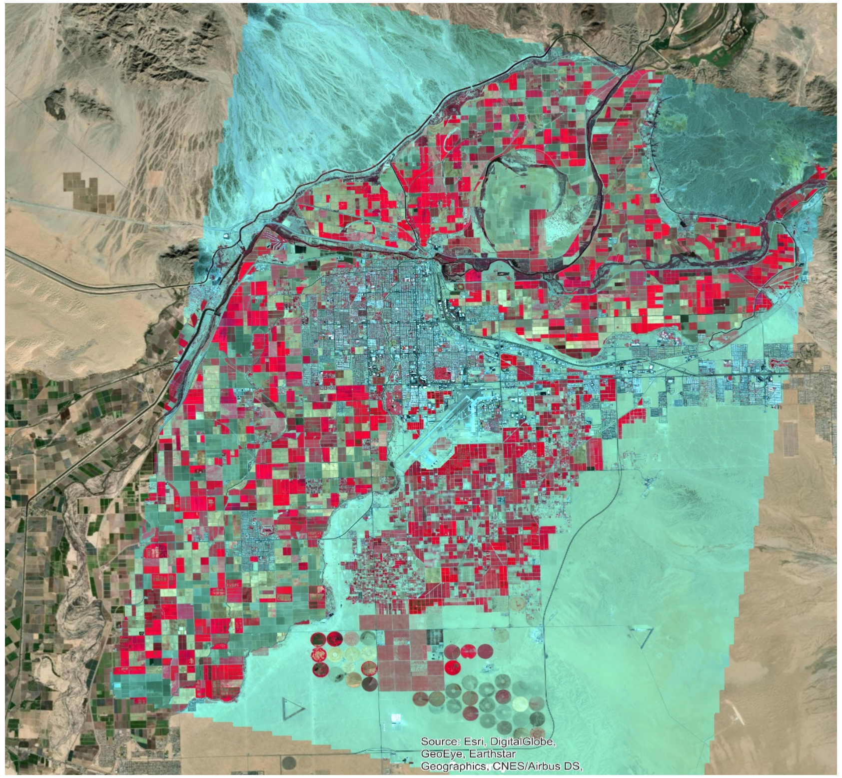
A New Crop Water Stress Index for Desert Agriculture Derived from Satellite Observations and Soil Hydraulic Parameters



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AGU American Geophysical Union

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Environmental Science

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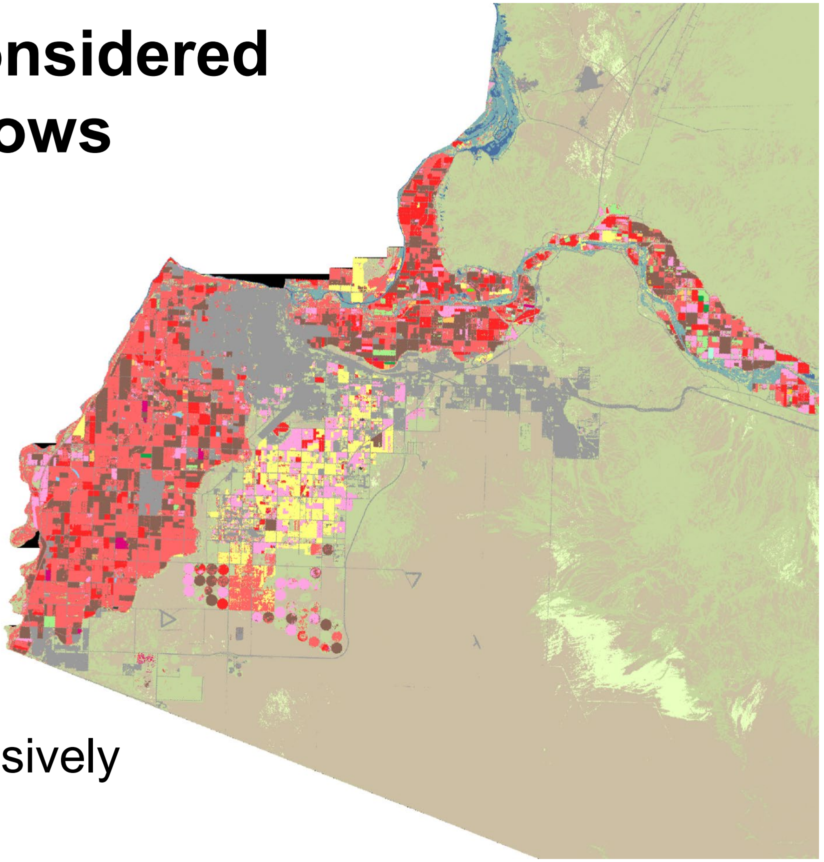
Yuma Desert Agriculture

- **The arid Yuma region in southwestern Arizona is considered as the Winter Vegetable Capital of the World that grows about 90% of winter vegetables in the U.S.**
- **Annual gross economic return of about $3.2 billion.**
  - Longest growing season in the U.S. with mild winters.
  - Sediments deposited by Colorado river over millions of years provide fertile soils.
  - Less than 3 inches of precipitation – high quality Colorado River irrigation water.
  - Declining irrigation water resources is a major concern for many intensively cultivated arid and semi-arid agricultural systems.



Quantification of Crop Water Deficit

1. Canopy Temperature – Jackson et al. (1981)

$$CWDI = 1 - \frac{\lambda E_\Gamma}{\lambda E_{\Gamma P}} = \frac{\gamma\left(1+\frac{r_c}{r_a}\right)-\gamma^*}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)}$$

$$\frac{r_c}{r_a} = \frac{\frac{\gamma r_a R_n}{\rho c_p} - (T_c - T_a)(\Delta + \gamma) - (e_a^* - e_a)}{\gamma\left[(T_c - T_a) - r_a R_n/(\rho c_p)\right]}$$

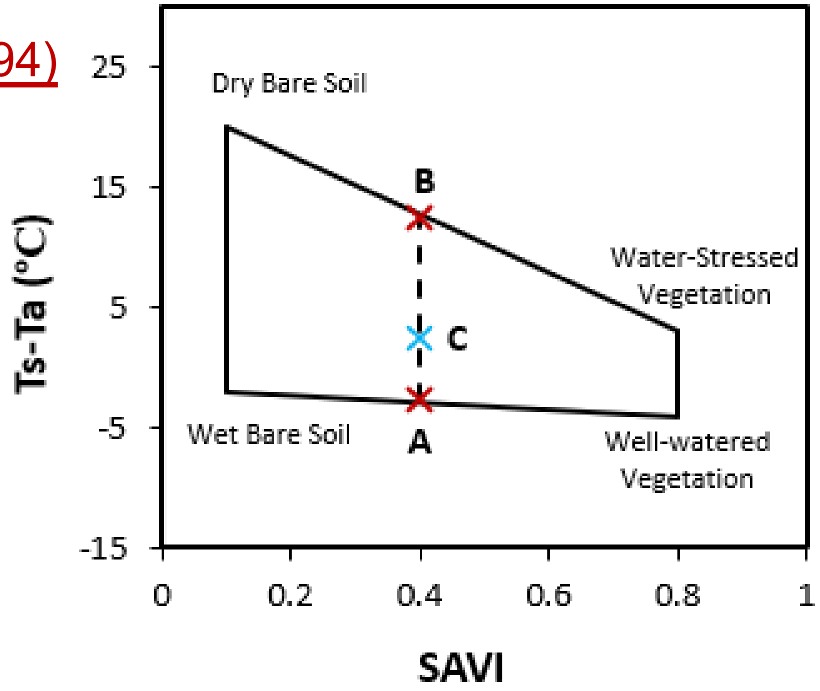
Complex computation of canopy temperature, canopy and aerodynamic resistances for partially vegetated fields

2. Temperature - Vegetation Index Trapezoid – Moran et al. (1994)

$$CWSI = \frac{(T_s - T_a)_m - (T_s - T_a)_r}{(T_s - T_a)_m - (T_s - T_a)_x}$$

T_s : Surface and air temperatures
T_a : Air temperatures

Subscripts: m: Minimum; r: Measured; x: Maximum



Water Flow in Soils and Root Water Uptake

Transient Water Flow in Soil

Richards Equation:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) - S$$

Sink Term

- **Microscopic Approach:** highly complex – vast number of difficult to obtain input parameters for the plant root system are required.
- **Macroscopic Approach:** simpler – less parameters.

1. Specification of spatial distribution of potential root water uptake (depends on atmospheric demand and root distribution).
2. Computation of a reduction to root water uptake due to water stress in dry soil and oxygen deficit in wet soil
3. Calculation of a compensated actual root water uptake rate

$$S_P(z,t) = T_P(t)b(z)$$

$$S_{ru}(z,t) = S_P(z,t).a(t)$$

S_P [T^{-1}] *:* Potential root water uptake
T_P [LT^{-1}] : Potential transpiration rate (*meteorological data and plant parameters*)
b [L]: Normalized root water uptake distribution function (integrates to unity)
S_{ru} [T^{-1}] *:* Reduced root water uptake

$a(t)$: Root water uptake/stress reduction function (low matric potential in dry soil and limited aeration in wet soil)

Root Water Uptake Reduction Function

Feddes et al. (1978)

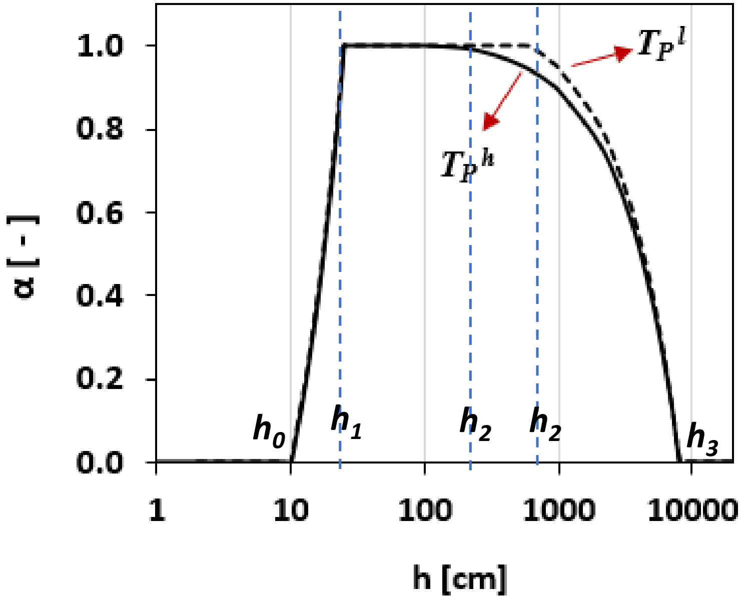
$$\alpha(h)=\begin{cases}0 & h_0 \le h\\ (h-h_0)/(h_1-h_0) & h_1 < h < h_0\\ 1 & h_2 \le h \le h_1\\ (h-h_3)/(h_2-h_3) & h_3 < h < h_2\\ 0 & h \le h_3\end{cases}$$

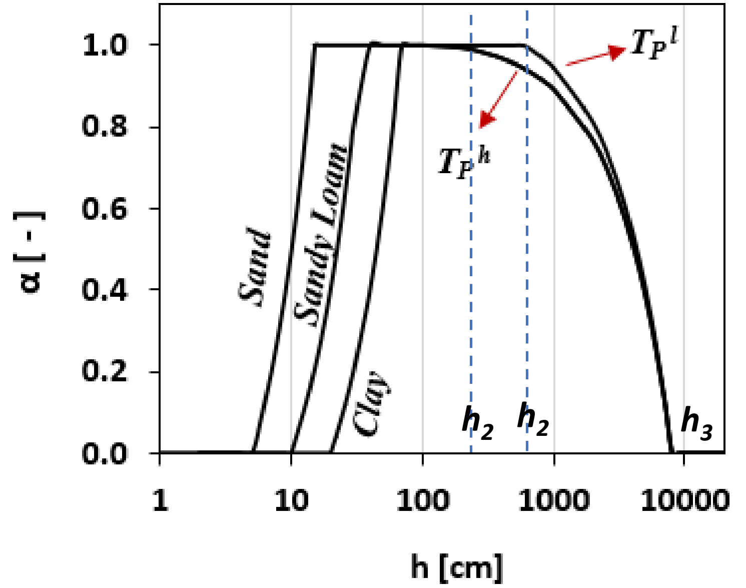
$$h_2(T_p)=\begin{cases}h_2^L & T_p \le r_L\ or\, T_P^l\\ h_2^H+(h_2^L-h_2^H/r_H-r_L)(r_H-T_p) & r_L\ or\ T_P^l < T_p < r_H\ or\ T_P^h\\ h_2^H & T_p \ge r_H\ or\ T_P^h\end{cases}$$

Peters et al. (2017)

$$\alpha_a(\theta_a)=\begin{cases}0 & \theta_a \le \theta_{a,c}\\ \theta_a-\theta_{a,c}/\theta_{a,o}-\theta_{a,c} & \theta_{a,c} < \theta_a < \theta_{a,o}\\ 1 & \theta_a \ge \theta_{a,o}\end{cases}$$

$$\alpha_d(h)=\begin{cases}0 & h \le h_3\\ h-h_3/h_2-h_3 & h_3 < h < h_2\\ 1 & h \ge h_2\end{cases}$$





Quantification of Crop Water Stress

$$a_t(\theta_a, h) = a_a(\theta_a).\,a_d(h)$$

a_t: total stress due to oxygen deficit in wet soil and low matric potential in dry soil

Proposed Crop Water Stress Index (CWSI)

$$CWSI(\theta_a, h, T_p) = [1 - \alpha_t(\theta_a, h, T_p)] \times 100$$

CWSI Range	Water Stress Class
> 80%	Extremely High
60 – 80 %	High
40 – 60 %	Medium to High
20 – 40 %	Low to Medium
10 – 20 %	Low
< 10 %	No Stress

Quantifying Soil Matric Potential

Hydraulic Soil Properties

Van Genuchten (1980):

$$S_r = [1 + |ah|^n]^{\frac{1}{n}-1}$$

$$h = \frac{1}{\alpha}\left[S_r^{-\frac{1}{m}} - 1\right]^{\frac{1}{n}}$$

Soil Moisture Estimation with Modified Optical Trapezoid Model – Sadeghi et al. (2017)

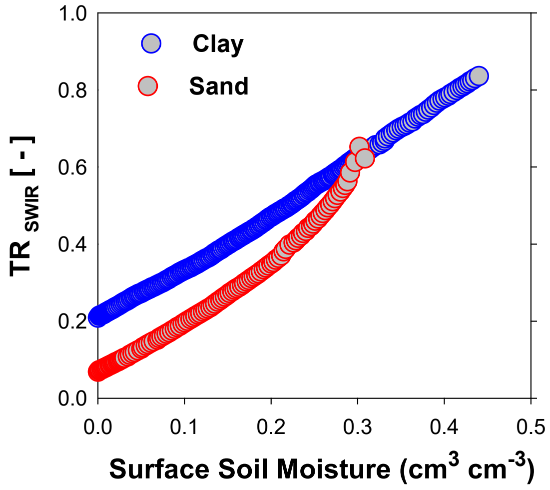
$$S_r = \frac{\theta - \theta_{dry}}{\theta_{wet} - \theta_{dry}} = \frac{TR_{SWIR} - TR_{SWIR,dry}}{TR_{SWIR,wet} - TR_{SWIR,dry}}$$

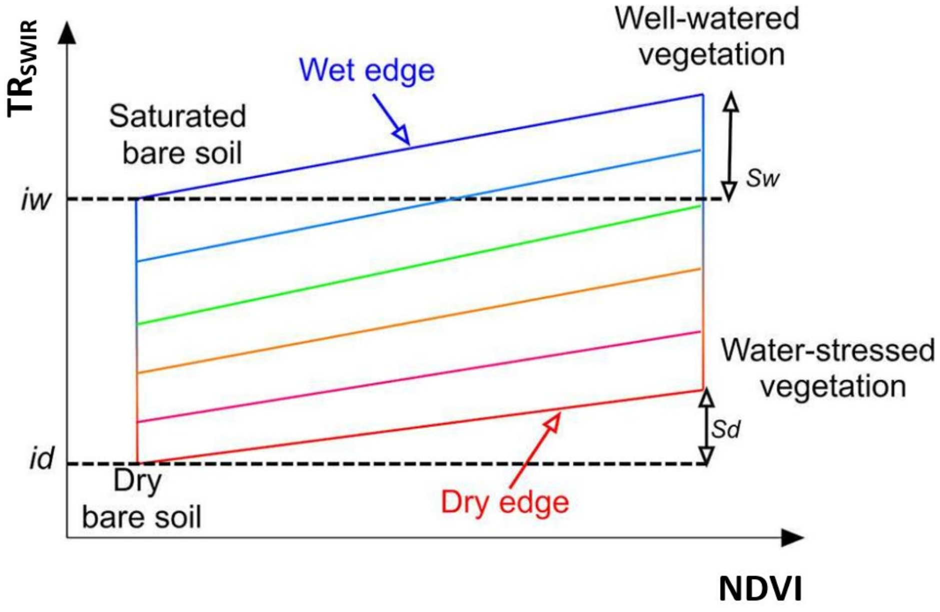
$$TR_{SWIR} = \frac{(1 - R_{SWIR})^2}{2R_{SWIR}}$$

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}}$$

$$S_r = \frac{TR_{SWIR} - exp(s_{d,1} NDVI^{s_{d,2}}) + (i_d - 1)}{exp(s_{w,1} NDVI^{s_{w,2}}) - exp(s_{d,1} NDVI^{s_{d,2}}) + (i_w - i_d)}$$

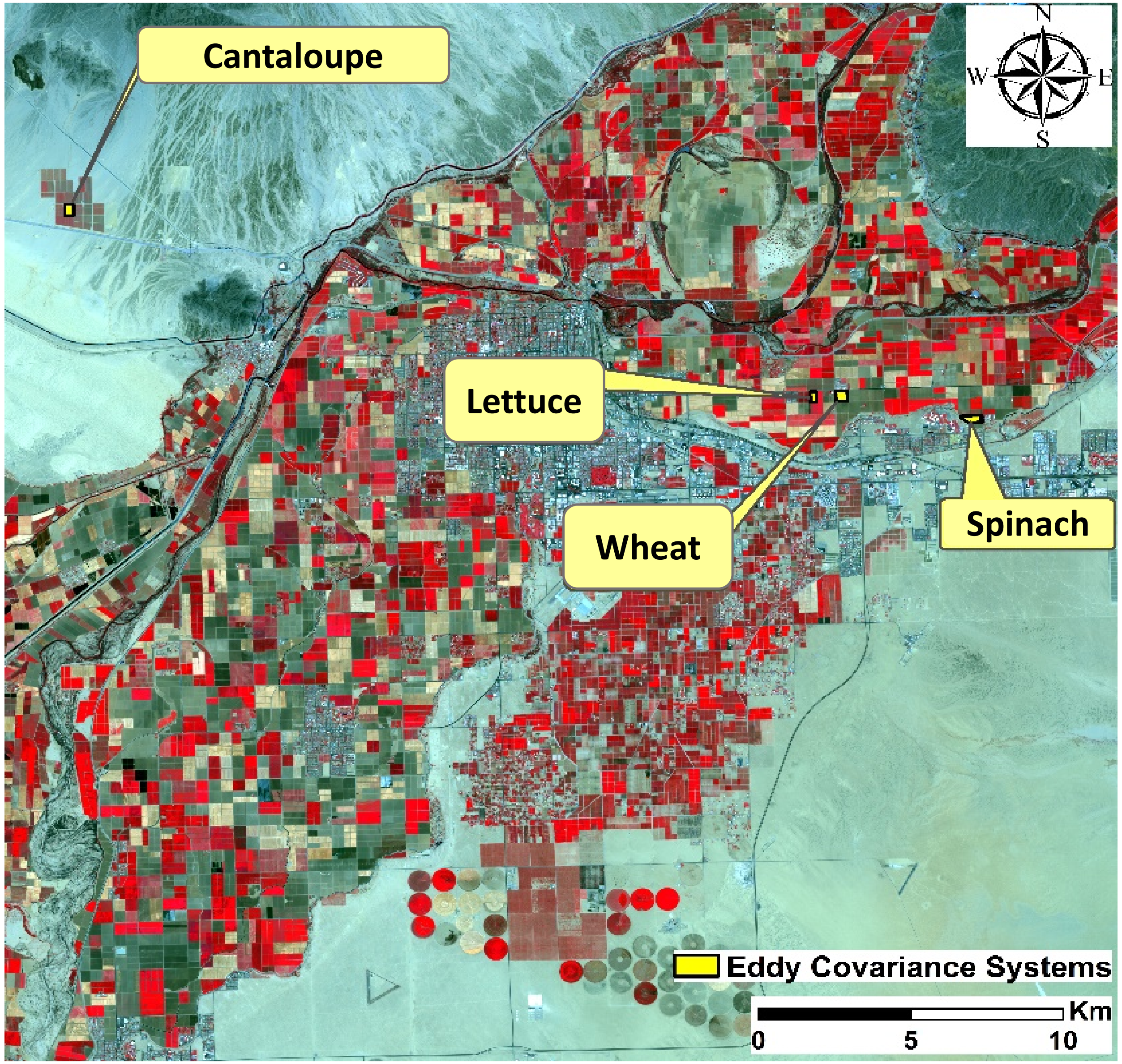
Sadeghi et al. (2015)





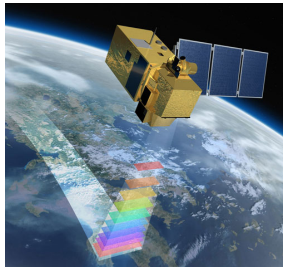
Selected Fields and Crops

- Lettuce
- Spinach
- Cantaloupe
- Wheat



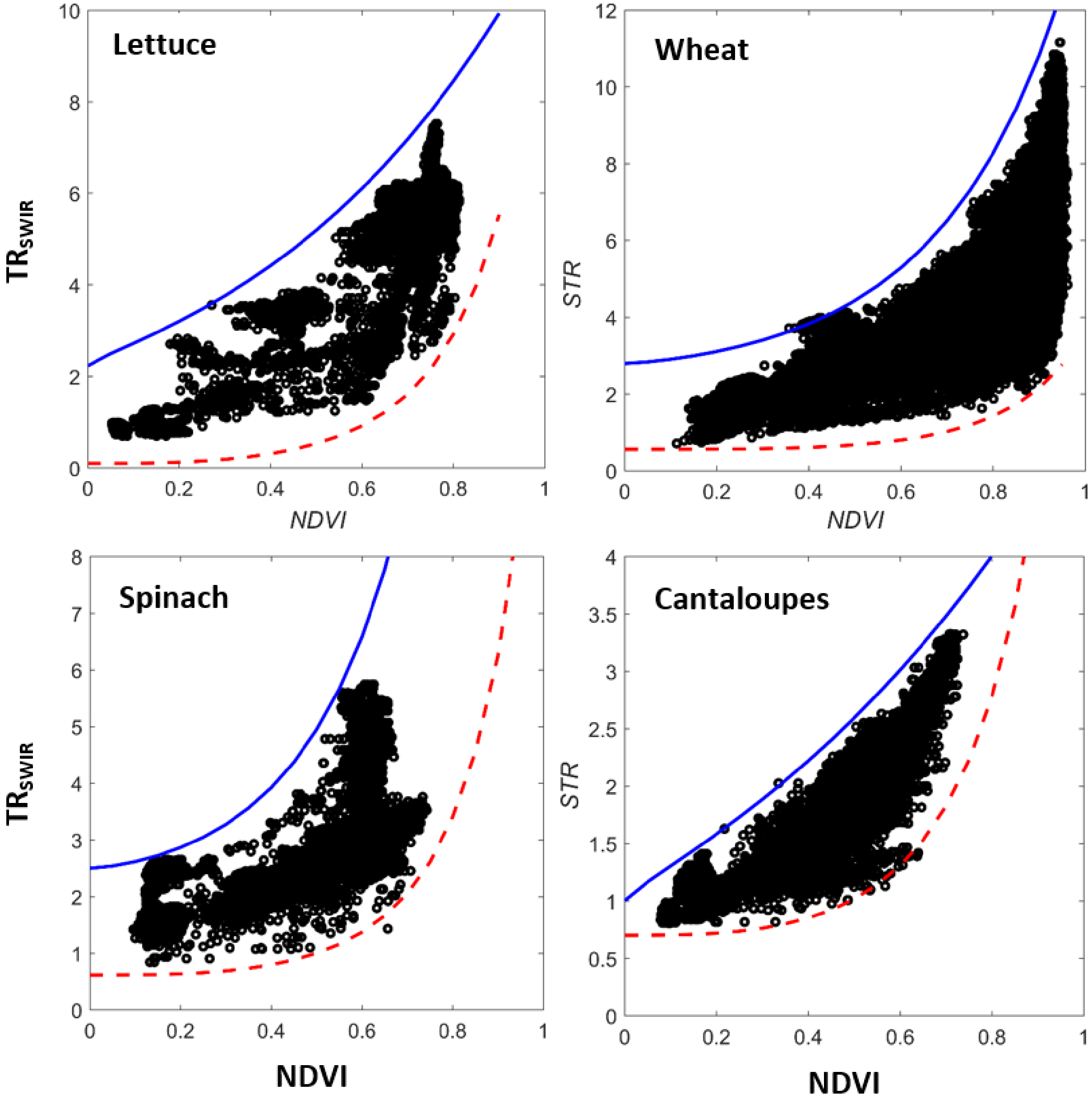
Soil Moisture Estimation – Optical Method

- **Sentinel-2AB Satellite Data**
  - Bands 12, 8, 4
  - Spatial and temporal resolution: 10-20m and ~5 days

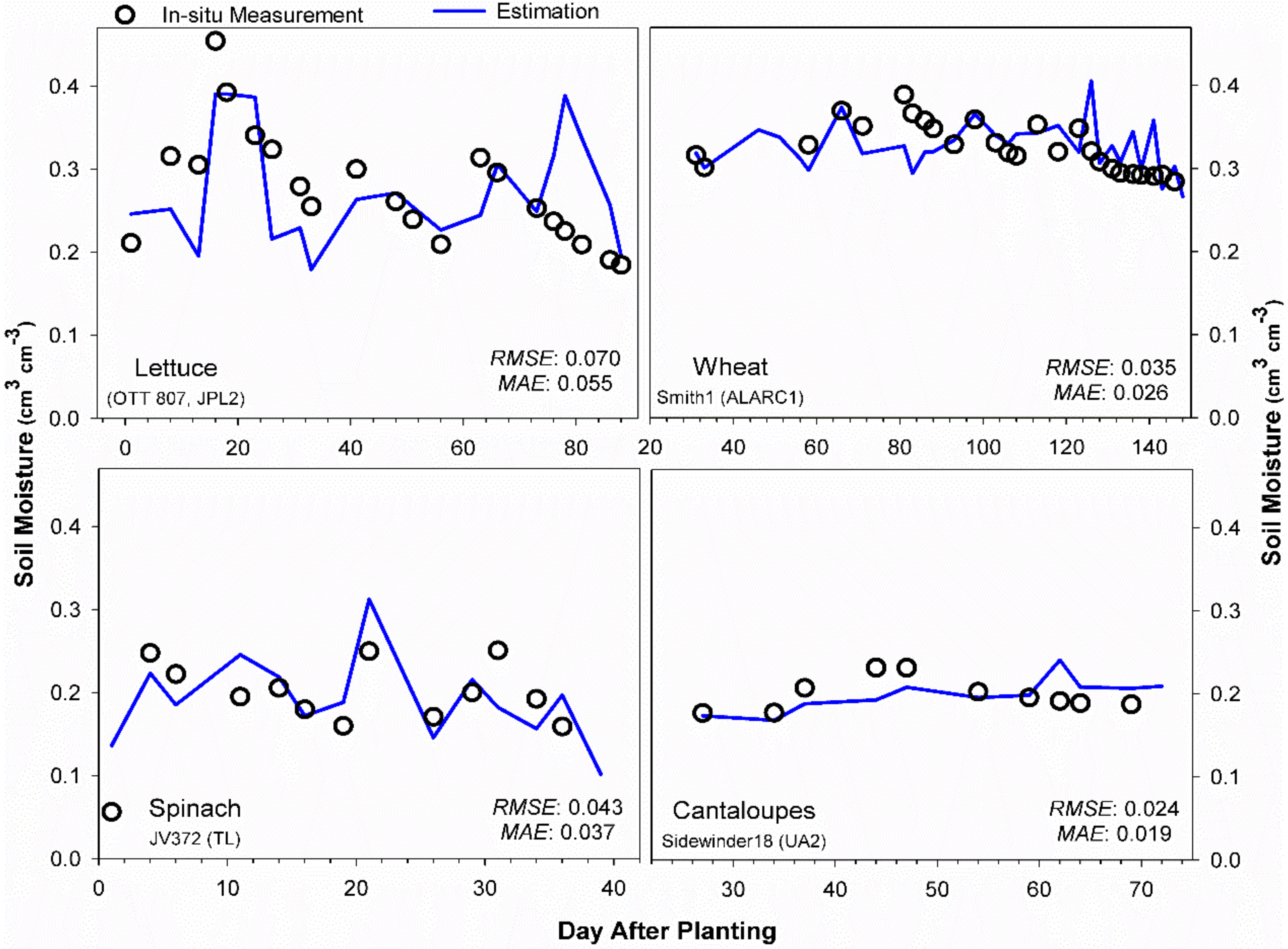


- **Parameterization of the Optical Model**
  - Fitting nonlinear functions to the upper and lower edges of the feature space
  - Determining the model parameters
  - Estimate S_r for all pixels with known TR_{SWIR} and NDVI:

$$S_r = \frac{TR_{SWIR} - exp(s_{d,1} NDVI^{s_{d,2}}) + (i_d - 1)}{exp(s_{w,1} NDVI^{s_{w,2}}) - exp(s_{d,1} NDVI^{s_{d,2}}) + (i_w - i_d)}$$

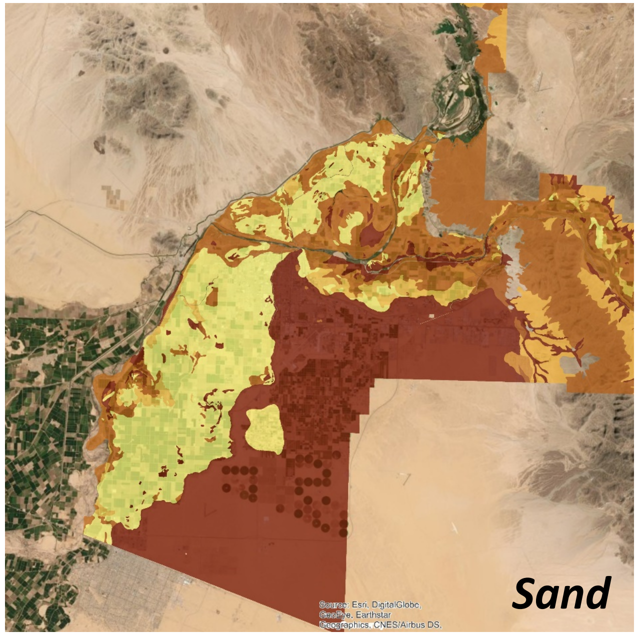


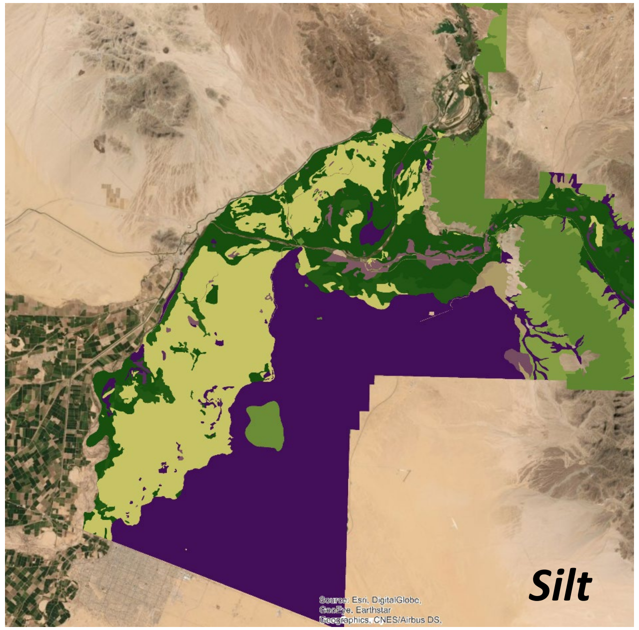
Validation of Remotely Sensed Soil Moisture

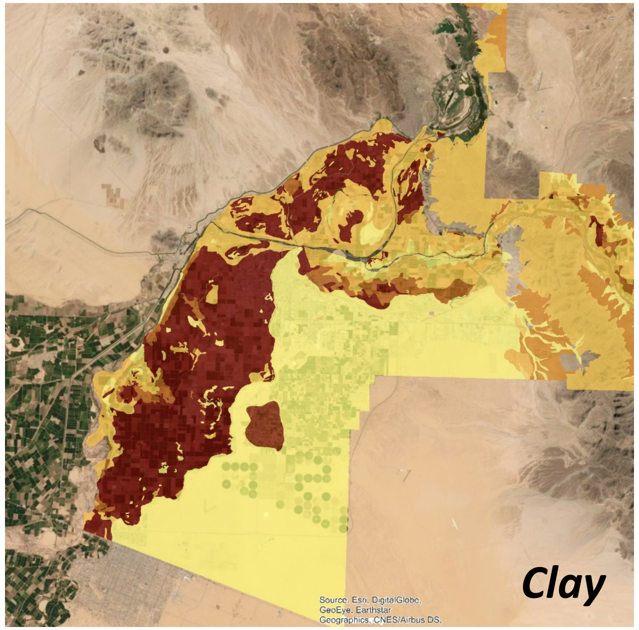


Soil Basic Parameters

- **Soil physical properties from the GSSURGO** (USDA-NRCS) **database**





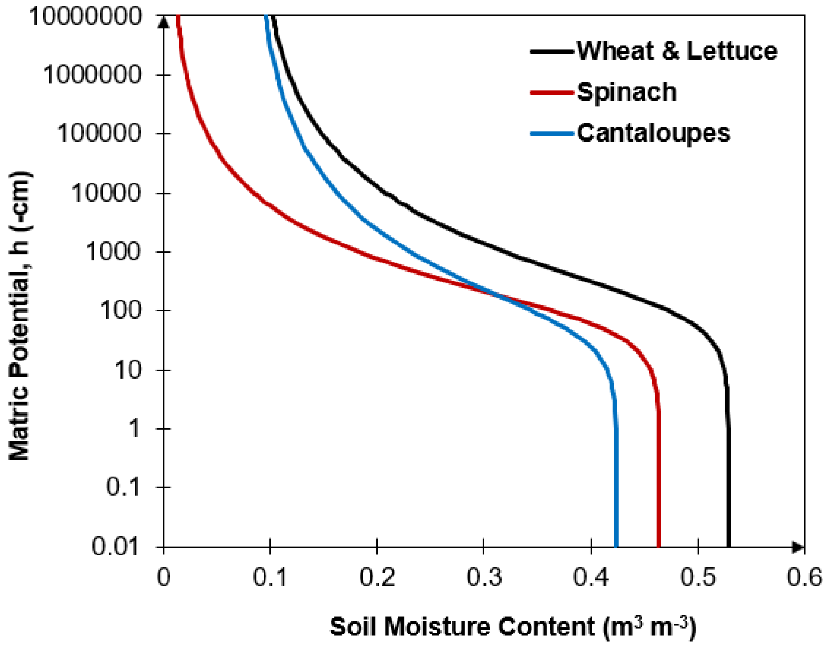


Field ID (Station ID)	Crop Type	Planting Date	Harvesting Date	Clay (%)	Silt (%)	Sand (%)	ρ_b (g cm^{-3})	θ_{FC} (cm^3 cm^{-3})	θ_{PWP} (cm^3 cm^{-3})
Smith1 (ALARC1)	Wheat	5 Jan. 18	31 May 18	50	27.9	22.1	1.22	0.426	0.263
OTT807 (JPL2)	Iceberg	8 Oct. 18	4 Jan. 19	50	27.9	22.1	1.22	0.426	0.263
JV372 (TL)	Spinach	4 Mar. 19	9 Apr. 19	31	62.3	6.7	1.25	0.303	0.158
Sidewinder18 (UA2)	Cantaloupes	22 Aug. 18	29 Oct. 18	31	62.3	6.7	1.25	0.303	0.158

Hydraulic Soil Parameters

- **The van Genuchten (1980) SWC model parameters were obtained from Rosetta Pedotransfer Functions** – Schaap et al. (2001)

Field ID (Station ID)	Crop Type	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	a (cm^{-1})	n (-)	K_s (cm d^{-1})
Smith1 (ALARC1)	Wheat	0.0855	0.529	0.0087	1.289	23.97
OTT807 (JPL2)	Iceberg	0.0855	0.529	0.0087	1.289	23.97
JV372 (TL)	Spinach	0.0667	0.464	0.0139	1.360	22.88
Sidewinder18 (UA2)	Cantaloupes	0.0841	0.424	0.0202	1.277	10.38



Root Water Uptake & Stress Function

- **Root water uptake reduction function parameters** – Wesseling et al. (1991)

Field ID (Station ID)	Crop	h_0 (cm)	h_1 (cm)	h_{2H} (cm)	h_{2L} (cm)	h_3 (cm)	r_{2H} (cm d^{-1})	r_{2L} (cm d^{-1})
Smith1 (ALARC1)	Wheat	0	-1	-500	-900	-16000	0.5	0.1
OTT807 (JPL2)	Iceberg	-10	-25	-400	-600	-8000	0.5	0.1
JV372 (TL)	Spinach	-10	-25	-400	-600	-8000	0.5	0.1
Sidewinder18 (UA2)	Cantaloupes	-10	-25	-350	-450	-8000	0.5	0.1

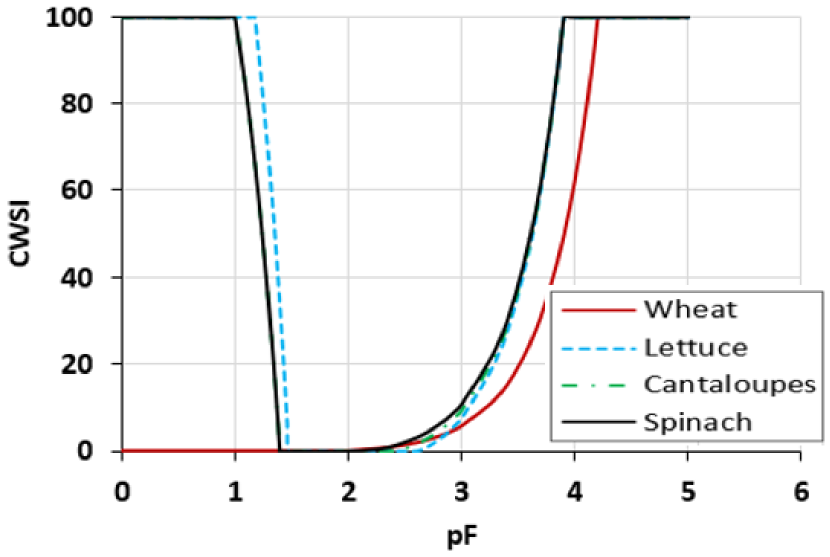
Wheat: r_2 or ET=0.9 cm d^{-1} ➔ h_2=-100 cm

Iceberg: r_2 or ET=0.6 cm d^{-1} ➔ h_2=-422 cm

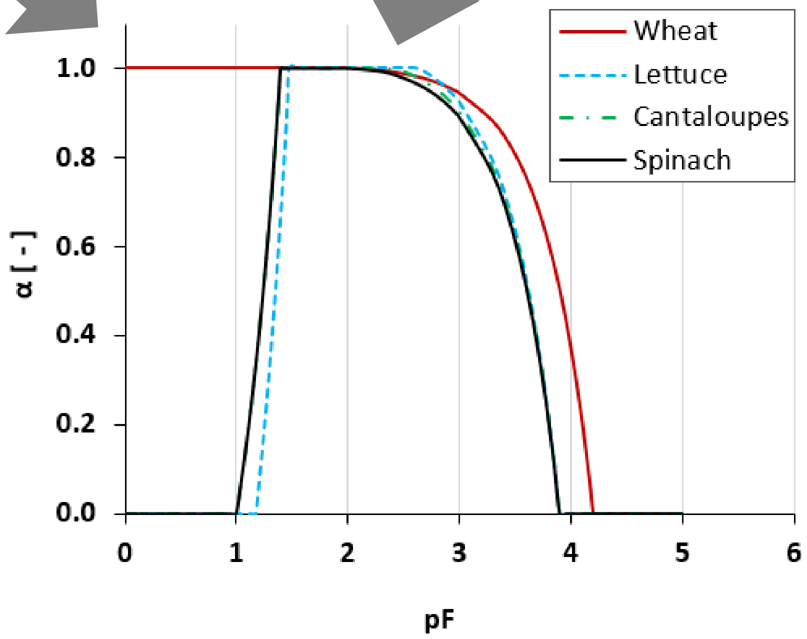
Spinach: r_2 or ET=1.0 cm d^{-1} ➔ h_2=-145 cm

Cantaloupes: r_2 or ET=0.85 cm d^{-1} ➔ h_2=-262 cm

For specific date

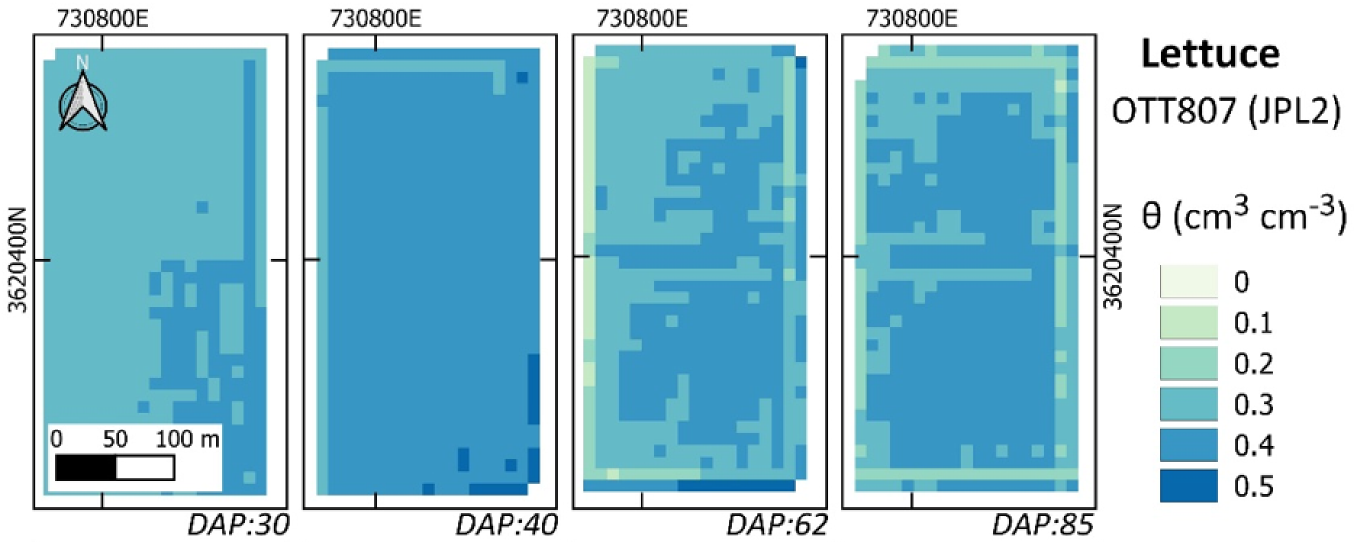


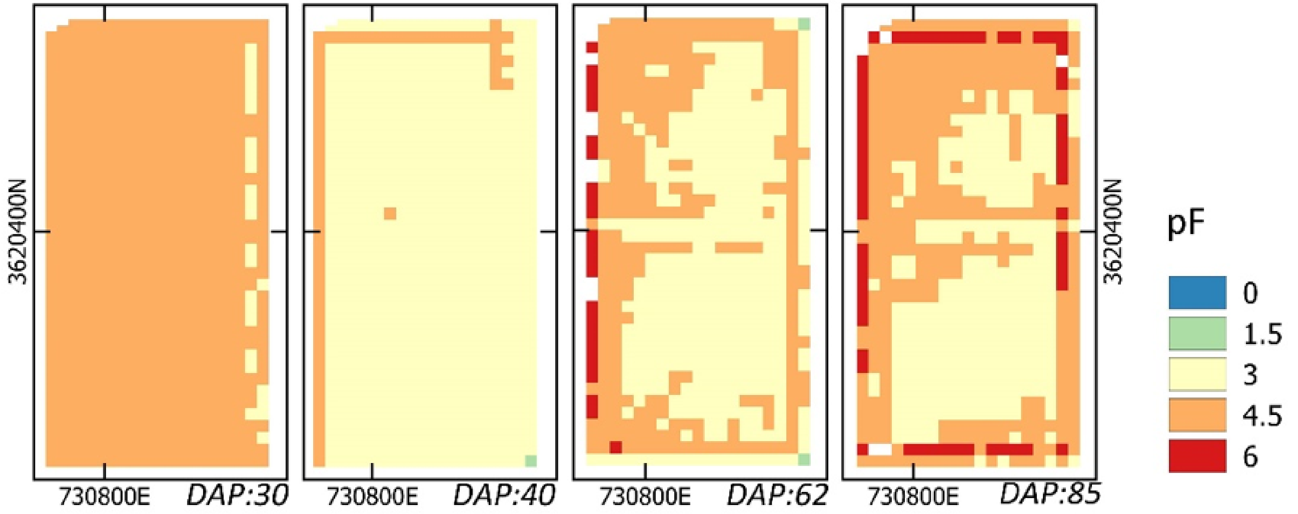
$$CWSI(h,T_p) = [1-\alpha_t(\theta_a,h,T_p)]\times 100$$



Spatiotemporal Dynamics of Soil Moisture, Matric Potential, and CWSI

Volumetric Water Content (cm^3 cm^{-3})

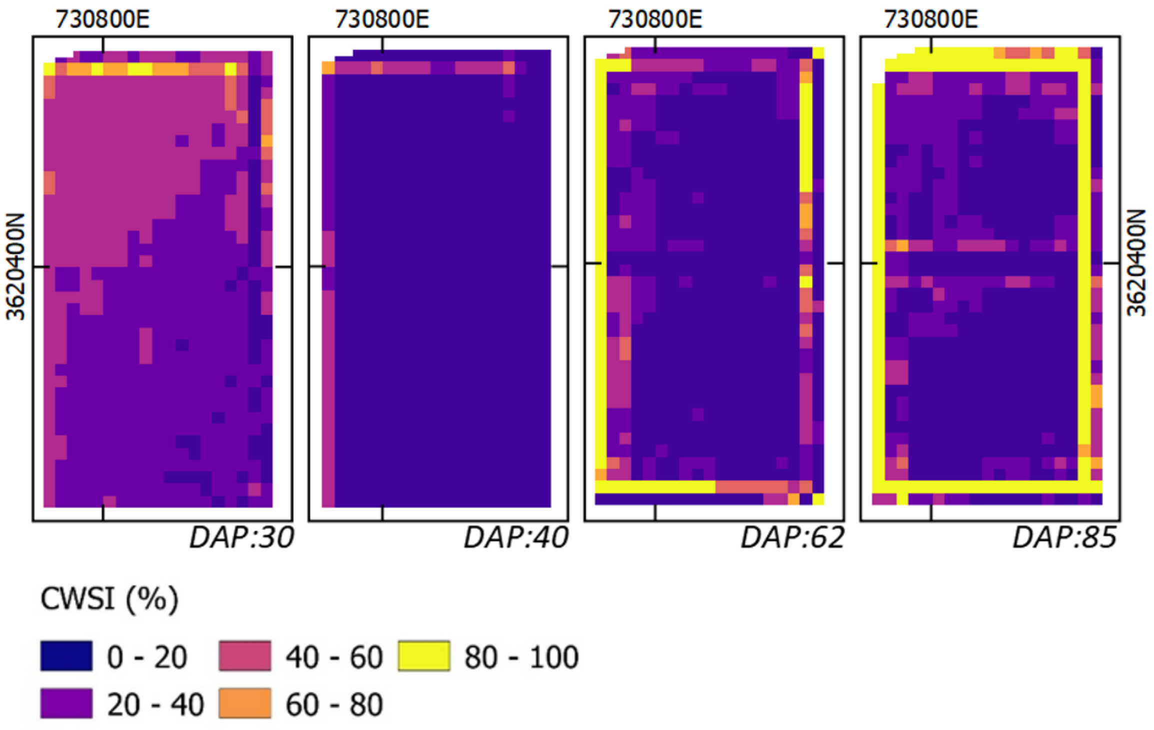




Matric Potential (pF = $\log_{10}$|-cm H_2O|)

Lettuce

Crop Water Stress Index (%)



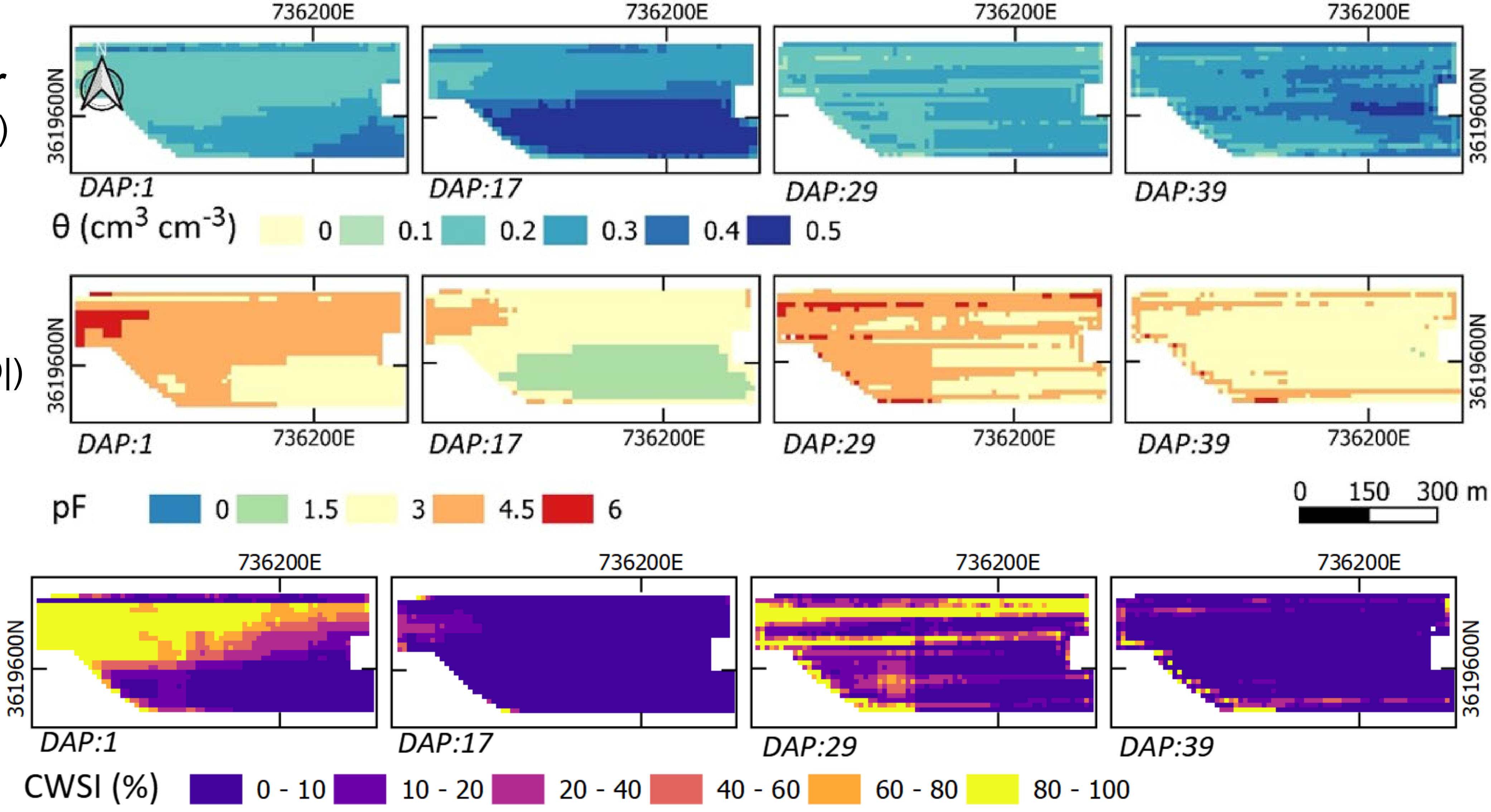
Spatiotemporal Dynamics of Soil Moisture, Matric Potential, and CWSI

Spinach

Volumetric Water Content (cm^3 cm^{-3})

Matric Potential
(pF = $\log_{10}$|-cm H_2O|)

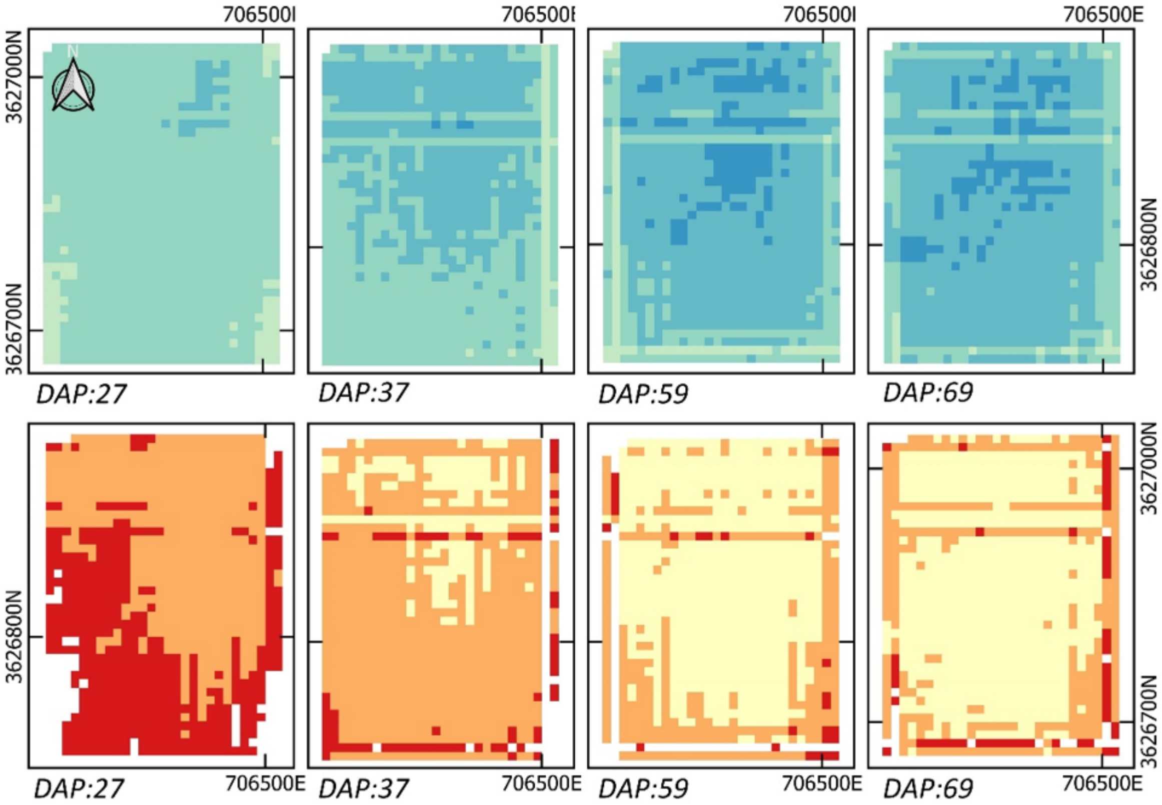
Crop Water Stress Index (%)

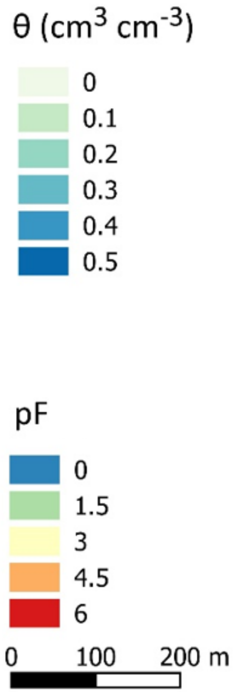


Spatiotemporal Dynamics of Soil Moisture, Matric Potential, and CWSI

Cantaloupe

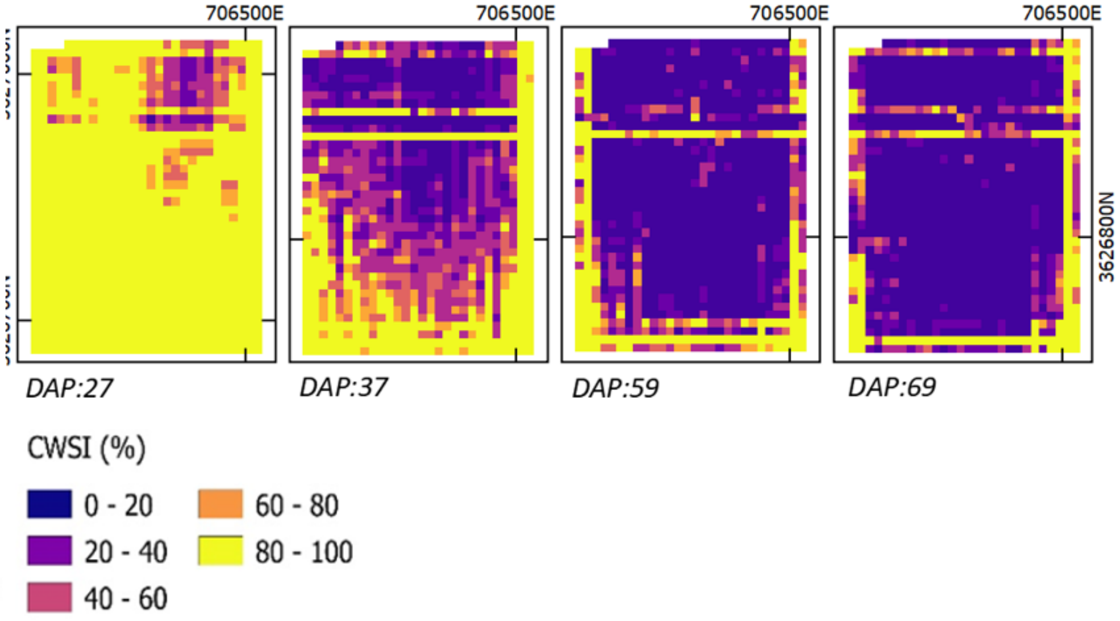
Volumetric Water Content ($cm^3\ cm^{-3}$)





Matric Potential (pF = $\log_{10}$|-cm H_2O|)

Crop Water Stress Index (%)

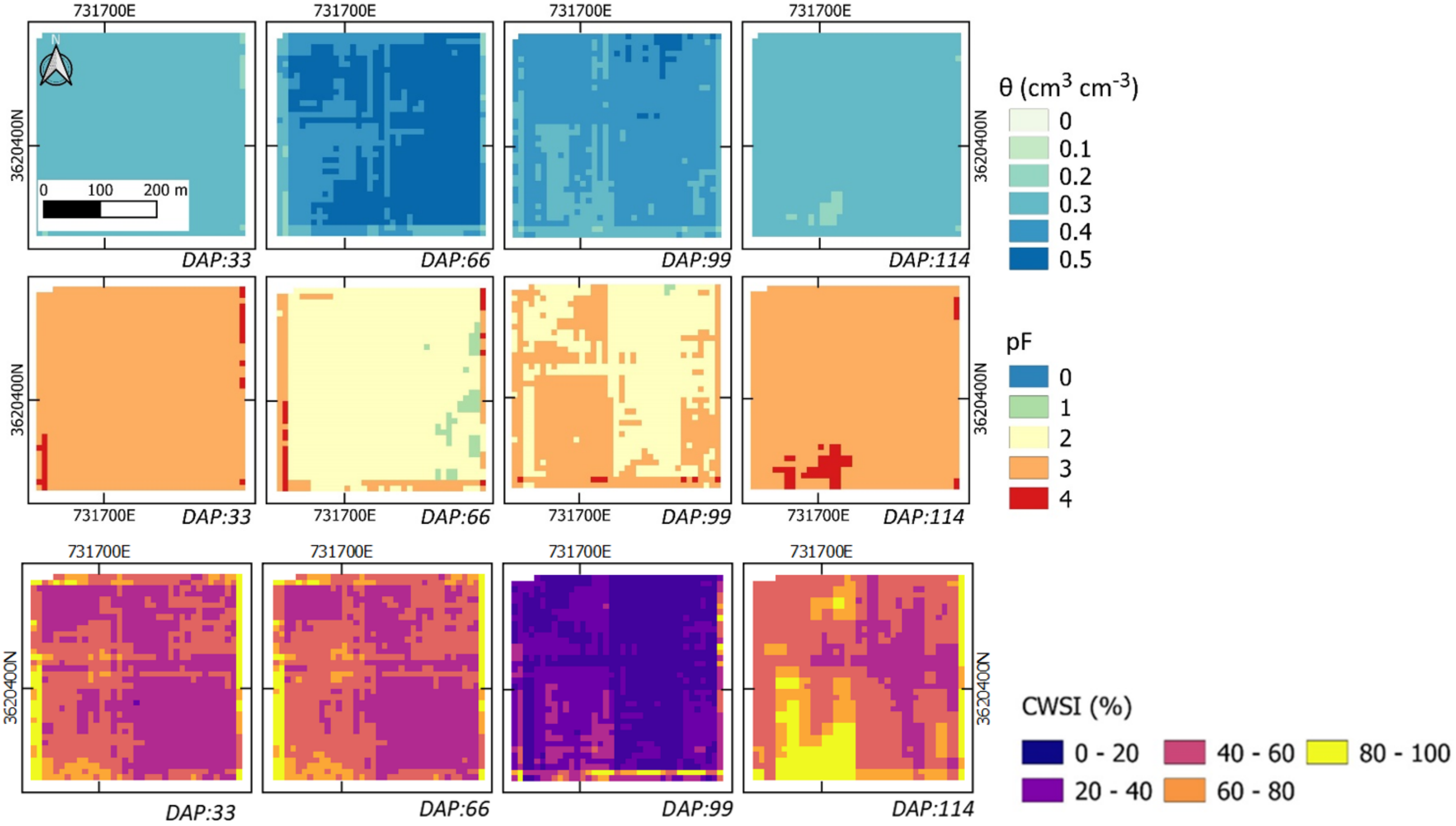


Wheat

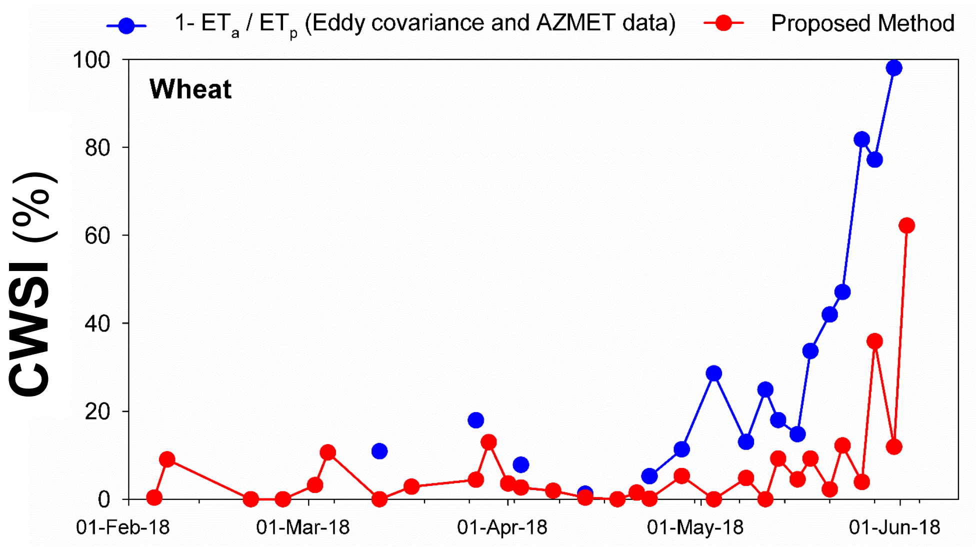
Volumetric Water Content (cm^3 cm^{-3})

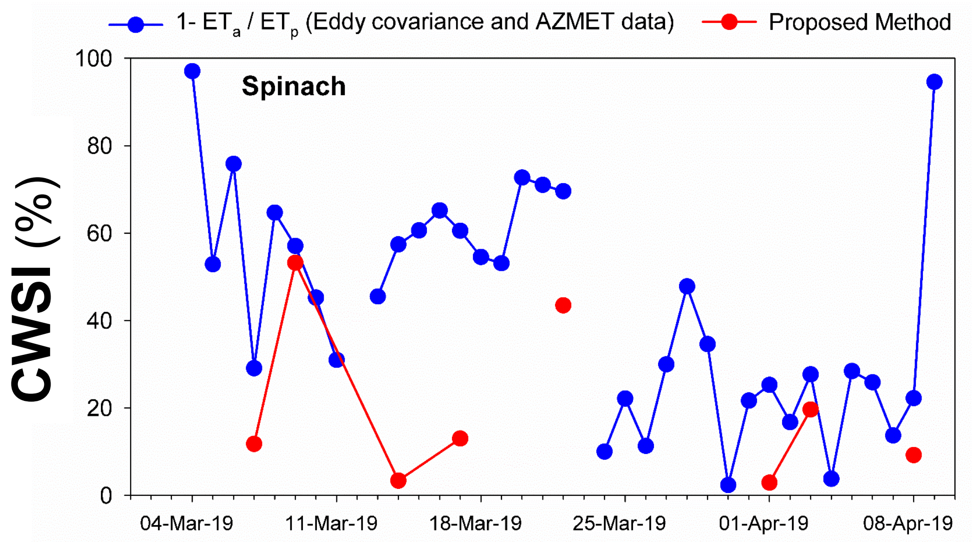
Matric Potential
(pF = $\log_{10}$|-cm H_2O|)

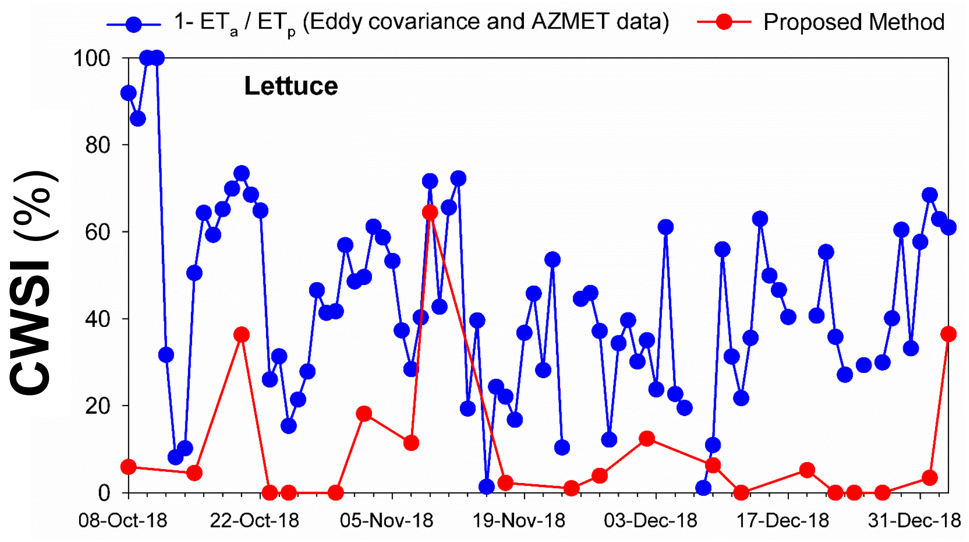
Crop Water Stress Index (%)



Comparison of Estimated CWSI with CWDI from Eddy Covariance Data







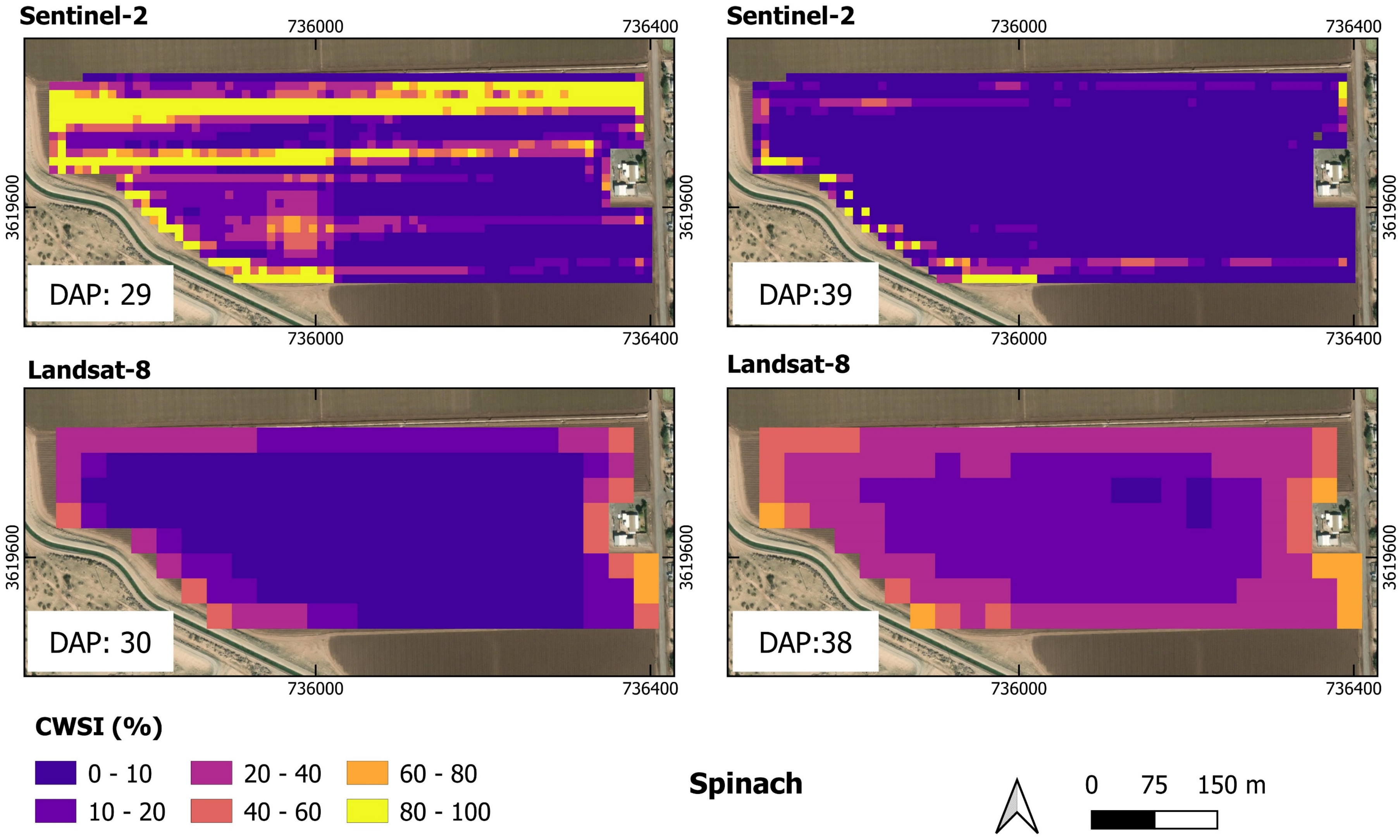
CWSI Range	Water Stress Class
> 80%	Extremely High
60 – 80 %	High
40 – 60 %	Medium to High
20 – 40 %	Low to Medium
10 – 20 %	Low
< 10 %	No Stress

Sentinel-2 CWSI vs. Landsat-8 CWDI

Spinach

$$CWSI(h, \theta_a, T_p) = [1 - \alpha_t(\theta_a, h, T_p)] \times 100$$

$$CWDI = 1 - \frac{\lambda E_\Gamma}{\lambda E_{\Gamma P}}$$

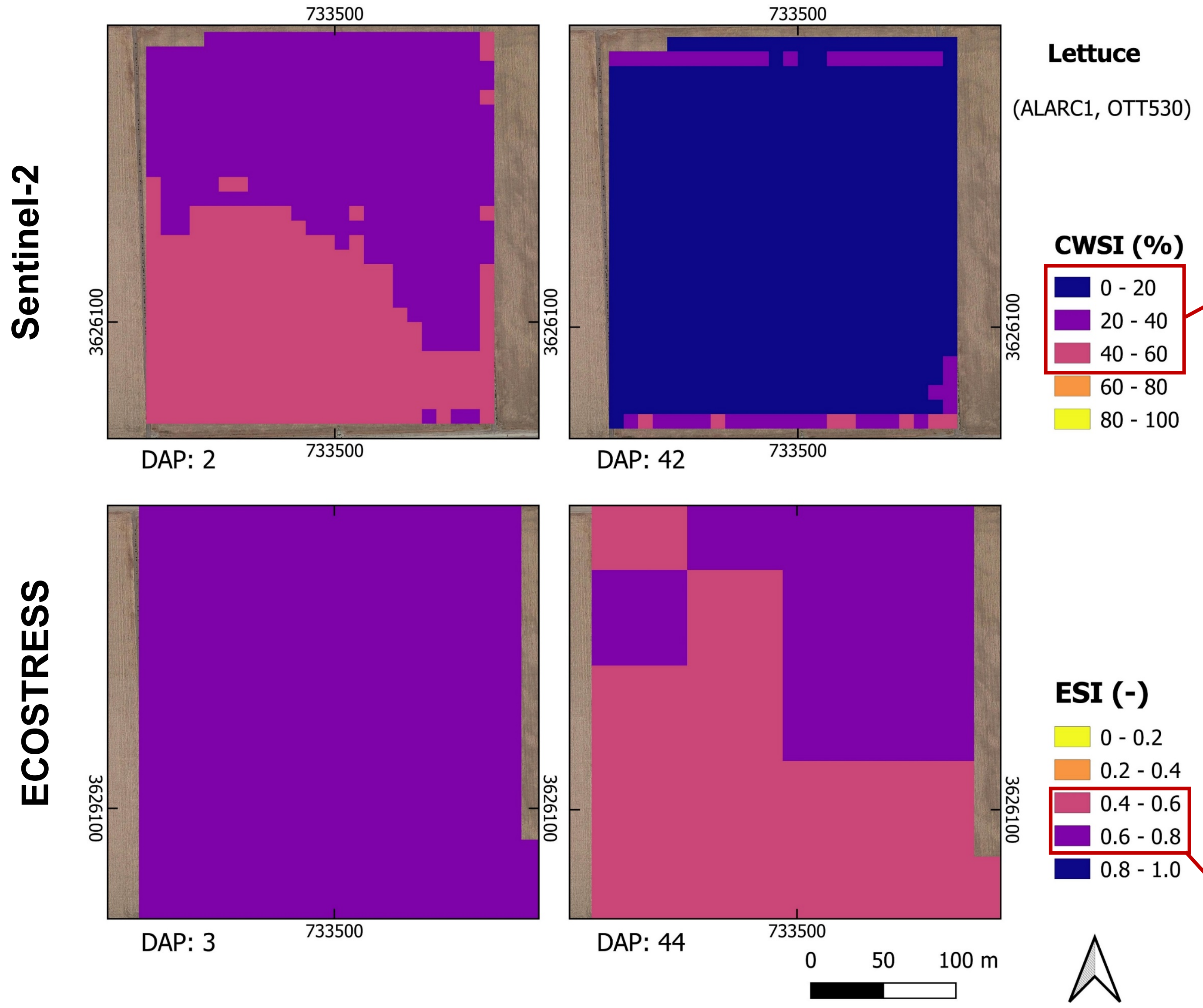


Sentinel-2 CWSI vs. ECOSTRESS ESI

Lettuce

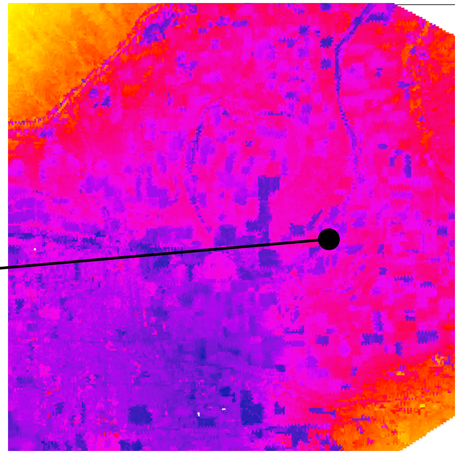
$$CWSI(h, \theta_a, T_p) = [1 - \alpha_t(\theta_a, h, T_p)] \times 100$$

$$ESI = \frac{\lambda E_\Gamma}{\lambda E_{\Gamma P}}$$



No Stress to Medium Stress

ECOSTRESS Satellite Evaporative Stress Index



Low Stress to Medium Stress

Conclusions and Outlook

- The modified optical trapezoid model shows promising potential for farm scale estimation of soil moisture variability.
- The new CWSI is obtained from remotely sensed soil moisture, hydraulic soil parameters and evapotranspiration rate.
- Pending further refinements and tests for a vast variety of crops, the new CWSI seems to be a great alternative means for crop water stress characterization and monitoring under full crop cover and for partially vegetated soils.
- The presented approach can be applied in conjunction with Unmanned Aerial System observations to assist with farm scale precision irrigation management and improve water use efficiency of cropping systems.

Acknowledgments

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