of the saturated vapor pressure-temperature curve
\( r_s \) = Resistance to water vapor transfer at leaf level
\( r_{ah} \) = Air resistance for heat diffusion

Estimating CWSI is relatively complicated. The method involves canopy temperature, which is easy to obtain, but it also involves a lot of other measurements.

\[
\frac{r_s}{r_{ah}} = \frac{0.81Q_{RAD}r_{ah} \gamma}{2LAI\rho C_p} - \left[ (T_c - T_a)(0.81 \gamma + \delta) \right] - \text{VPD} \\
\gamma \left[ (T_c - T_a) - \frac{Q_{RAD}r_{ah}}{2LAI\rho C_p} \right]
\]
$$ET_{c\,adj} = K_s \cdot K_c \cdot ET_0$$

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1 - p) \cdot TAW}$$
Relative Crop Yield ($Y_a/Y_m$)

\[
\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{ET_{c,adj}}{ET_c}\right)
\]

where:
- $K_y$: a yield response factor [-]
- $ET_{c,adj}$: adjusted (actual) crop evapotranspiration [mm d$^{-1}$]
- $ET_c$: crop evapotranspiration for standard conditions (no water stress) [mm d$^{-1}$]
Canopy Energy Balance

\[ R_n + lE + H + G + aA = 0 \]

- \( R_n \) = Net radiation
- \( lE \) = Latent heat flux
- \( H \) = Sensible heat flux.
- \( G \) = Soil heat flux
- \( aA \) = energy utilized in photosynthetic activity.
Bowen Ratio

\[ \beta = \frac{H}{LE} \]

\[ = \gamma \left( \frac{T_s - T_a}{e_s - e_a} \right) \]

Where \( H \) and \( LE \) are the sensible and latent heat flux, respectively,

\( T_s \) and \( T \) are the water surface and air temperatures respectively, in degrees Celsius,

\( e_s \) and \( e_a \) are vapor pressures at the water surface and air, respectively, in kilopascals, and

\( \gamma \) is the psychrometric constant, in kilopascals per degree Celsius.
The 2015 Drought

- Puerto Rico experienced a prolonged drought during the months of April through September.
- Water
Irrigation Districts

- Agricultural water requirements are not well island
- Canals have limited spatial extent
- Canals are in disrepair in some areas, and water is lost from the system
- Water is essentially free to farmers
June 19, 2015, aerial photo shows the drought-affected lakeshore of La Plata reservoir in Toa Alta, Puerto Rico.
Water Conflicts

- Conflicts exist between the agriculture and non-agricultural sectors. For example, in the Guayama Irrigation District, 28% of the water is used for agriculture, 72% for domestic/industrial use.

- Expansion of agricultural production is being promoted, which will result in more competition for water resources.
Groundwater

- Salinity levels are increasing in some of the wells near the ocean.
- Induced aquifer recharge systems have been designed and are operational in Guanica and Juana Diaz areas.
- The interior of the island is characterized by relatively low permeable rock.
Weekly maps can be viewed by clicking on the following links:
- Rainfall
- Agricultural rainfall deficit
- Agricultural rainfall deficit (negative values only)
- Soil Moisture Saturation
- Volumetric Soil Moisture Content
- Crop Stress Coefficient
- Reference (Potential) Evapotranspiration
- Actual Evapotranspiration
- Natural Log of the Bowen Ratio

Monthly maps can be viewed by clicking on the following links:
- Rainfall
- Agricultural Rainfall Deficit
- Soil Moisture Saturation
- Volumetric Soil Moisture Content
- Crop Stress Coefficient
- Reference (Potential) Evapotranspiration
- Actual Evapotranspiration
- Natural Log of the Bowen Ratio

Progress of 2015 Puerto Rico Drought – Selected Soil and Water Parameters
Water and Energy Balance
November 24, 2015

- Rainfall
- Runoff
- Aquifer Recharge
- Soil Moisture
- Actual ET
- Net Radiation
- Latent Heat Flux
- Sensible Heat Flux
El Yunque Tropical Rain Forest

NOAA’s Advanced Hydrologic Prediction Service

RAINFALL (mm)

Apr

May

Jun

Jul

Aug

Sep

Oct

Nov
Volumetric Soil Moisture Content (cm³/cm³)
Rainfall Deficit (negative values only) (mm)
Effective Crop Coefficient

AVERAGE MONTHLY CROP COEFFICIENT, Kc Apr15

AVERAGE MONTHLY CROP COEFFICIENT, Kc May15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Jun15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Jul15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Aug15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Sep15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Oct15

AVERAGE MONTHLY CROP COEFFICIENT, Kc Nov15
Water Stress Coefficient

- April
- May
- June
- July
- August
- September
- October
- November
Log of the Bowen Ratio

- April
- May
- June
- July
- August
- September
- October
- November
Natural Log of Bowen Ratio along Transect 18.21 N Latitude from Jun 20 to Jul 10.
Comparisons of Rainfall in NW PR for drought and non-drought years

<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Avg. rain drought yrs.</th>
<th>Avg. rain non-drought yrs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coloso</td>
<td>72.88</td>
<td>77.48</td>
</tr>
<tr>
<td>Hacienda constanza</td>
<td>68.7</td>
<td>69.51</td>
</tr>
<tr>
<td>Maricao fish hatchery</td>
<td>81.92</td>
<td>98.62</td>
</tr>
<tr>
<td>Mayaguez city</td>
<td>62.31</td>
<td>67.44</td>
</tr>
<tr>
<td>Mayaguez airport</td>
<td>62.44</td>
<td>78.24</td>
</tr>
<tr>
<td>San sebastian 2 wnw</td>
<td>86.26</td>
<td>91.24</td>
</tr>
</tbody>
</table>

Compared average of:

17 Drought Years

94 Non-Drought Years
Climate & Drought Information

**DISCLAIMER:** Graphical display of observed rainfall is derived from a combination of USGS raingauge sensors and radar data retrieved by the Advanced Hydrologic Prediction Service (AHPS). Graphical display of Normal rainfall is derived from Puerto Rico 1981-2010 PRISM data. Please note, quality control is not performed on a daily basis.

**Click here to access the PR & USVI Daily Precipitation & Deficits from AHPS**

**PRAGWATER Soil Moisture**  
Click to enlarge

**PRAGWATER Soil Saturation**  
Click to enlarge

**PRAGWATER Yesterday Rainfall**  
Click to enlarge
How do we avoid crop water stress?

Irrigation Scheduling
Irrigation Scheduling Methods used in Puerto Rico (preliminary data)

- Experience: 35%
- Soil moisture: 35%
- Evapotranspiration: 19%
- Water balance: 3%
- Other: 8%
How much water should be applied?

Plant Water Requirement

= Crop Evapotranspiration

(under well-watered conditions)
1-INCH PER WEEK IRRIGATION

- Volumetric Soil Moisture Content
- Threshold Moisture Content: Start Irrigating
- Soil Field Capacity: Stop Irrigating

Crop Stress Factor Vs. Time

Cumulative ET
Cumulative Irrigation
The most commonly used method for determining the Crop Water Requirement is:

$$ET_c = K_c \cdot ET_o$$

where

- $ET_c$ = evapotranspiration under well-watered conditions = crop water requirement
- $K_c$ = Crop Coefficient (unique for every crop)
- $ET_o$ = Reference Evapotranspiration (function of climate)
Many weather stations ($1,700 approx.) will calculate the daily reference evapotranspiration.
What if a farmer doesn’t have a weather station?

Here’s a relatively simple web-based method for scheduling irrigation

1. Define problem (location, farm size, crop, etc.)
2. Determine $ET_0$
3. Determine average $K_c$ for the time period
4. Determine rainfall from onsite gauge or NEXRAD
5. Estimate Crop Water Requirement
   $$ET_c = K_c \times ET_0$$
6. Determine the number of hours to run the pump
   $$T = 17.817 \times \frac{D \times A}{Q \times \text{eff}}$$

Detailed Example

- Determine the irrigation requirement for the 5 day period, February 15-19, 2012, for a tomato crop in Juana Diaz, Puerto Rico.

Required Hyperlinks

<table>
<thead>
<tr>
<th>Length of Growth Stages (Table 11) and Crop Coefficients (Table 12)</th>
<th><a href="http://www.fao.org/docrep/X0490E/x0490e00.htm">http://www.fao.org/docrep/X0490E/x0490e00.htm</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Reference ET Results for Puerto Rico^4</td>
<td><a href="http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/reference_ET/">http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/reference_ET/</a></td>
</tr>
<tr>
<td>Daily NEXRAD Rainfall For Puerto Rico</td>
<td><a href="http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/rainfall/">http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/rainfall/</a></td>
</tr>
</tbody>
</table>
### Step 1. Information used in example problem.

<table>
<thead>
<tr>
<th>Location</th>
<th>Juana Diaz, Puerto Rico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Latitude</td>
<td>18.02 degrees N</td>
</tr>
<tr>
<td>Site Longitude</td>
<td>66.52 degrees W</td>
</tr>
<tr>
<td>Site Elevation above sea level</td>
<td>21 m</td>
</tr>
<tr>
<td>Crop</td>
<td>Tomato</td>
</tr>
<tr>
<td>Planting Date</td>
<td>1-Jan-12</td>
</tr>
<tr>
<td>Rainfall information</td>
<td>A rain gauge is not available on or near the farm</td>
</tr>
<tr>
<td>Type of irrigation</td>
<td>Drip</td>
</tr>
<tr>
<td>Irrigation system efficiency</td>
<td>85%</td>
</tr>
<tr>
<td>Field Size</td>
<td>10 acres</td>
</tr>
<tr>
<td>Pump capacity</td>
<td>300 gallons per minute</td>
</tr>
</tbody>
</table>
Step 2. Crop growth stage and crop coefficient data for example problem.

(http://www.fao.org/docrep/X0490E/x0490e00.htm)

**Tomato Growth Stages and Crop Coefficients**

<table>
<thead>
<tr>
<th>Initial Crop Growth Stage</th>
<th>30 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop Development Growth Stage</td>
<td>40 days</td>
</tr>
<tr>
<td>Mid-Season Growth Stage</td>
<td>40 days</td>
</tr>
<tr>
<td>Late-Season Growth Stage</td>
<td>25 days</td>
</tr>
<tr>
<td>Total Length of Season</td>
<td>135 days</td>
</tr>
<tr>
<td>$K_{c\text{ ini}}$</td>
<td>0.6</td>
</tr>
<tr>
<td>$K_{c\text{ mid}}$</td>
<td>1.15</td>
</tr>
<tr>
<td>$K_{c\text{ end}}$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Crop Coefficient

- The average $K_c$ value of 0.85 for the five-day period was obtained.

Crop coefficient curve for the example problem. The heavy dashed line applies to the example problem with day of season 46-50 (i.e., Feb 15-19) corresponding to an approximate crop coefficient of 0.85 (vertical axis).
Step 3. Rainfall

(\url{http://academic.uprm.edu/hdc/GOES-PRWEB_RESULTS/rainfall/})

- Inspection of the rainfall maps at the URL provided indicates that there was no rainfall during the five day period.

- Therefore, all of the crop water requirement will have to be satisfied with irrigation.
Step 4. Reference Evapotranspiration ($E_{T_o}$)

http://academic.uprm.edu/hdc/GOES-PRWEB_RESULT/reference_ET/

- Inspection of the $E_{T_o}$ maps at the URL provided above indicates that there was 16.1 mm of $E_{T_o}$ during the five day period.
Step 5. Crop Water Requirement

- The crop water requirement ($ET_c$) for the time period can now be estimated as follows:

$$ET_c = K_c \ ET_o = (0.85)(16.1 \ mm) = 13.7 \ mm$$
Step 6. Number of hours to run the pump

- Pumping time is estimated from a form of the well-known irrigation equation (Fangmeier et al., 2005) can be used:

\[
T = 17.817 \times \frac{D \times A}{Q \times \text{eff}}
\]

- where \(T\) is time in hours, \(D\) is depth of irrigation water \((=\text{ET}_c)\) in mm, \(A\) is effective field area in acres, \(Q\) is flow rate in gallons per minute and \(\text{eff}\) is irrigation system efficiency.
Number of hours to run the pump to satisfy the crop water requirement for the example problem.

- Using $D = ET_c = 13.7$ mm
- $A = 10$ acres
- $Q = 300$ gallons per minute
- $\text{eff} = 0.85$, yields:

$$T = 17.817 \times \frac{13.7 \times 10}{300 \times 0.85} = 9.57 \text{ hours}.$$ 

- Total volume = 172,300 gallons
Reference ET for PR, USVI, Hispaniola, Jamaica and Cuba

pragwater.com
Reference ET for the U.S. Virgin Island

pragwater.com

St. Croix

St. Thomas

St. John
Conclusions

• The 2015 drought has shown us how vulnerable our water supply system is in Puerto Rico.

• Reservoirs were overdrawn and the irrigation districts were operating at a fraction of their production potential.

• Daily values of soil moisture and crop stress-related parameters from an operational water and energy balance model for the period of the drought were presented.

• An example of irrigation scheduling was given that a farmer in the Caribbean Region can use to help avoid crop water stress.
ACKNOWLEDGEMENT

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