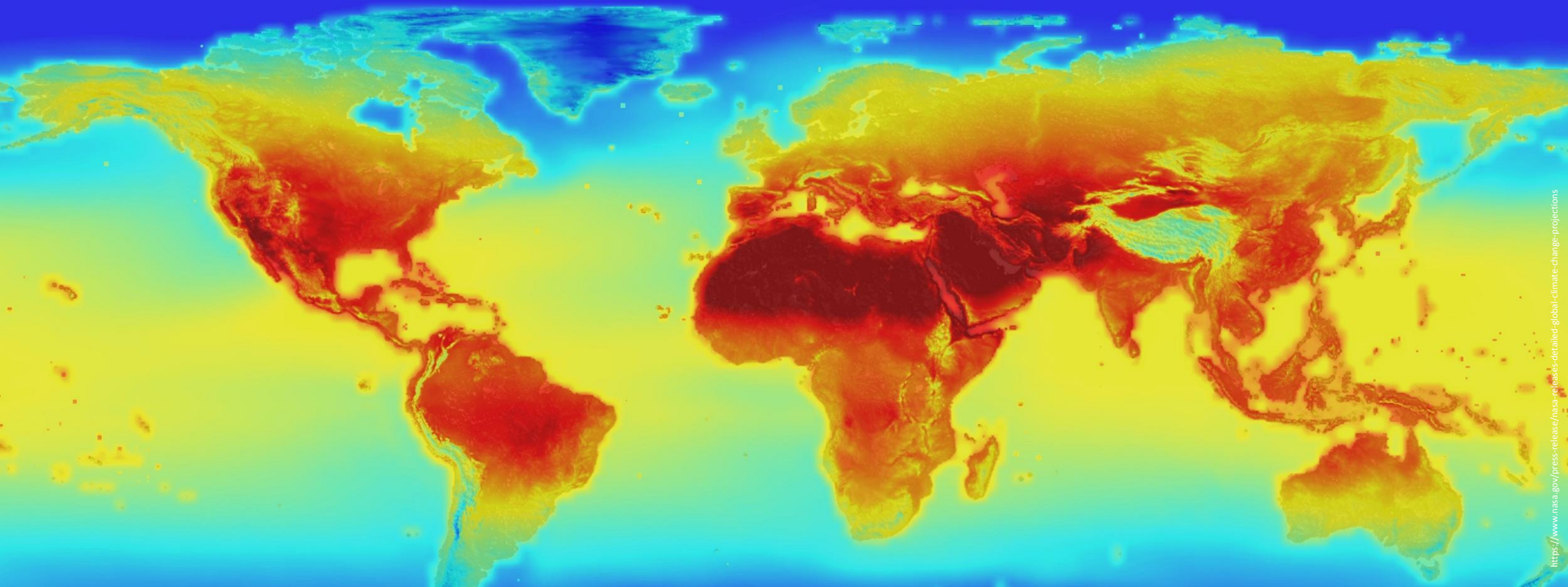




<https://www.nasa.gov/press-release/nasa-releases-detailed-global-climate-change-projections>

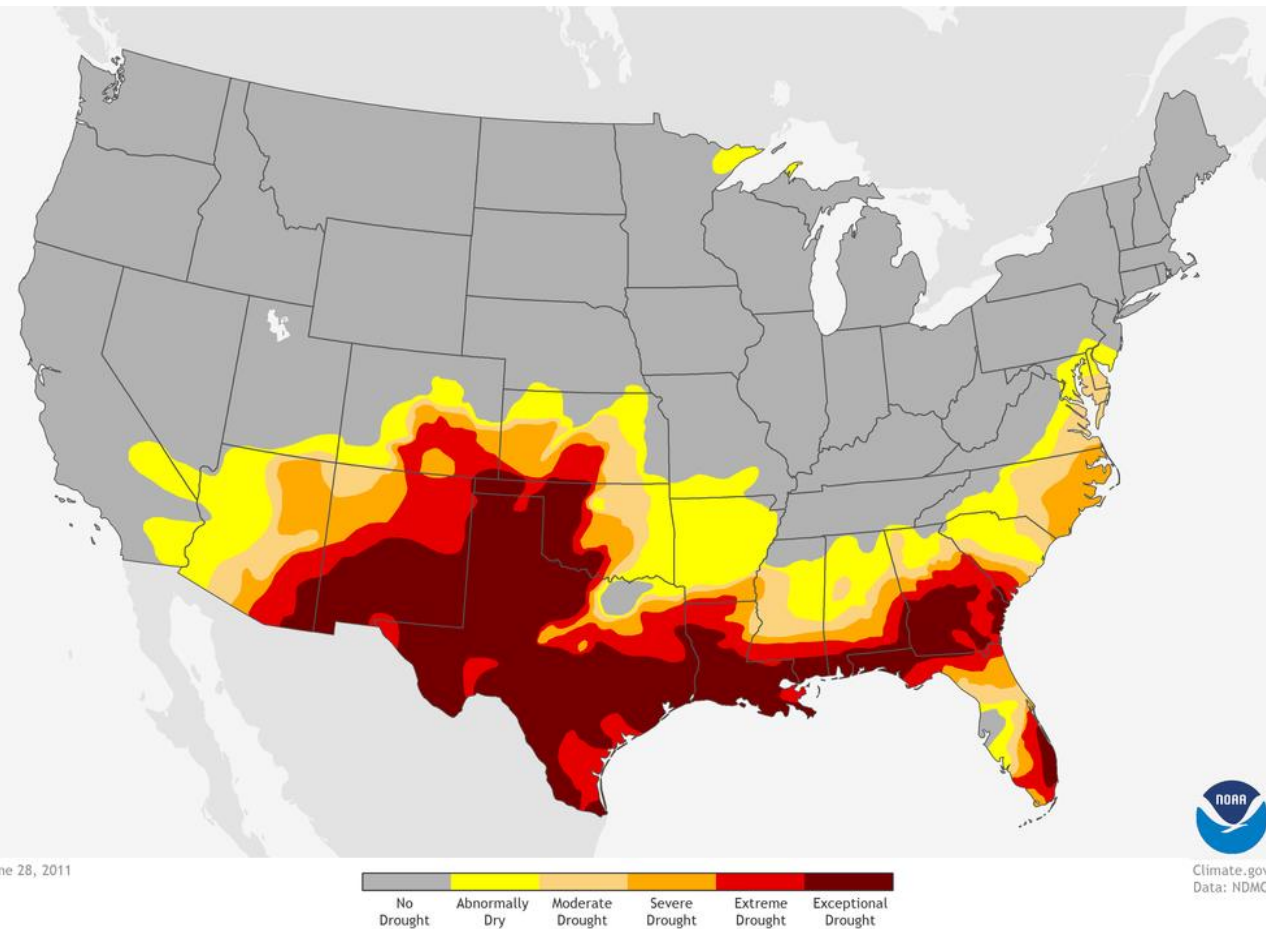
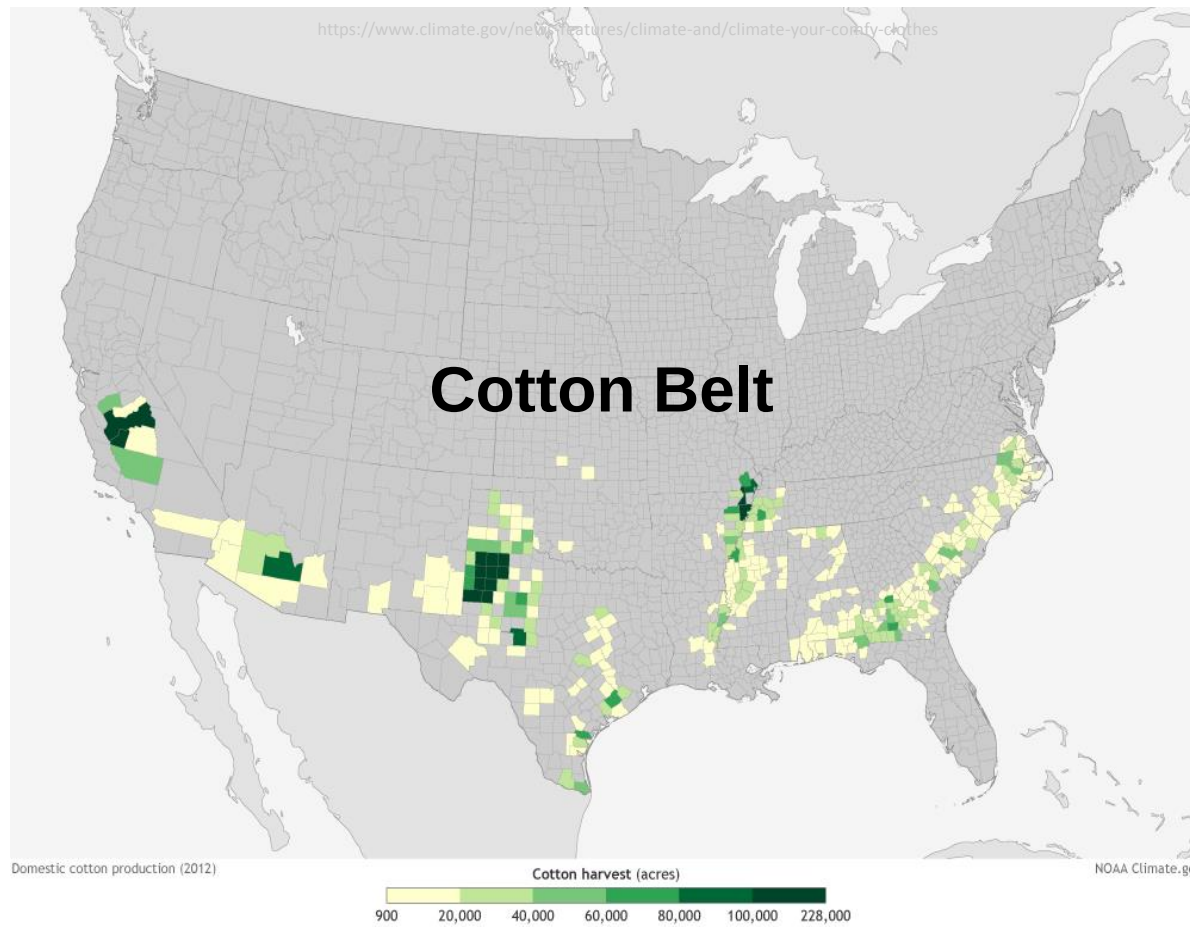
Integration of Phenomics and Quantitative Genetics to Improve Cotton Resiliency

Duke Pauli, PhD
Cotton Inc. Fellow, Gore Lab, Cornell University
(University of Arizona, Jan 1st, 2018)

2017 Cotton Breeders' Tour



Sustainable agricultural production is threatened by increasingly variable weather patterns and diminishing fresh water



- Drought of 2011, 2.2 billion dollar economic loss in cotton production
- 55% of planted acres abandoned
- Global data supports same pattern in other cotton producing regions
- **Challenge: Developing drought and heat stress tolerant varieties**

Plant breeding as a solution

- The drought “phenotype” is a whole plant response
 - A phenotype entirely reliant on the environment in which it is expressed
 - No “single gene” solution
- Improvement must be at the whole plant level
 - Understand the underlying biology and genetics of stress-responsive traits
- Integrate physiology and genetics to increase genetic gain and more efficiently develop stress resilient cultivars

$$\text{YIELD} = \text{WU} \times \text{WUE} \times \text{HI}$$

Photo-Protection

Leaf morphology

- wax/pubescence
- posture/rolling

Pigments

- chl a:b
- carotenoids

Partitioning (HI)

Partitioning to stem carbohydrates

Harvest index

- *Rht* alleles

Transpiration Efficiency

WUE of leaf photosynthesis

- low 12/13C discrimination

Water Uptake (WU)

Rapid ground cover

- protects soil moisture

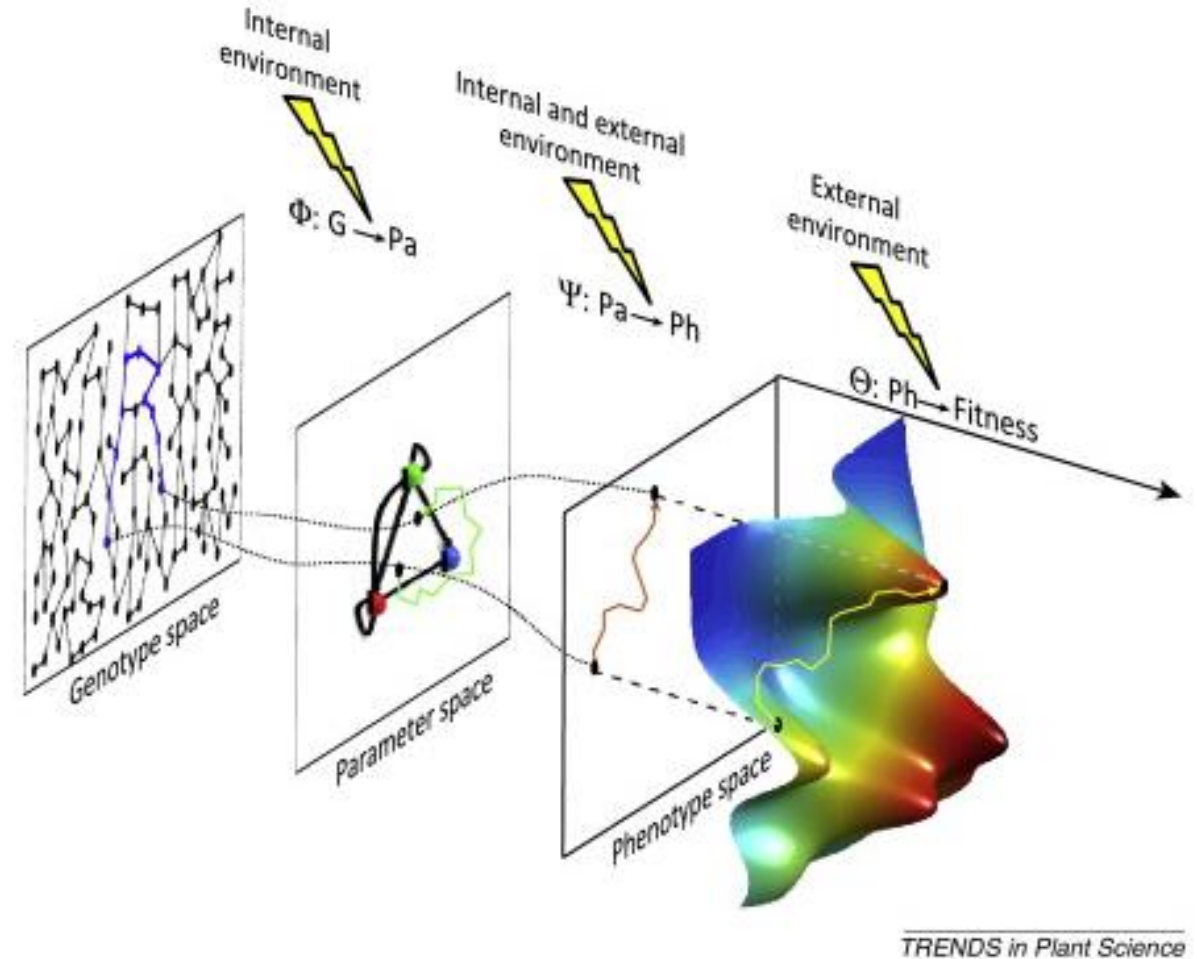
Access to water by roots

- cool canopy



Genetics of abiotic stress tolerance

- Can we collect meaningful, physiologically relevant data under field conditions?
- Is there exploitable variation for stress-adaptive traits in cotton?
- What is the temporal basis of QTL expression patterns in cotton?
- Can physiological traits predict agronomic traits?



High-Throughput Phenotyping (HTP) is essential

- Evaluate plants under field conditions (imperative for drought research)
- Measure throughout trait development
- Utilize larger populations
- Lower cost and minimized subjectivity

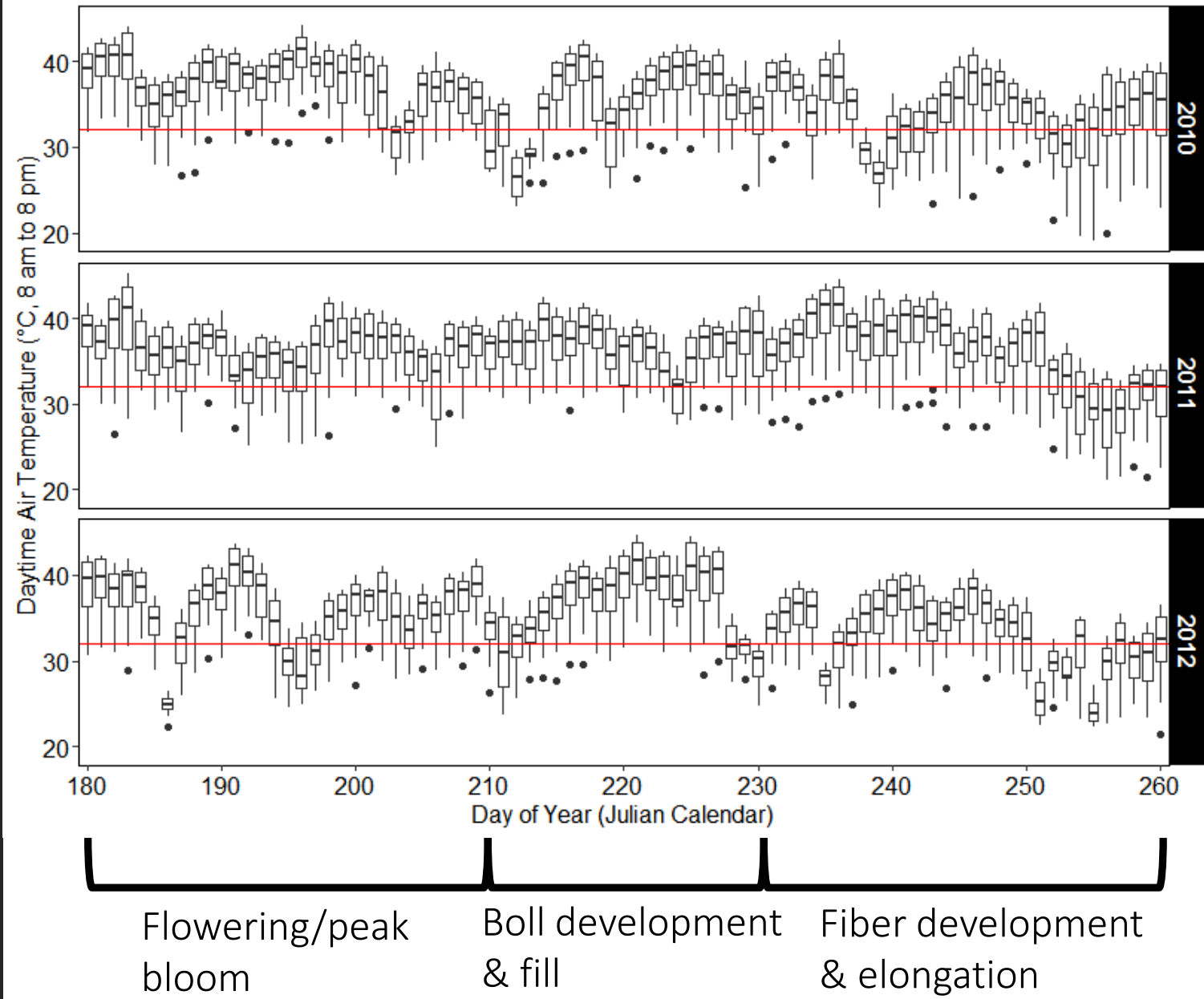




HTP Field Experiment at
MAC/USDA-ARS in
Maricopa, AZ

HTP Experimental Design

- **Maricopa Agricultural Center:** clear skies, limited rain, high temperatures
- **Managed Stress:** Precision irrigation provided consistent drought and heat conditions
- **Two Irrigation Regimes:**
 - Water-limited (Dry, 50% daily ET)
 - Well-watered (Wet, 100% daily ET)
 - Drip irrigation, FAO-56 Crop ET model for wet and dry regimes
 - Subsurface drip irrigation
 - Initiated at flowering

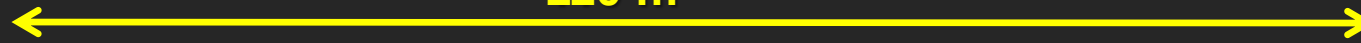


Red line at 32°C is the temperature at which yields are significantly impacted

HTP Experimental Design

- TM-1×NM24016 mapping population
 - 95 recombinant inbred lines (RILs)
 - Community resource
 - TM-1 is the reference genome
- Field design, arranged as (0,1) alpha lattice
 - 9 meter long single row plots
 - Two replications per irrigation regime

110 m



Wet Rep 2

Dry Rep 2

Wet Rep 1

Dry Rep 1

Phenotyped Traits

- HTP Canopy
 - Temperature, NDVI, height
- Physiological
 - ABA, CID, Chlorophyll
- Agronomic
 - Lint yield, boll size
- Fiber quality
 - Length, strength, fineness
- Seed ionomics

HTP: Proximal sensors, platform, and vehicle

- Active, multispectral crop canopy sensor
 - Canopy reflectance
- Infrared thermometer
 - Canopy temperature
- Ultrasonic transducer
 - Canopy height
- Data Loggers
 - Onboard data storage
- GPS-RTK
 - Geolocating each collected data point with position and time stamp

Modified high-clearance tractor

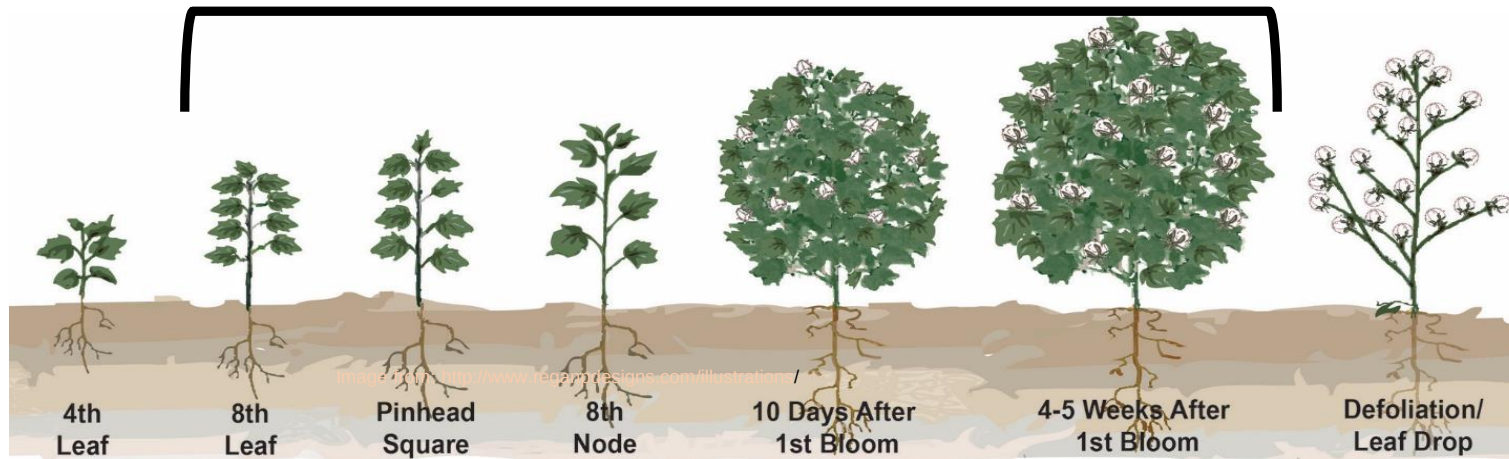


Average speed of 2.82 km/h
1 data point/meter (1 Hz)

Longitudinal assessment of phenotypes over time

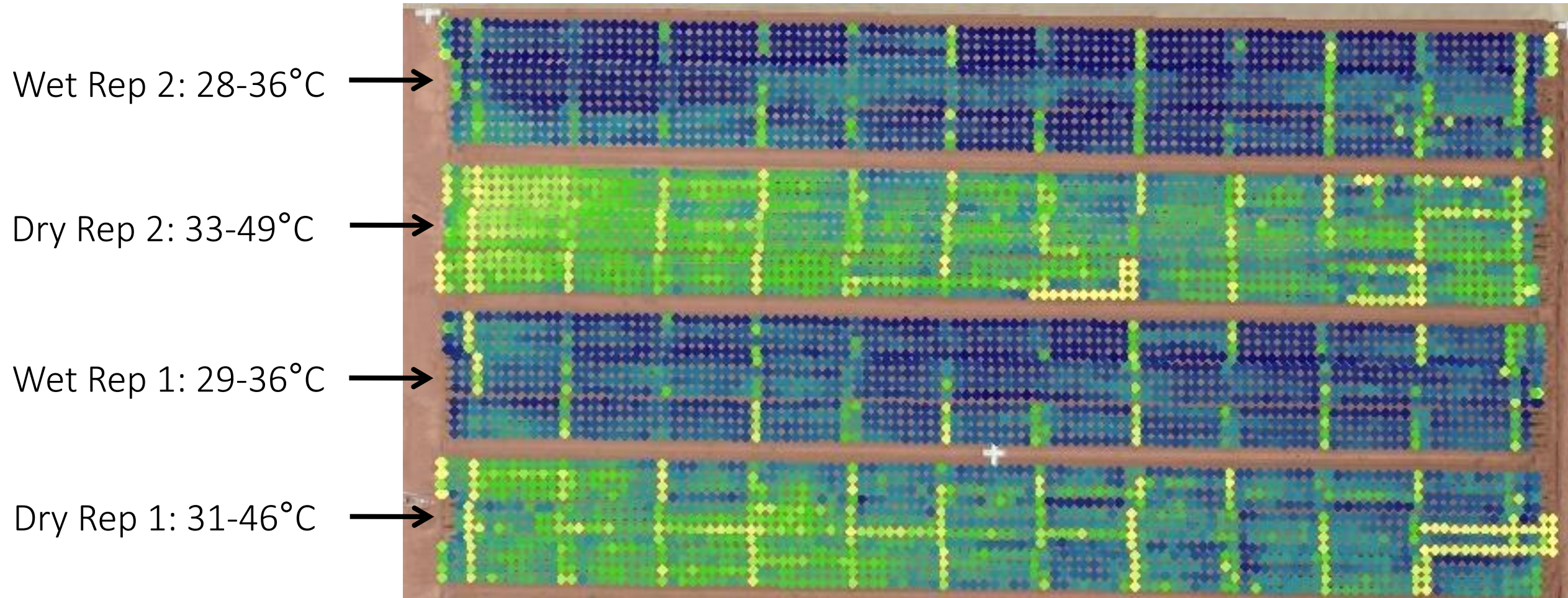
- Canopy traits
 - Canopy temperature – plant-water relations
 - NDVI – used to quantify change in canopy architecture as a function of wilting
 - Canopy height & LAI – whole plant response

Canopy data collection initiated at flowering, collected weekly



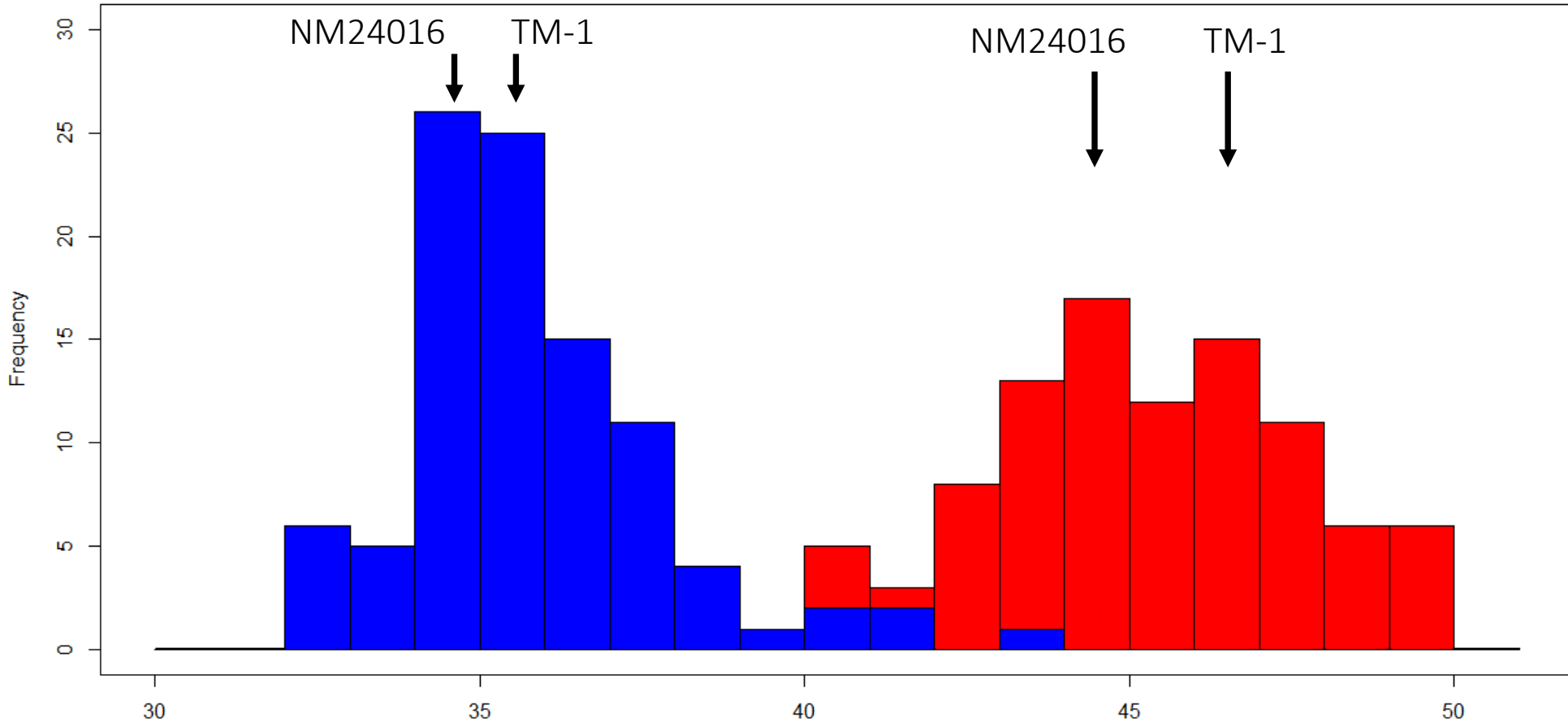
HTP Geoprocessed Canopy Temperature Data

- Each circle represents a canopy temperature data point, multiple measurements per plot
- Data from August 12, 2010 at 1 pm (MST)
- Well-watered (Wet) is approximately 3-10°C cooler than water-limited (Dry)



Transgressive variation for canopy temperature (°C)

Wet and Dry Plots at 1 pm on Day 222, 2012



Mean = 35.7°C

SD = 1.9

$H^2 = 0.83$

Mean = 45.2°C

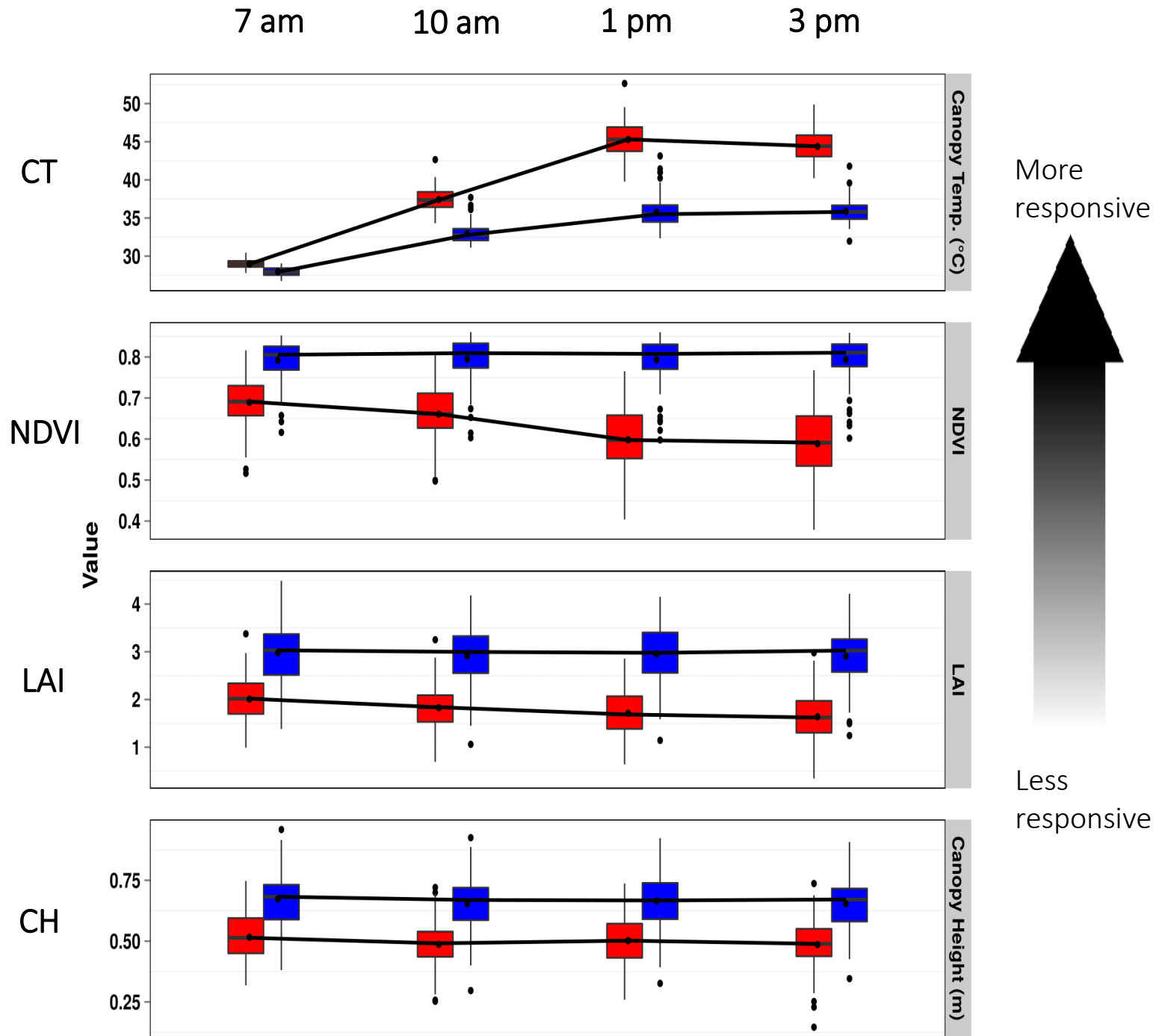
SD = 2.3

$H^2 = 0.90$

Differential time-by-treatment interactions for canopy traits

Wet and Dry Plots at 1 pm on Day 222, 2012

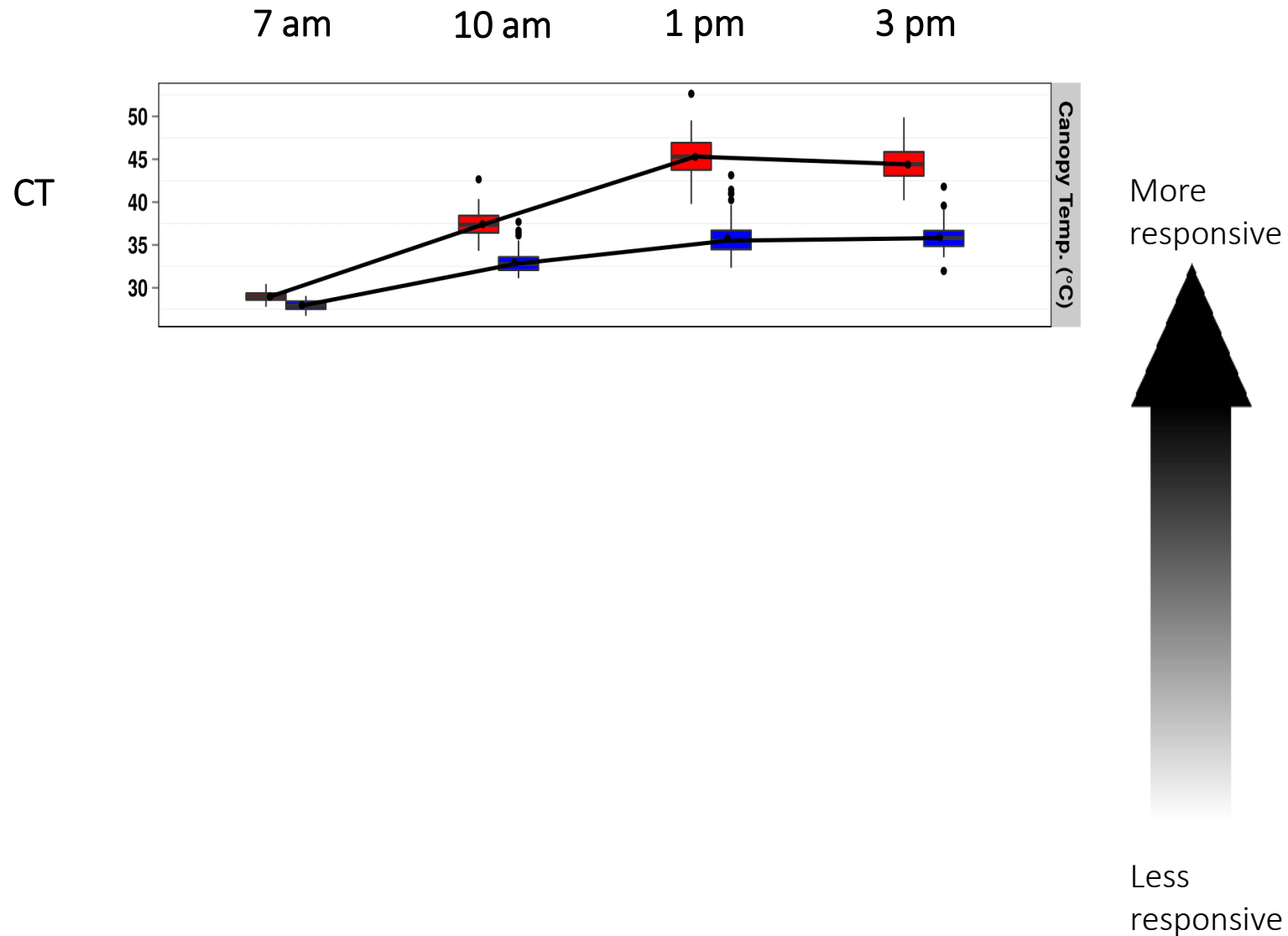
- CT = Canopy temperature
- NDVI = Normalized difference vegetation index
- LAI = Leaf area index
- CH = Canopy height



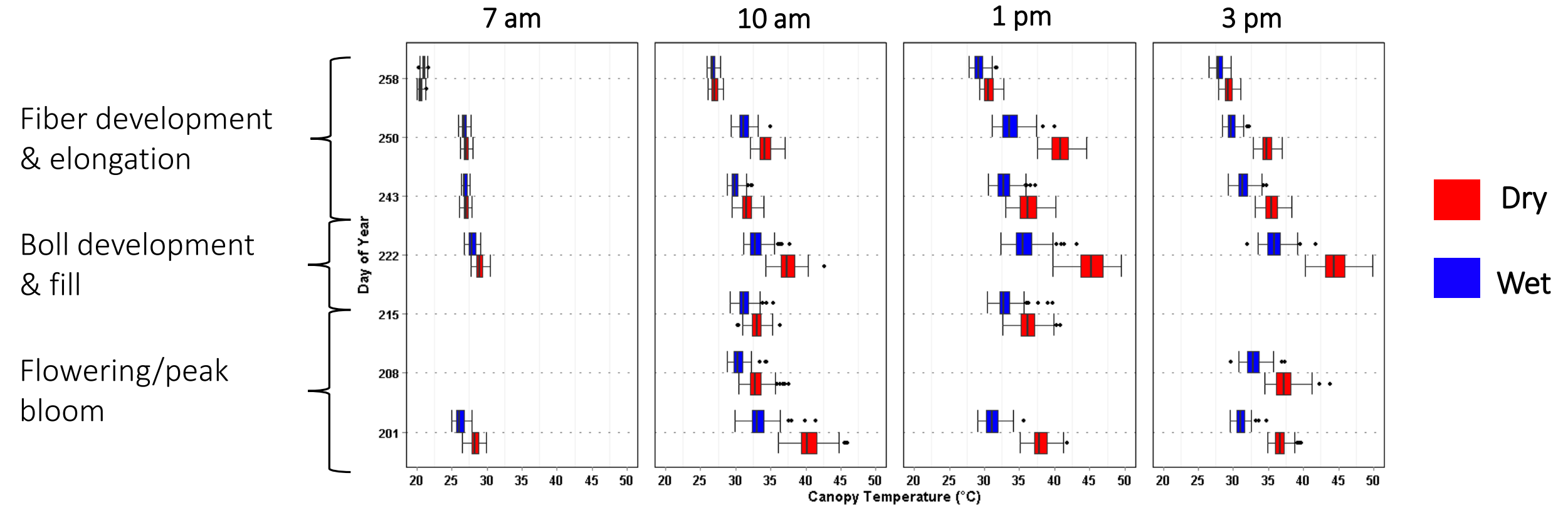
Differential time-by-treatment interactions for canopy traits

Wet and Dry Plots at 1 pm on Day 222, 2012

- CT = Canopy temperature
- NDVI = Normalized difference vegetation index
- LAI = Leaf area index
- CH = Canopy height

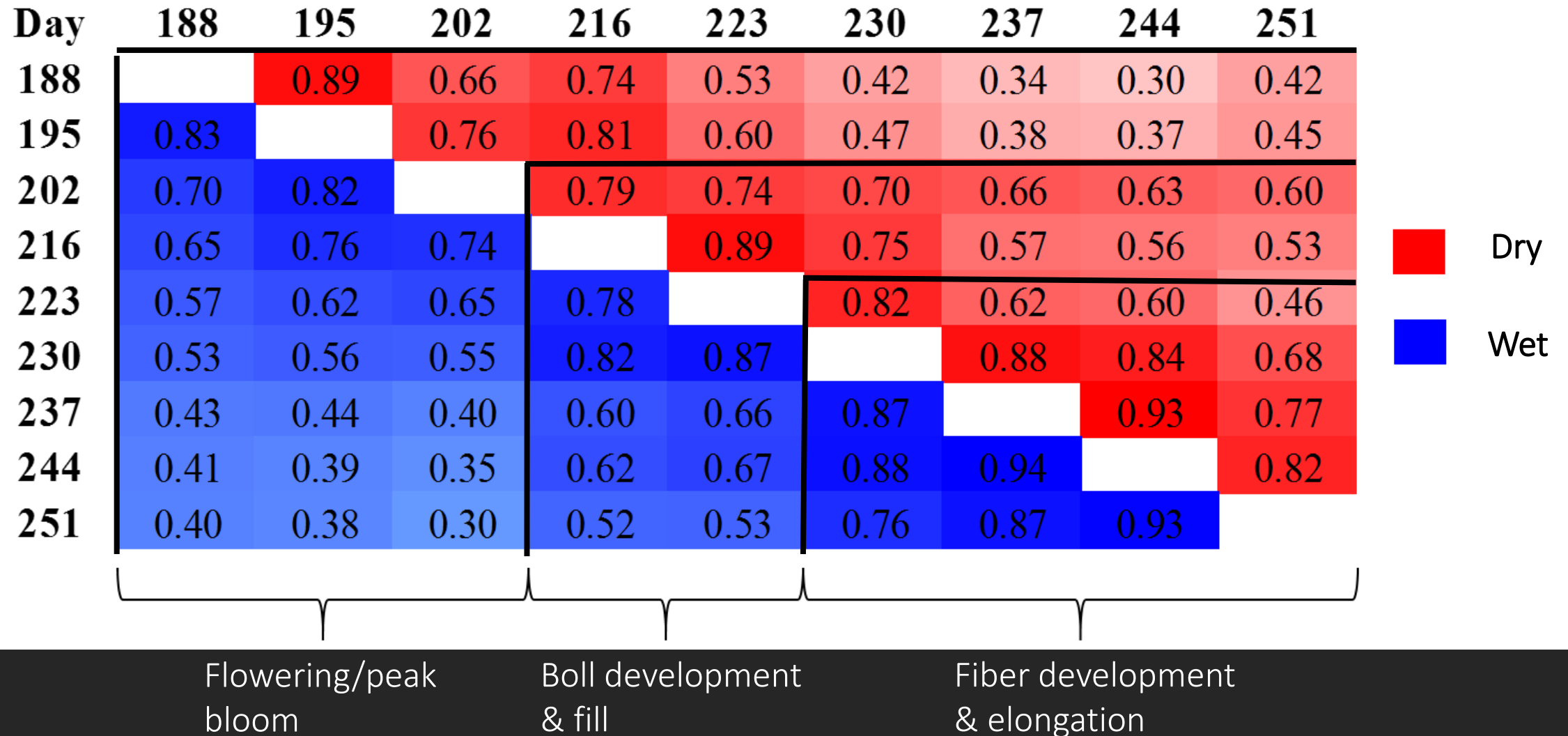


Dynamic response of canopy temperature to irrigation regime at multiple times and days



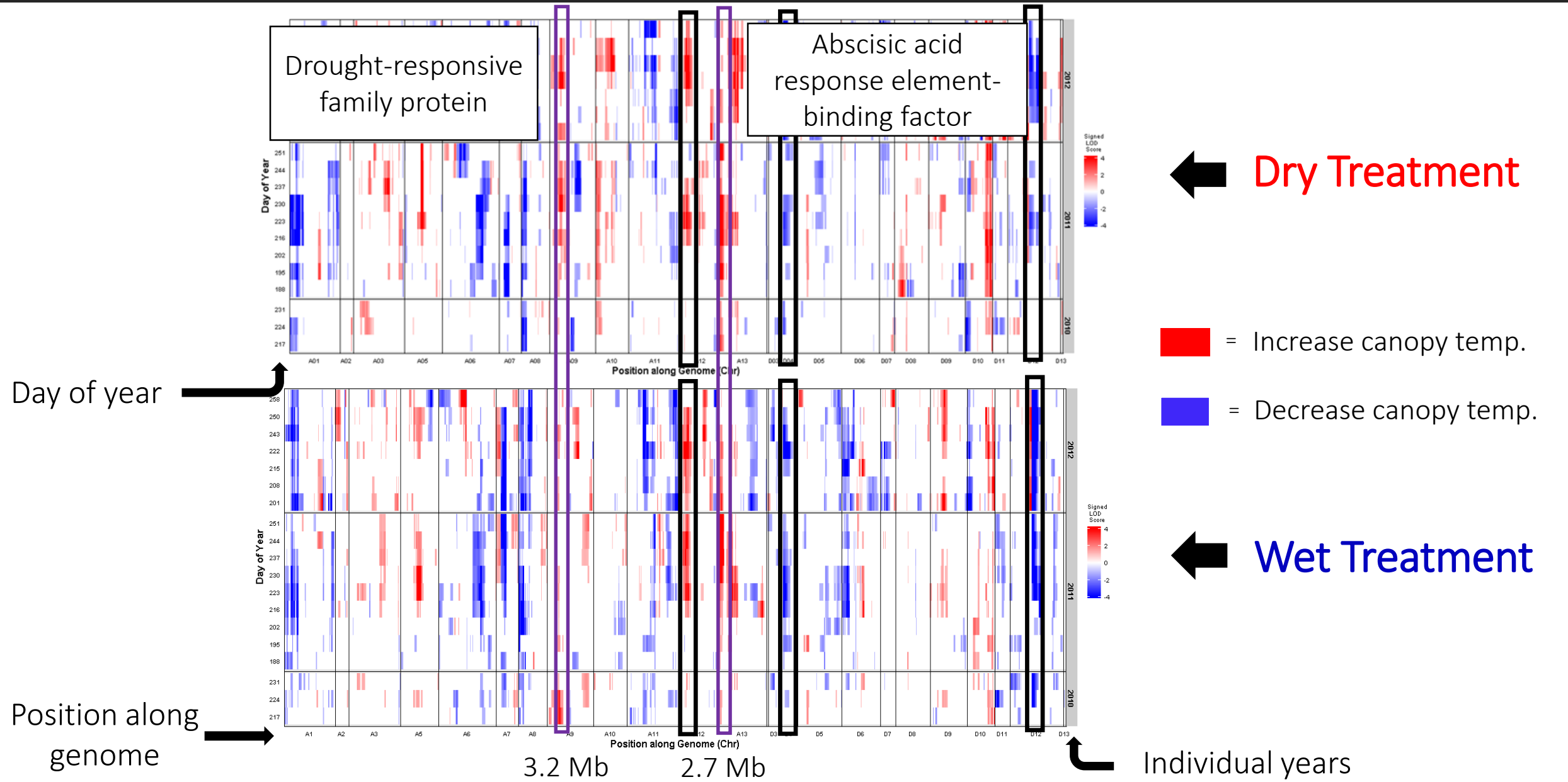
Phenotypic variation for canopy temperature at each time of day that data were collected under two irrigation treatments from 19 July – 14 Sept. 2012

Canopy temperature measurements are more highly correlated within a plant growth stage



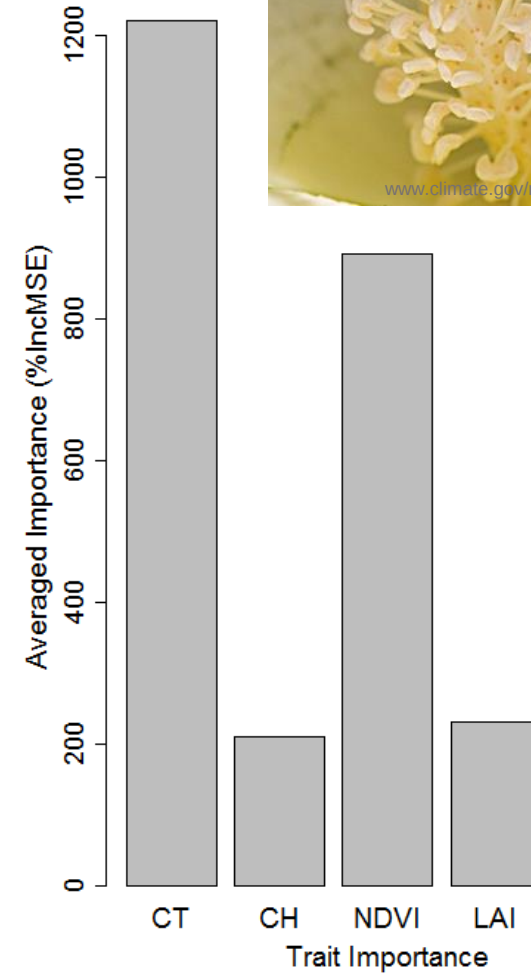
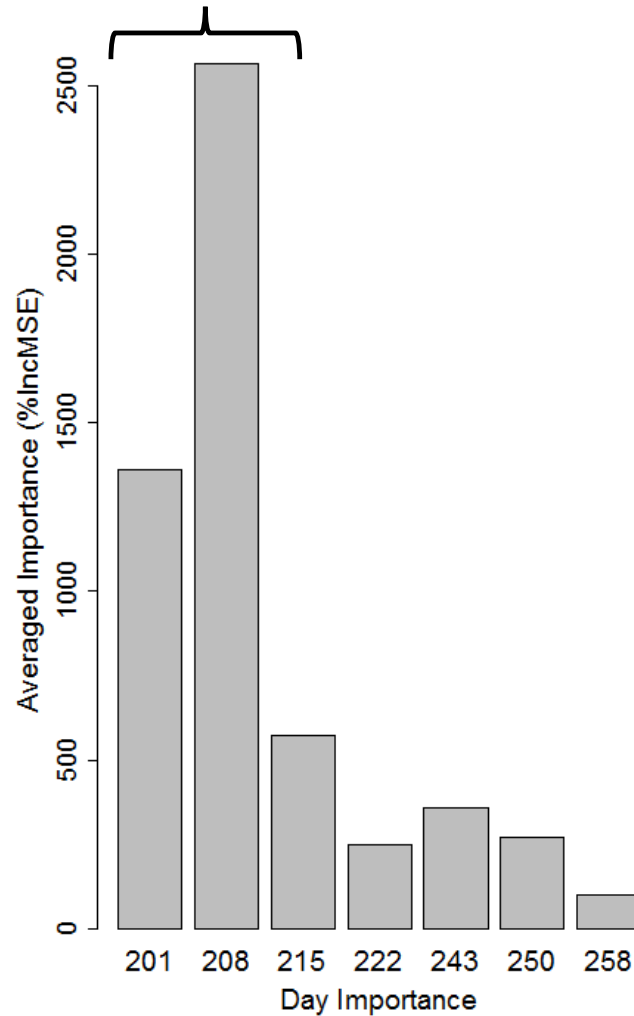
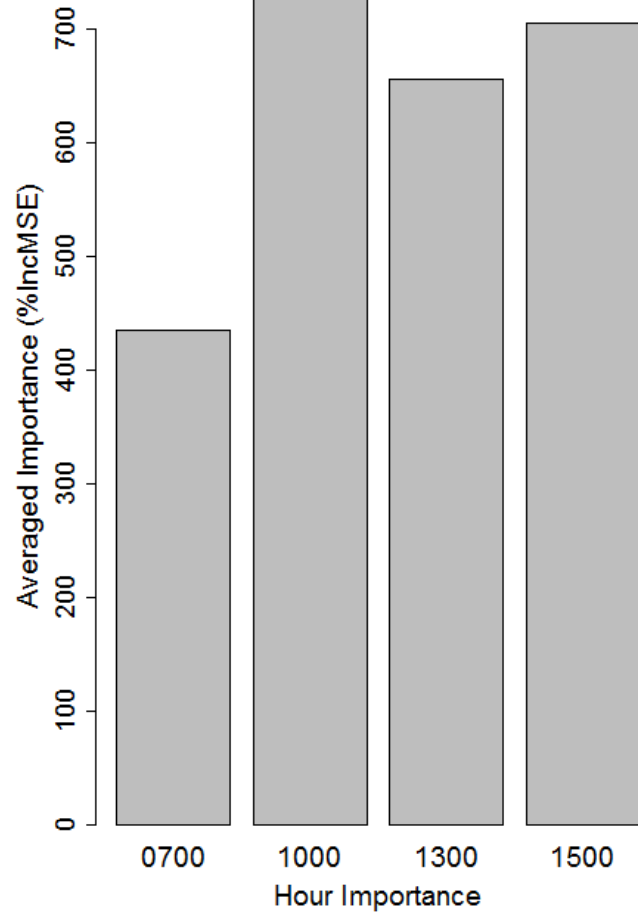
Pearson's correlations for mean canopy temperature under two irrigation treatments from 7 July – 8 Sept. 2011

Distinct temporal patterns of genetic effects control variation in canopy temperature



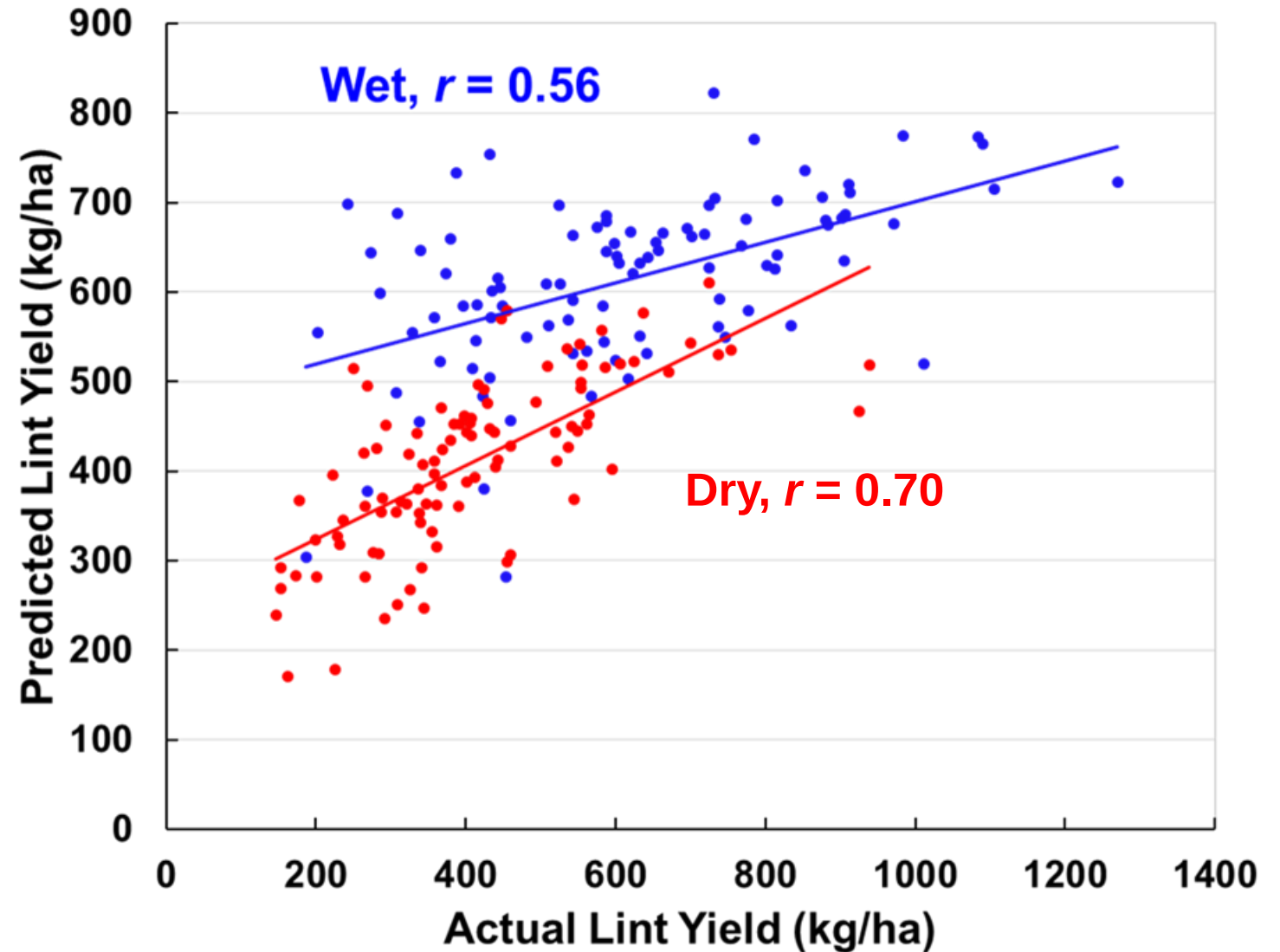
Canopy temperature at flowering/peak bloom is most predictive of lint yield

Flowering/peak bloom



High prediction accuracies of lint yield using canopy temperature data from flowering/peak bloom

2012 lint yield



Understanding environmental effects:

Phenotype = Genotype + Environment + Genotype×Environment

- Current phenotyping efforts only tell half the story (the top half)
- In-field root phenotyping in its infancy
- How do plants interact with their soil environment?



lonomics: another HTP technology

- Ionomics: rapid profiling of elemental concentration, 20 elements
- Elements are essential components of every cell
- Change in elemental concentration due to:
 - **Abiotic stress (drought)**
 - **Soil composition**
 - Plant morphology
 - Development stage of plant
- Provide information about overall health and function of the plant

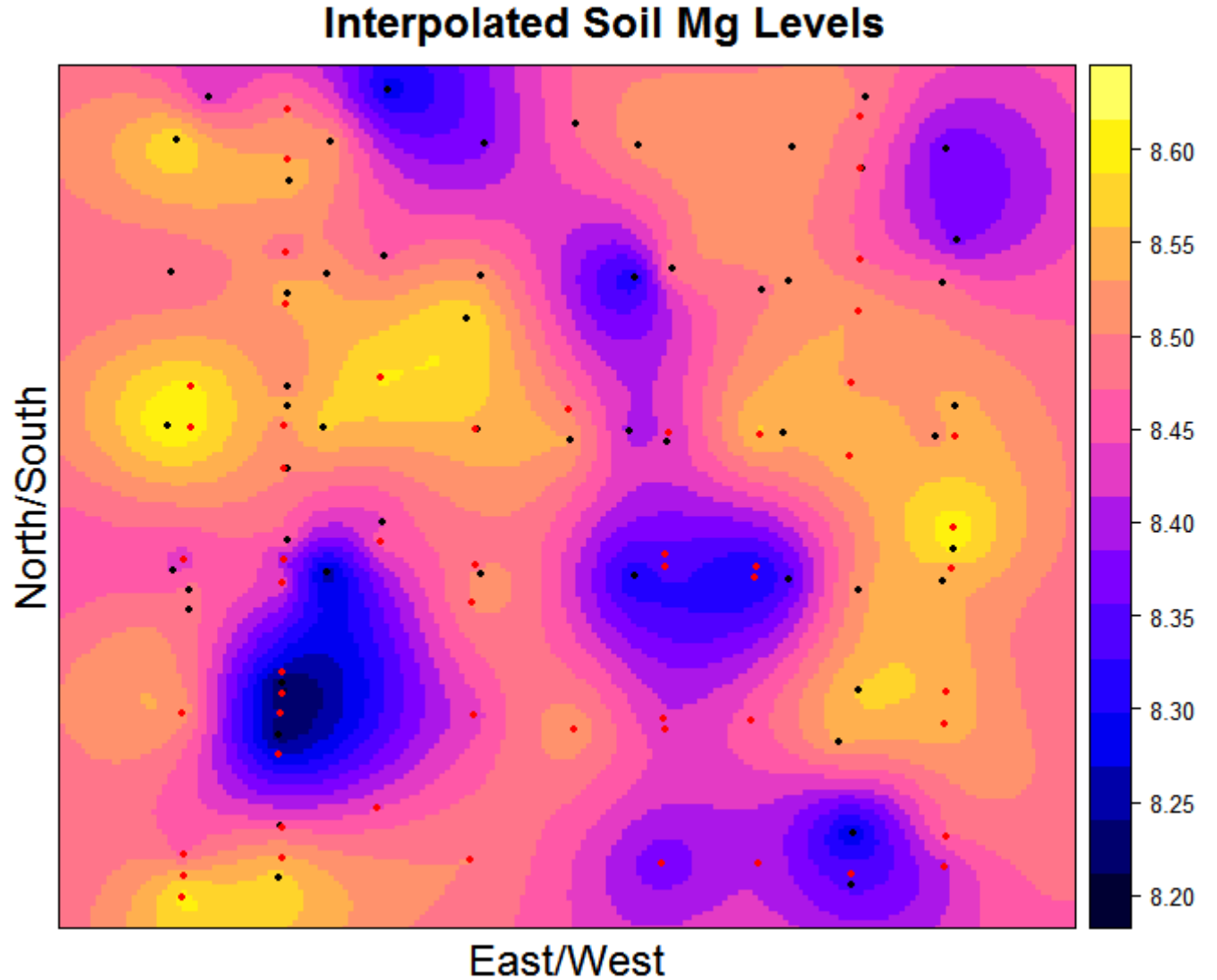
Periodic Table of the Elements

1 H Hydrogen 1.01																	2 He Helium 4.00	
3 Li Lithium 6.94	4 Be Beryllium 9.01											13 B Boron 10.81	14 C Carbon 12.01	15 N Nitrogen 14.01	16 O Oxygen 16.00	17 F Fluorine 19.00	18 Ne Neon 20.18	
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95	
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 84.80	
37 Rb Rubidium 84.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.25	
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides		72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.09	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium [208.98]	85 At Astatine 209.99	86 Rn Radon 222.02
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides		104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Unoctium unknown

- Green boxes = essential elements for plant growth and health
- Purple boxes = nonessential and trace elements

Soil environment is highly heterogeneous

- Magnesium concentration of soil where HTP experiments were carried out, samples taken from 5 depths
- Red & black circles = sampling locations
- Yellow = high magnesium content
- Blue = low magnesium content
- Soil magnesium concentrations were significantly correlated with seed magnesium concentrations

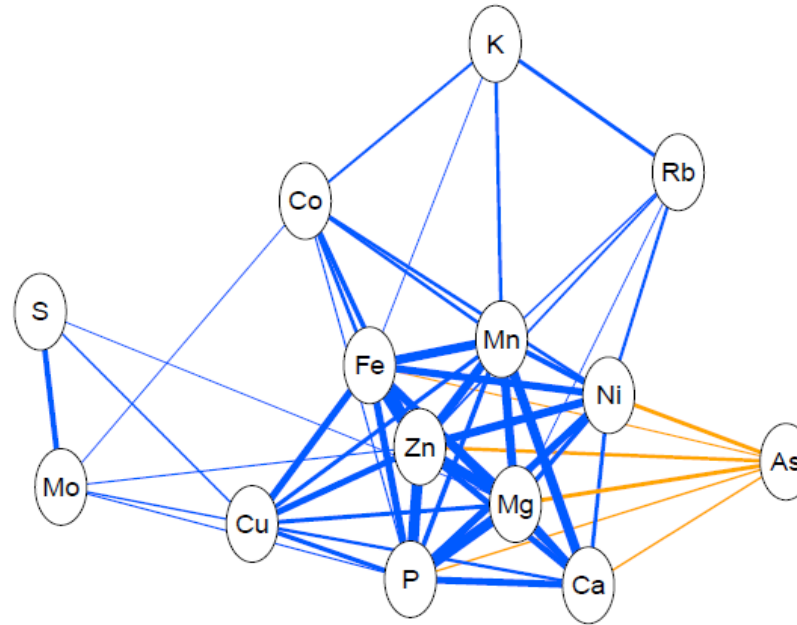


Ionome is highly
interrelated
genotypically

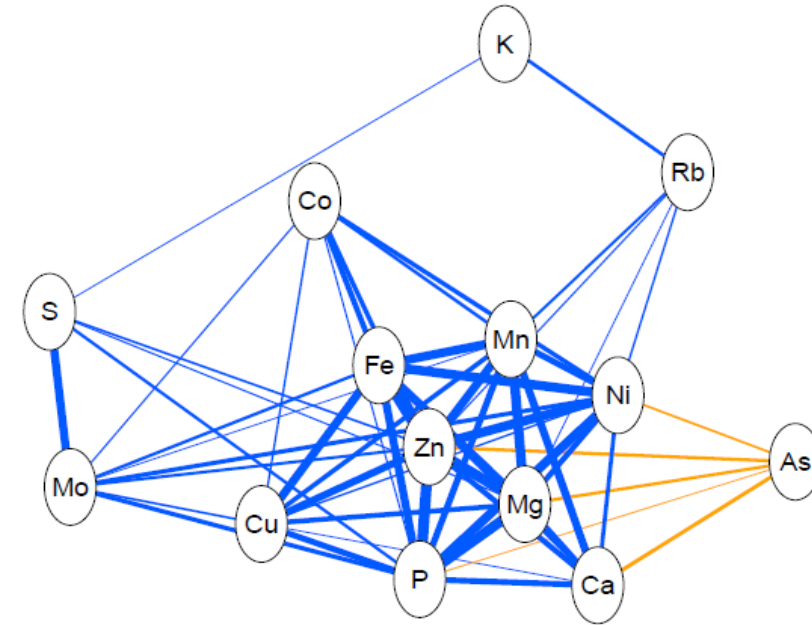
Correlation Values

Strength
0.2
0.4
0.6

Direction
Positive
Negative



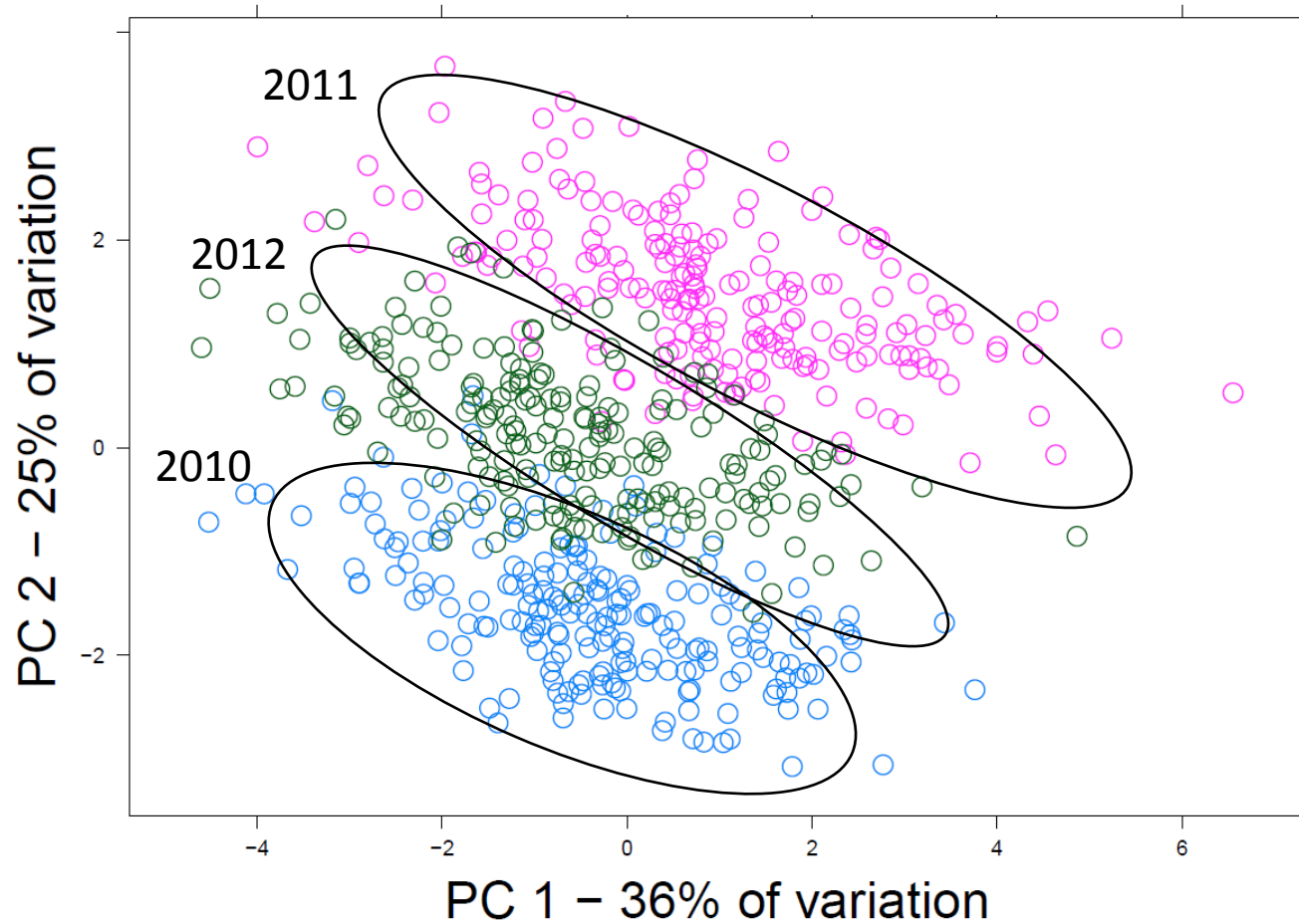
Genotypic Correlations Dry



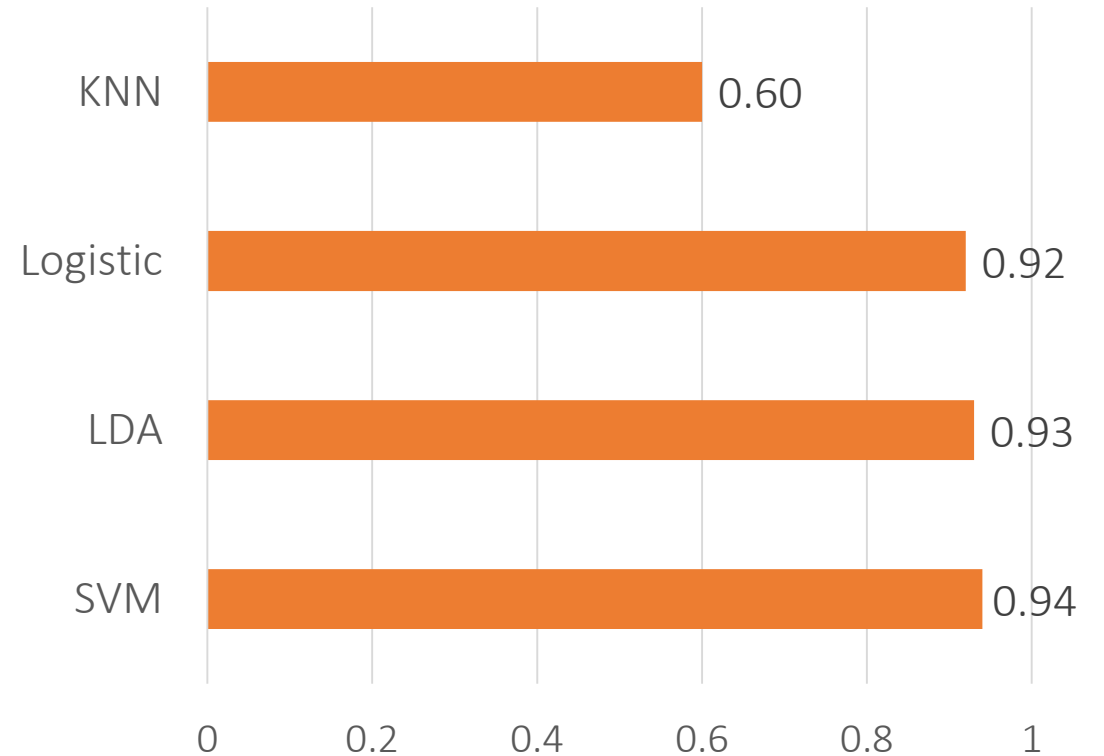
Genotypic Correlations Wet

The ionome predicts abiotic stress

Strong Year Effect



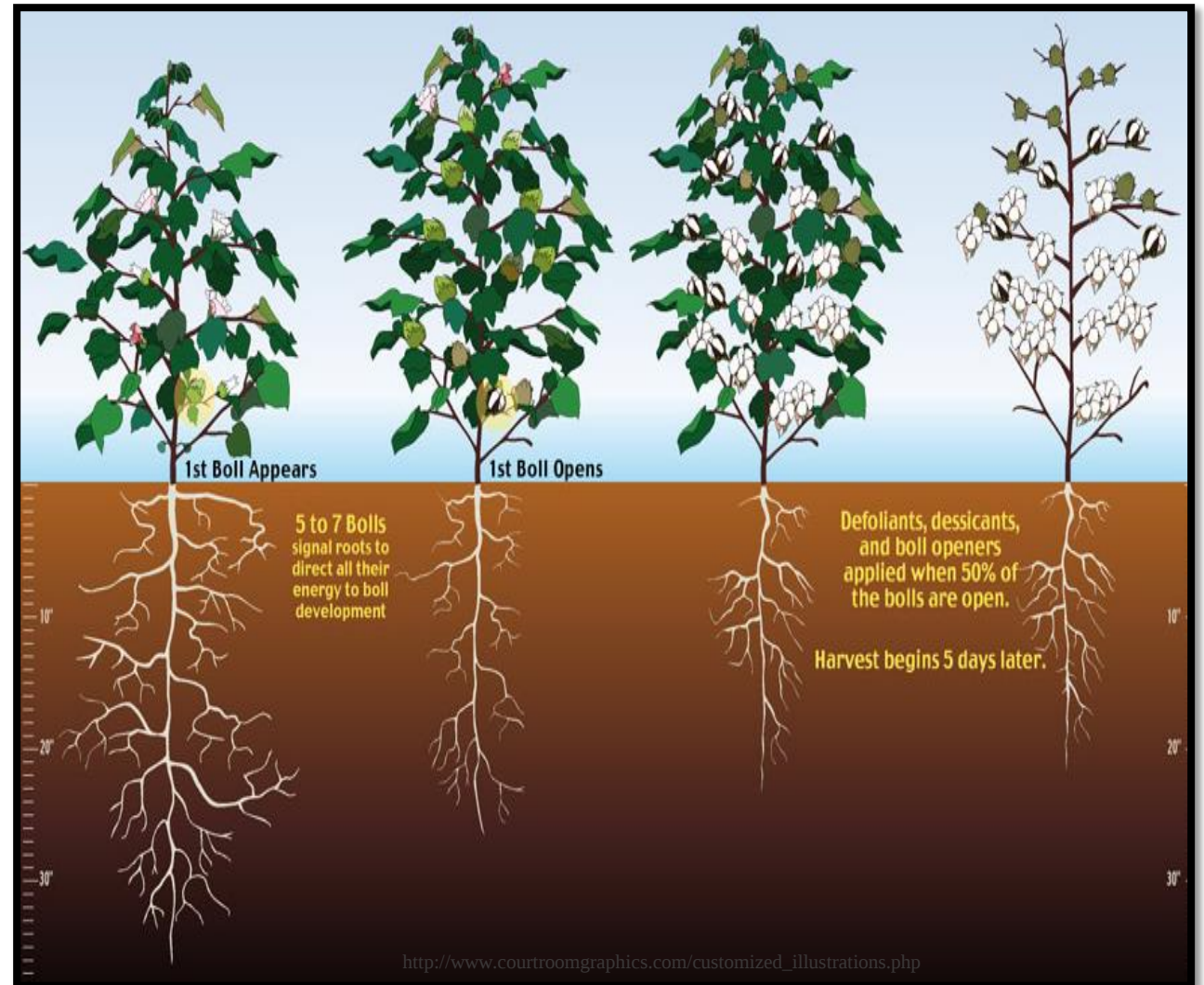
Prediction Accuracies



Prediction of irrigation treatment achieved accuracy of 94%

Summary of Cotton HTP Experiments

- Field-based HTP
 - Novel platform
 - Dynamic traits
 - Temporal QTL
 - Yield prediction
- Ionomics HTP
 - Incorporation of environment
 - Interrelated system
 - Predictive of stress



Acknowledgements

Cornell University

Gore lab
Yupei Lui
Elodie Gazave
Tim Setter
Abraham Stroock
Piyush Jian

NMSU

Jinfa Zhang

Donald Danforth Center

Ivan Baxter
Greg Ziegler

U.S. ALARC Maricopa, AZ

Andrew French
Jeffrey White
Douglas Hunsaker
Elizabeth Carmo-Silva
Kelly Thorp
Joel Gilley
Kristen Harbour
Virginia Moreno
Sara Wyckoff
Brian Nadon
Mike Salvucci
Bob Strand

University of Arizona

Pedro Andrade-Sanchez
John Heun

Kansas State University

Jesse Poland

USDA-ARS

Richard Percy
David Fang

Purdue University

Min Zhang



National Science Foundation
WHERE DISCOVERIES BEGIN