Physiological Responses of Grain Sorghum to High Temperature and Drought Stress: Understanding, Opportunities and Challenges

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Outline

1. Short Episodes of Temperature Stress: Sensitivity / Response
2. Mechanisms of Reproductive Failure
3. Longer Duration Stress: Thresholds and Response
4. Genetic Variability: Important Traits and Opportunities (sorghum and other cereals)
5. Drought Stress: Sensitivity / Response
6. Genetic Variability: Important Traits and Opportunities (sorghum and other cereals)
7. Challenges: Facilities and High Throughput Phenotyping

Economic Impact of Drought and/or High Temperature

Crop yield losses in Kansas

Crops	Crop Grain Yield Loss (million)	
	2011	2002
1. Wheat	$ 286	$ 387
2. Sorghum	$ 214	$ 272
3. Maize	$ 966	$ 261
4. Soybean	$ 310	$ 97

2013: States that suffered the most

Drought-related issues	
State	Value (million)
1. Illinois	$ 2,222
2. Iowa	$ 1,621
3. Nebraska	$ 1,117
4. Kansas	$ 980

Heat-related issues	
State	Value (million)
1. Kansas	$ 190
2. Nebraska	$ 154
3. Texas	$ 76
4. Illinois	$ 70

Source: Economic impact of 2001-2003 drought: income and financial condition of Kansas farmers. Kansas Farm Management Association.
Source: Associated Press, September 14, 2011. Kansas crop losses from drought reach $1.7 billion.

High temperature and drought stresses are major environmental concerns.
Insurance claims associated yield losses due to environmental stresses in Kansas were: 2011 ($ 1.8 billion); 2013 (~$ 1.2 billion).

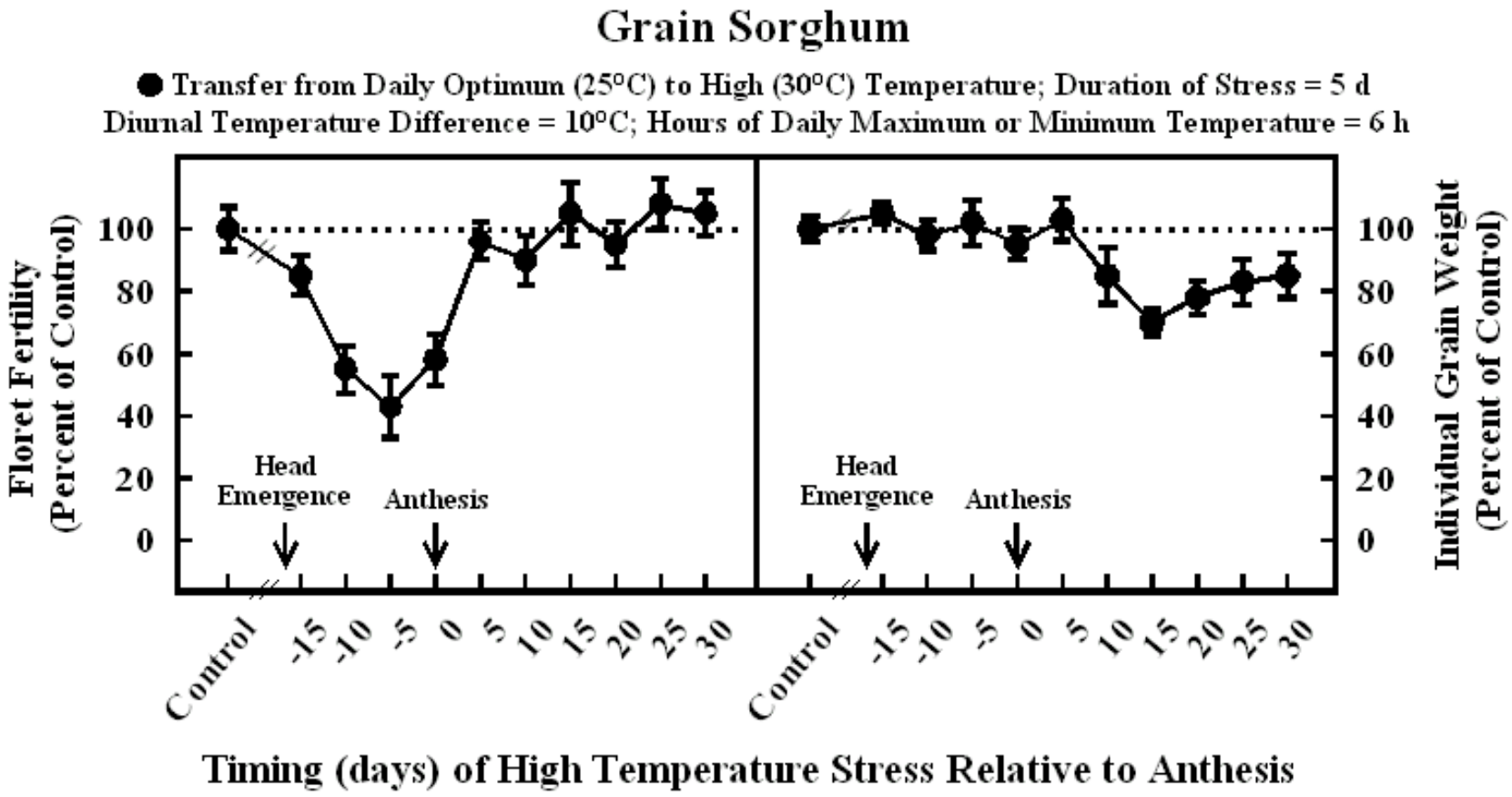
High Temperature Stress: Short Episodes – Sensitive Stages and Responses

High Temperature Stress: Short Episodes – Sensitive Stages and Responses

Multiple experiments were conducted with objectives to determine most sensitive stages during floral and seed development for high temperature stress; and to quantify responses of floret fertility, seed-set and grain growth to short episodes of high temperature stress. Plants were grown in controlled environment growth chambers under optimum temperature from sowing to end of vegetative stage. At a specific reproductive stage, set of plants were transferred to various temperatures for different durations, and returned back to optimum temperatures. Florets were marked and specific stage noted at start of stress. After the stress period, data on floret fertility (florets with grain) and individual grain weight from tagged florets were determined.

All experiments were fully irrigated to avoid water stress.

High Temperature Stress: Sensitive Stages



Prasad et al. (Unpublished)

Floret fertility decreased by short episodes (5 d) of stress.
Maximum decreases during gametogenesis and fertilization.
Grain weight was decreased during early rapid grain filling stage.

High Temperature Stress: Sensitive Stages

Heat could damage sorghum yield

18 Jan, 2014 01:00 AM A+ A-

Comments 0 Share

SORGHUM growers in Australia's northern cropping belt are being urged to closely monitor crops for yield damage in the wake of record-breaking new year temperatures.

The recent spate of hot weather coincided with a critical development phase for many crops and growers are being warned that heat can have severe impacts on yield, even in crops that are not moisture stressed.

> *"The recent spate of hot weather coincided with a critical development phase for many crops"*

Heat-affected sorghum heads.

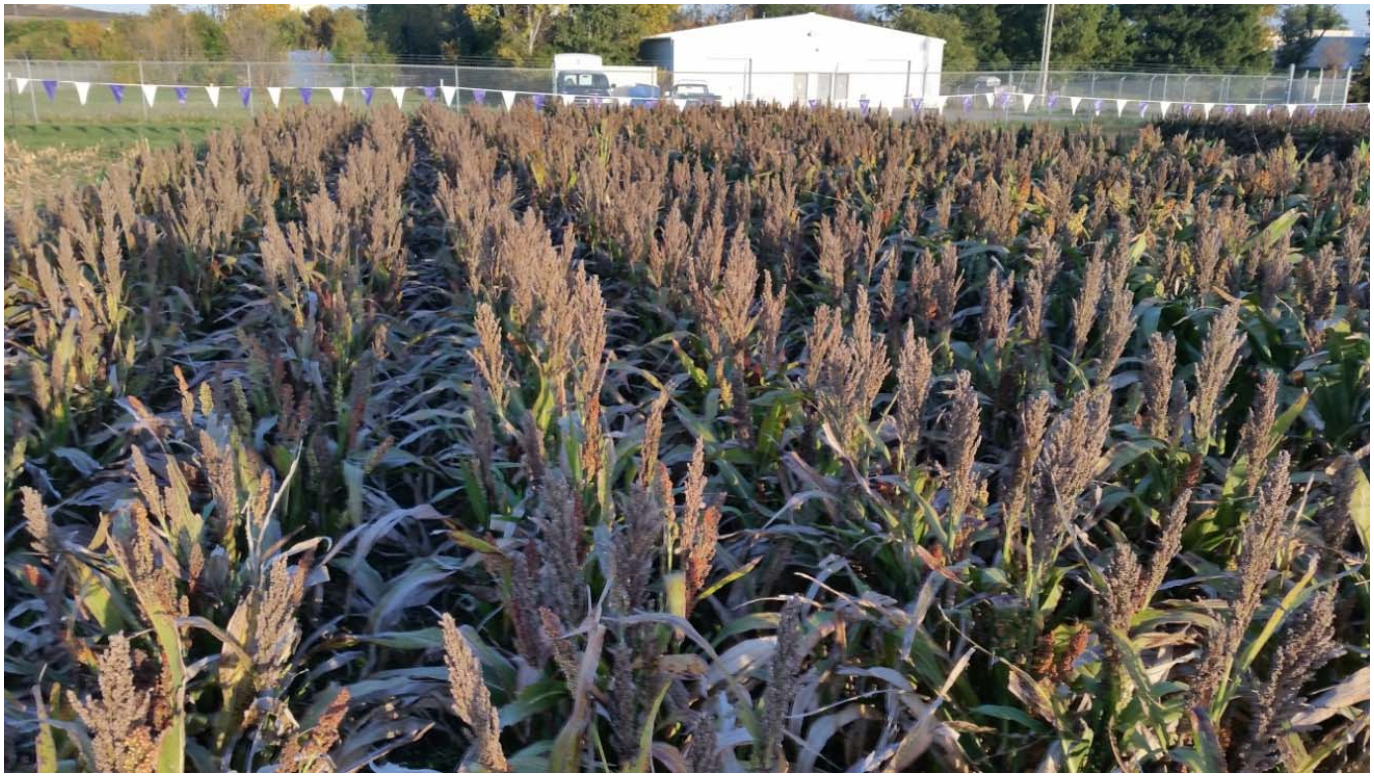
FarmWEEKLY

Australia (2014)

Sorghum panicles effected by high temperature during critical phase (gametogenesis / fertilization) – Low grain/seed numbers.

High Temperature Stress: Sensitive Stages

Field in Kansas - 2014



Ciampitti et al. (Planting date experiment)

Sorghum field effected by short periods of high temperatures during gametogenesis/flowering in Kansas.

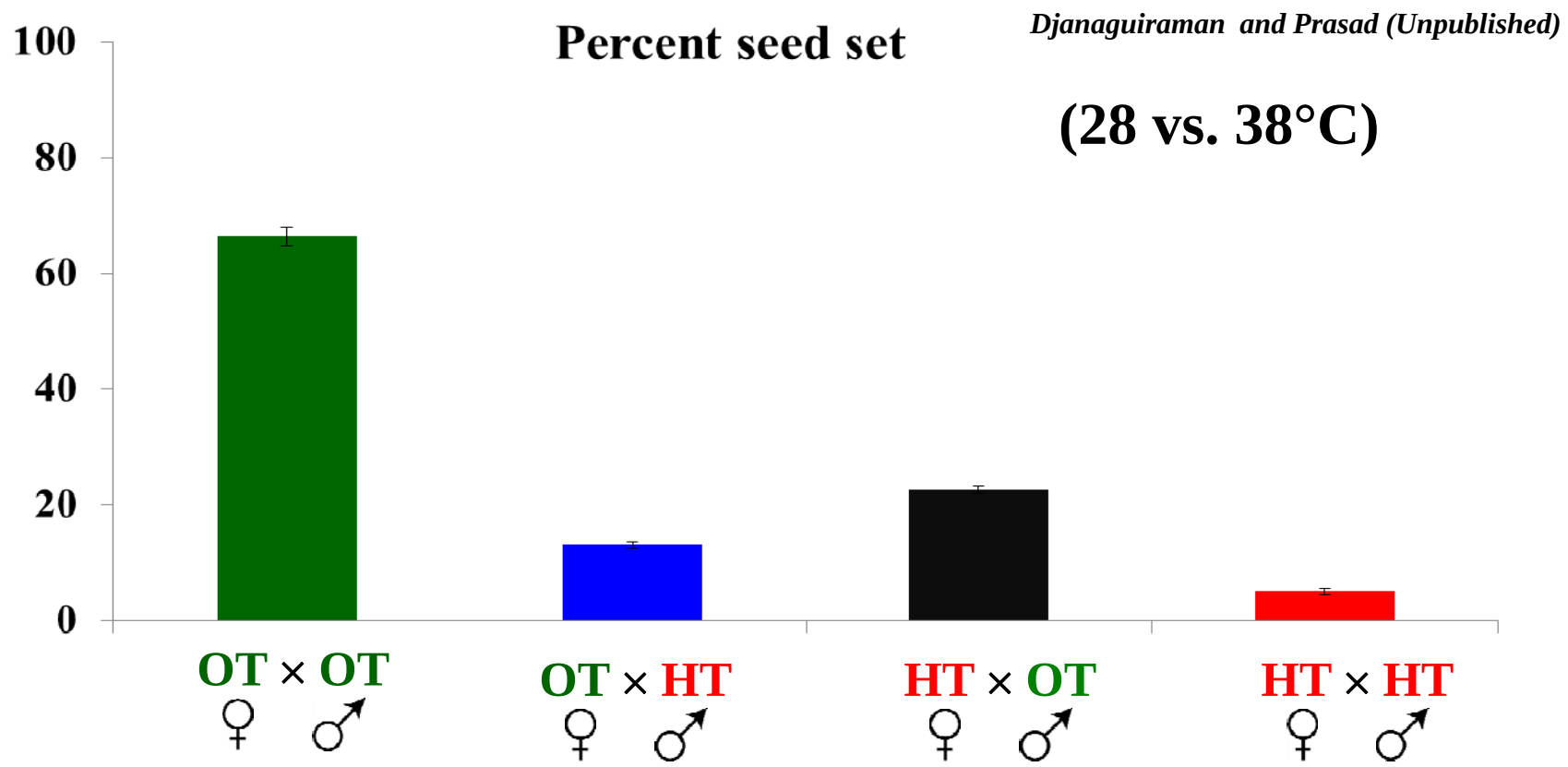
Lower seed-set and lower grain/seed numbers.

Sensitive Stages: Summary for Crops

Crops	Most Sensitive Stage(s)
Wheat	8 d prior to anthesis; and pollination / fertilization
Sorghum	10 d prior to anthesis; and pollination / fertilization
Rice	6 to 10 d prior to anthesis and pollination / fertilization
Pearl millet	10 d prior to anthesis and anthesis / fertilization
Maize	Tasseling and pollen shed
Peanut	3 d prior to anthesis and anthesis / fertilization
Soybean	6 d prior to anthesis and anthesis / fertilization
Cowpea	9 to 11 d prior to anthesis and anthesis / fertilization
Dry bean	6 to 15 d prior to anthesis and anthesis / fertilization
Canola	3 to 5 d prior to anthesis and anthesis
Cotton	5 d prior to anthesis and anthesis / fertilization

For most crops there are two critical stages that are sensitive to temperatures:
First at micro- or mega-sporogenesis (~ 3 to 12 d prior to anthesis) leading to loss of fertility;
Second at pollination/fertilization leading to decreased pollen shed, pollen reception on stigma, pollen tube growth, fertilization and early abortion.

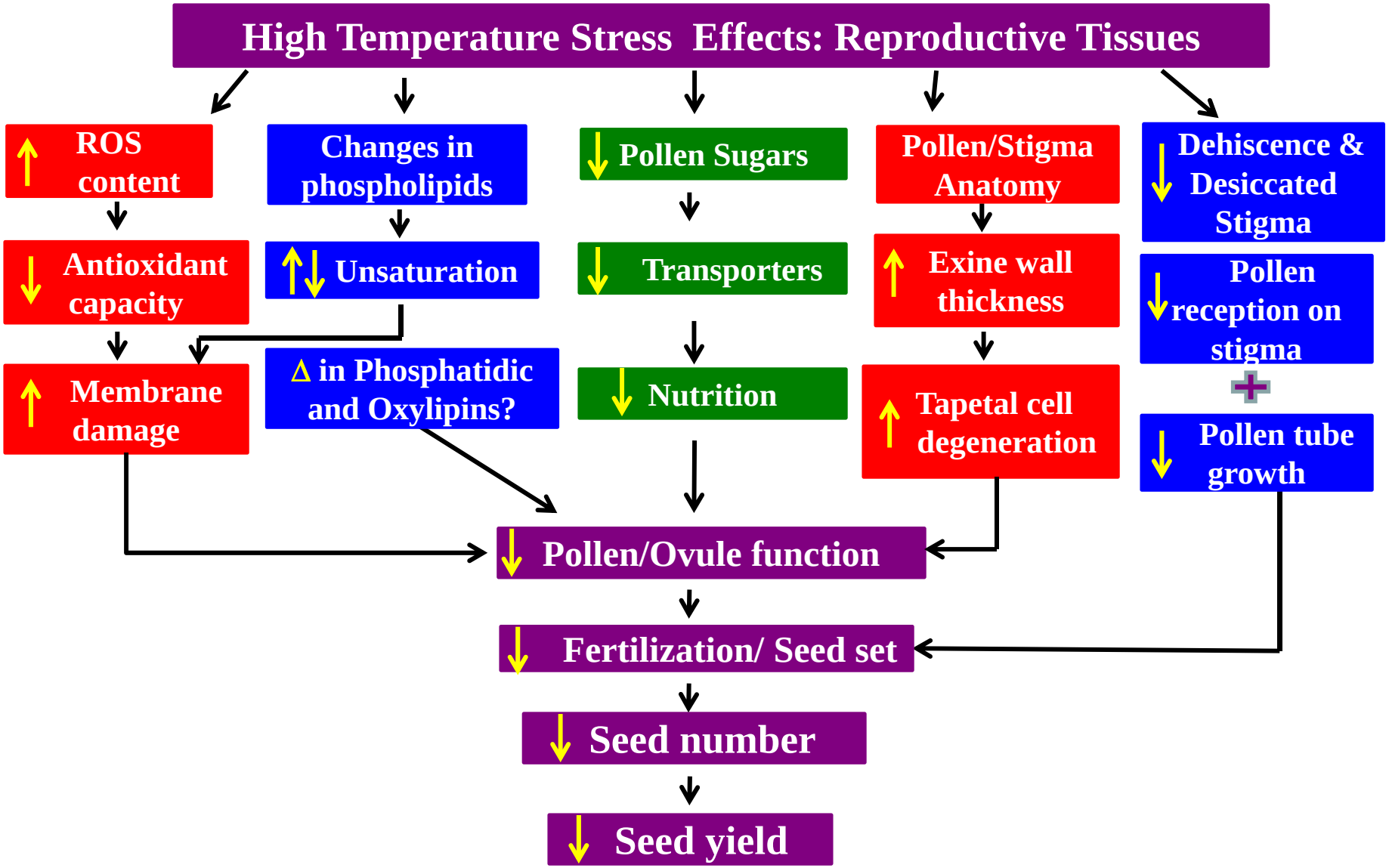
Reproductive Failure: Mechanisms – Relative Sensitivity of Male and Female: Reciprocal Crosses



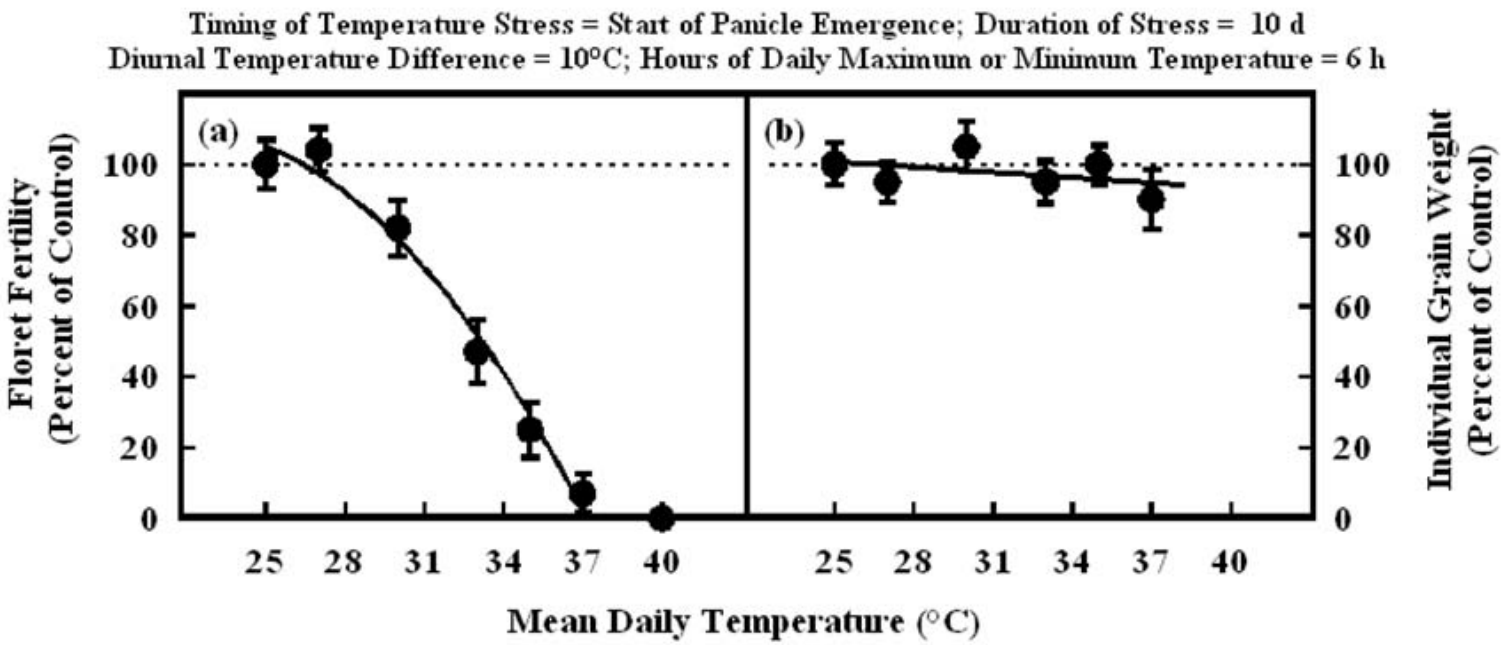
At high temperatures (38°C) both pollen and ovary are sensitive.

At moderate temperatures (36°C) pollen is relatively more sensitive than ovule/stigma.

Reproductive Failure: Mechanisms – Summary



Short Episodes of Stress: Temperature Thresholds – Start of Head (Panicle) Emergence

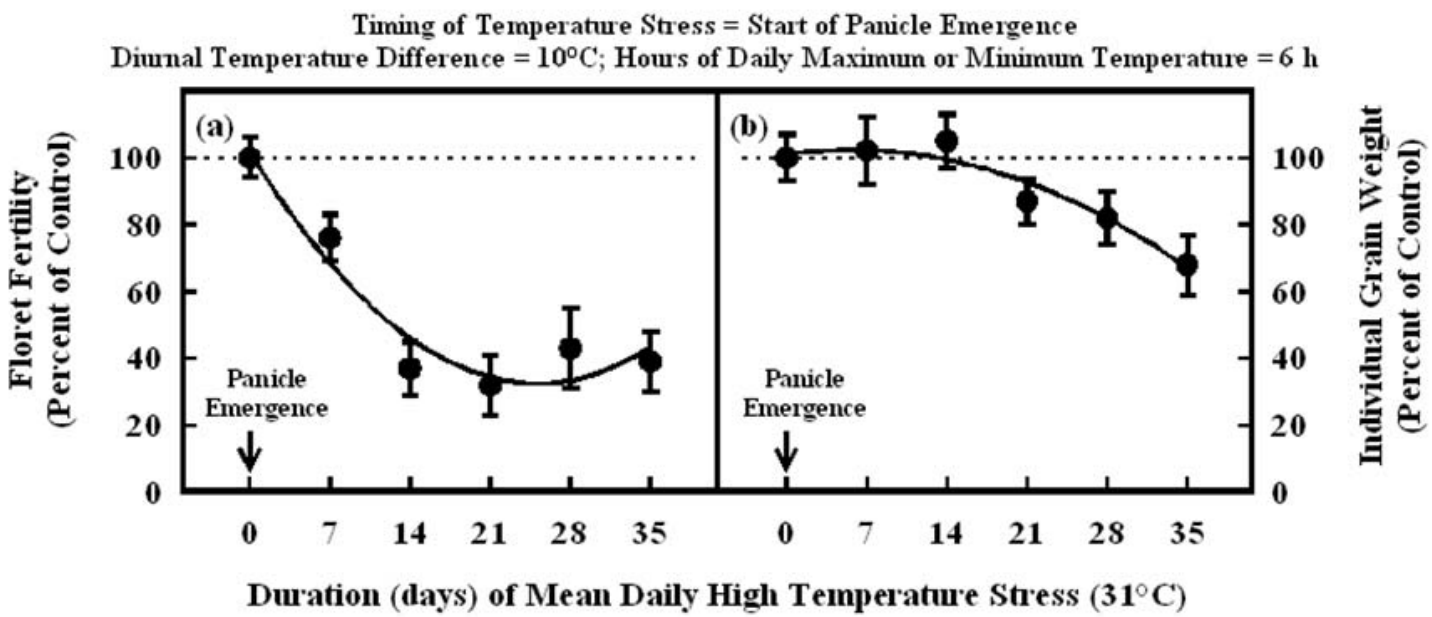


Prasad et al. (Unpublished)

Short episodes (10 d) of stress decreased floret fertility.

These short periods (10 d) did not impact individual grain weight.

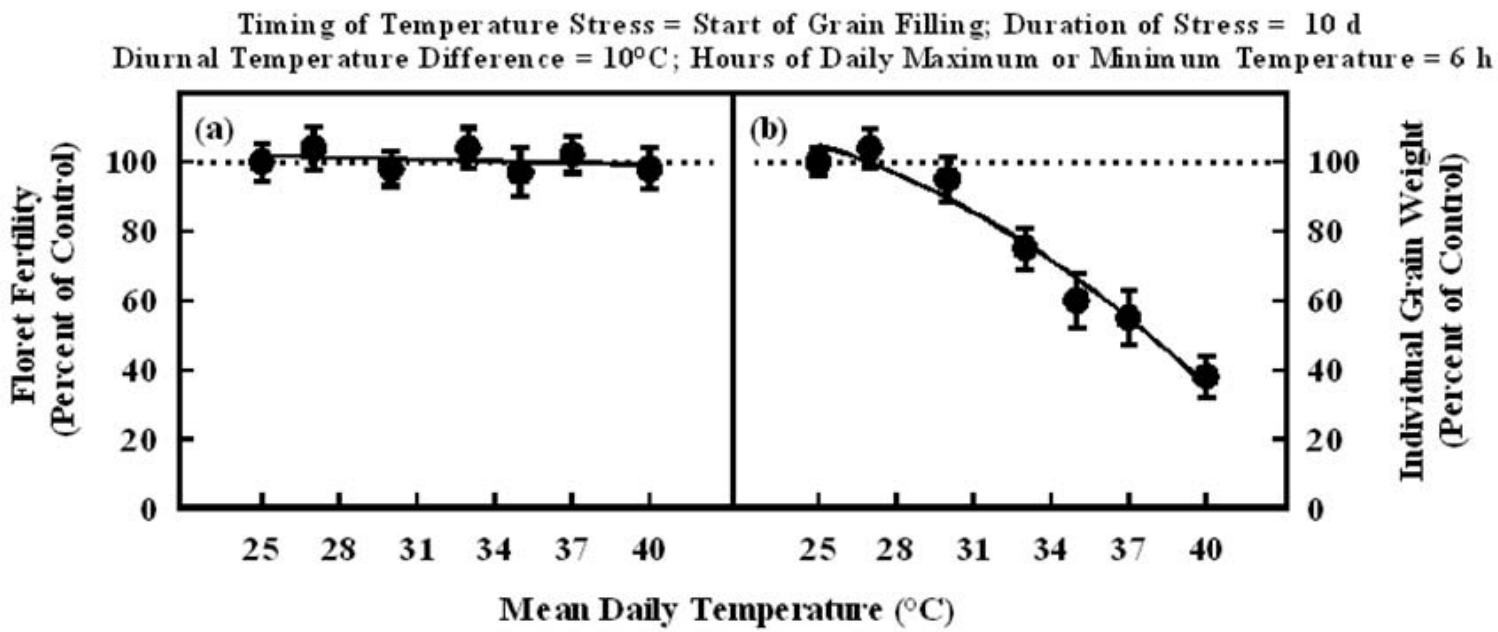
Short Episodes of Stress: Duration Thresholds – Start of Head (Panicle) Emergence



Prasad et al. (Unpublished)

Increasing duration (0 to 21 d) of stress decreased floret fertility.
Individual grain weight decreased with duration > 14 days.

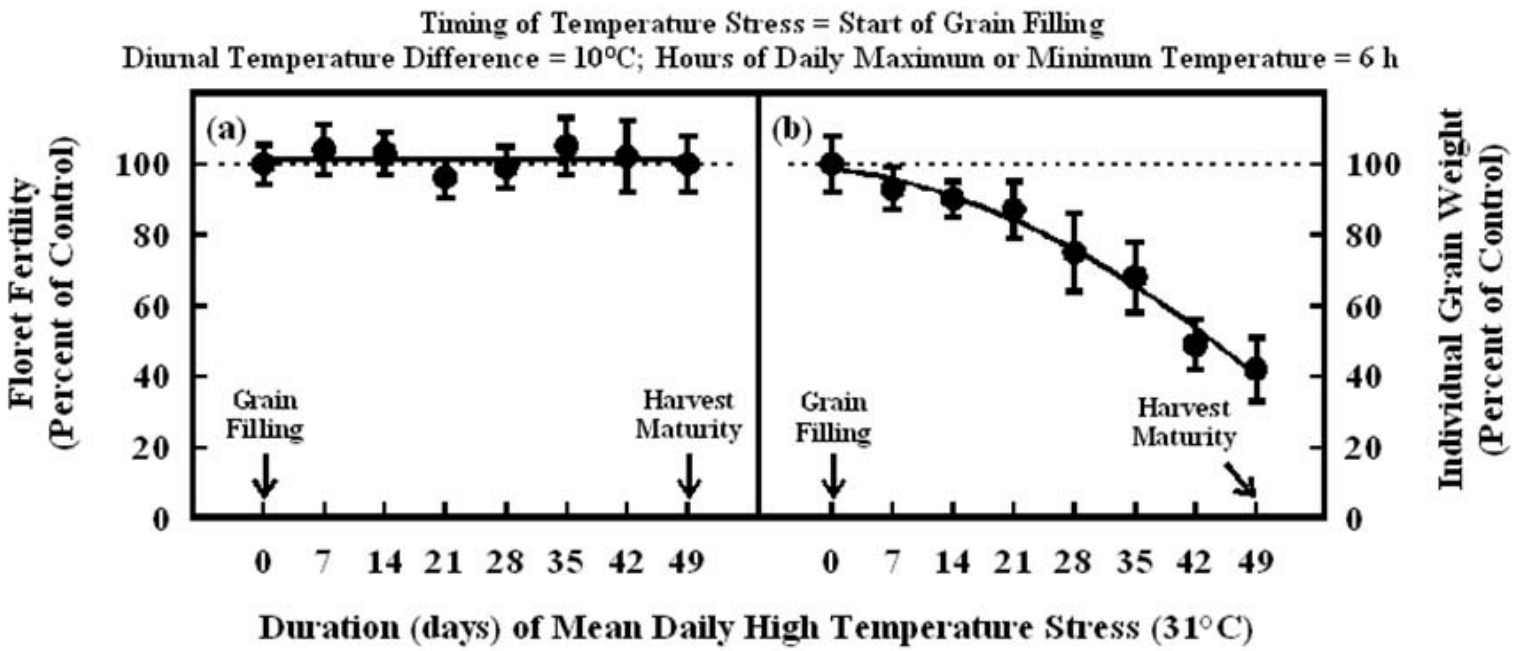
Short Episodes of Stress: Temperature Thresholds – Start of Grain Filling



Prasad et al. (Unpublished)

Stress decreased individual grain weight in a quadratic fashion.
These short periods (10 d) did not impact floret fertility.

Short Episodes of Stress: Duration Thresholds – Start of Grain Filling



Prasad et al. (Unpublished)

Plants started with similar floret fertility (i.e. seed numbers).
Individual grain weight decreased quadratically with increasing duration of stress (from 0 to 49 d – harvest maturity).

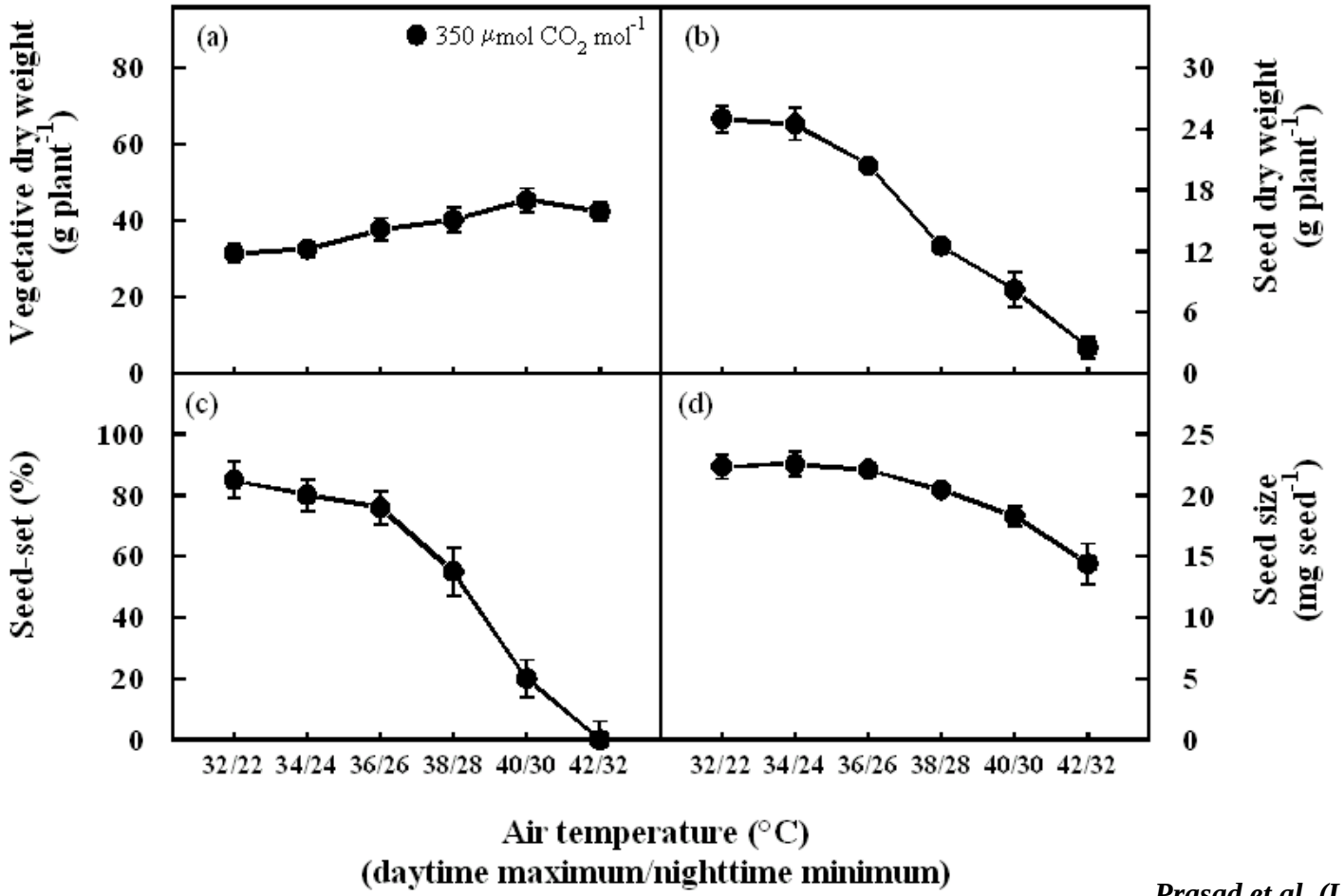
High Temperature Stress: Longer Duration – Thresholds and Responses

High Temperature Stress: Longer Duration
Temperature Thresholds

Multiple experiments were conducted with objectives to quantify the impact of various temperatures and durations of stress on physiological traits, floret fertility, seed-set and grain growth and yield components. Plants were grown in controlled environments under optimum temperature until emergence or end of vegetative stage. Thereafter exposed to various temperature regimes until maturity. Leaves, spikelet or seeds were marked and data on photosynthesis, fertility (florets with grain), seed-set, grain numbers, individual grain weight from tagged organs or plants were determined. At final harvest data on biomass was measured the used to determine harvest index to capture season long effects.

Temperature thresholds vary based on the timing, duration and intensity of temperature stress and stage of crop development.

Longer Duration Stress: Temperature Thresholds – Emergence to Maturity



Prasad et al. (Unpublished)

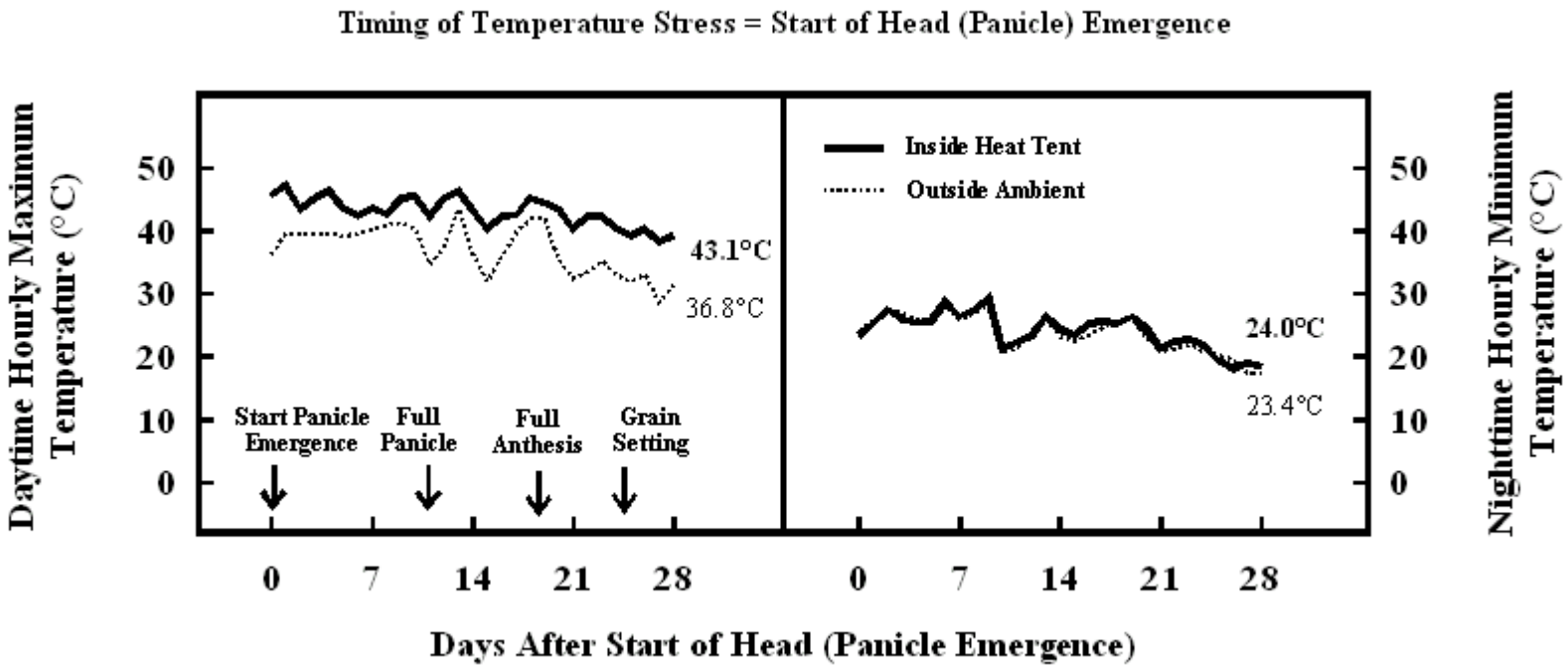
Temperatures stress decreased seed yield due to decreased seed-set and seed size leading to decreased harvest index.

Longer Duration Stress: Field Conditions – Responses

Experiments were conducted with objectives to quantify the impact of high temperature and duration of stress on floret fertility and grain growth. Plants were grown in field conditions at ambient temperature conditions from sowing to end of vegetative stage. At a specific reproductive stage, heat tents were moved to increase daytime temperature stress for specific duration. Panicles were marked and specific stage noted at start of stress. After the stress period, data on floret fertility (florets with grain), grain numbers, individual grain weight and grain weight per panicle from tagged plants were determined.

All experiments were irrigated to avoid water stress.

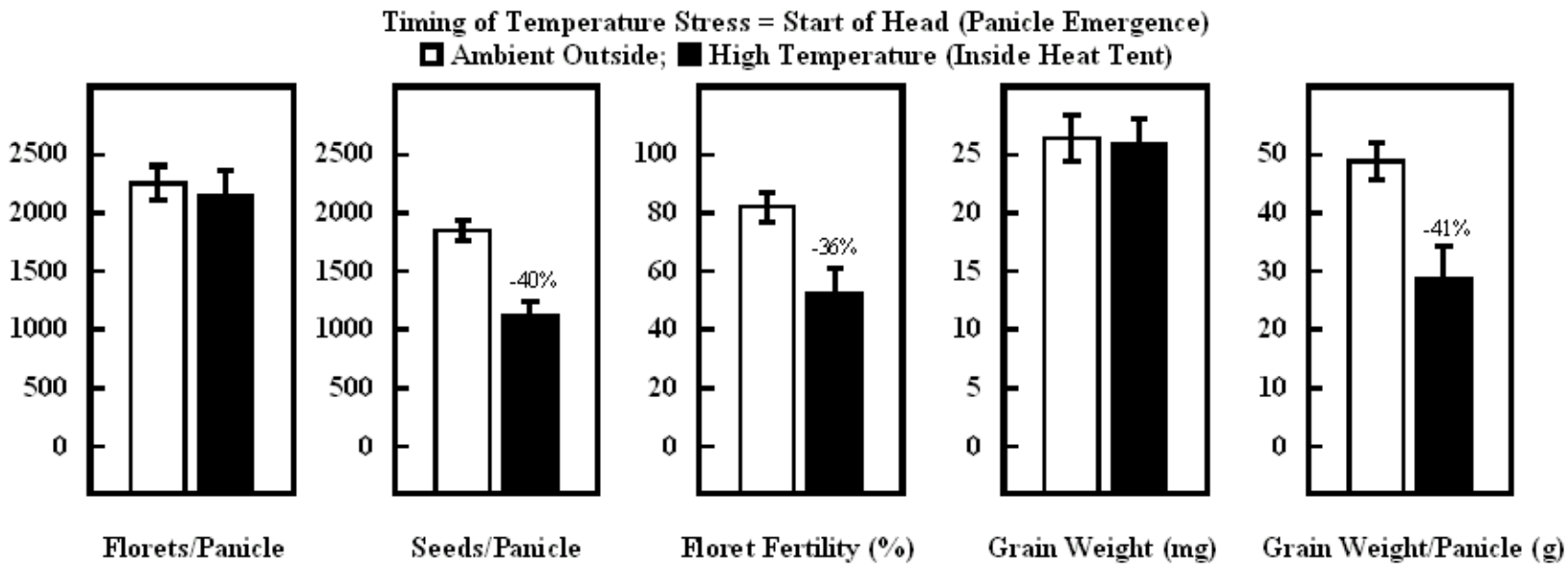
High Temperature Stress: Field (Heat Tents) – Start of Head (Panicle) Emergence



Prasad et al. (Unpublished)

Heat tents increased daytime temperatures by ~ 5 to 8°C.
Nighttime temperature were similar outside and inside heat tents.

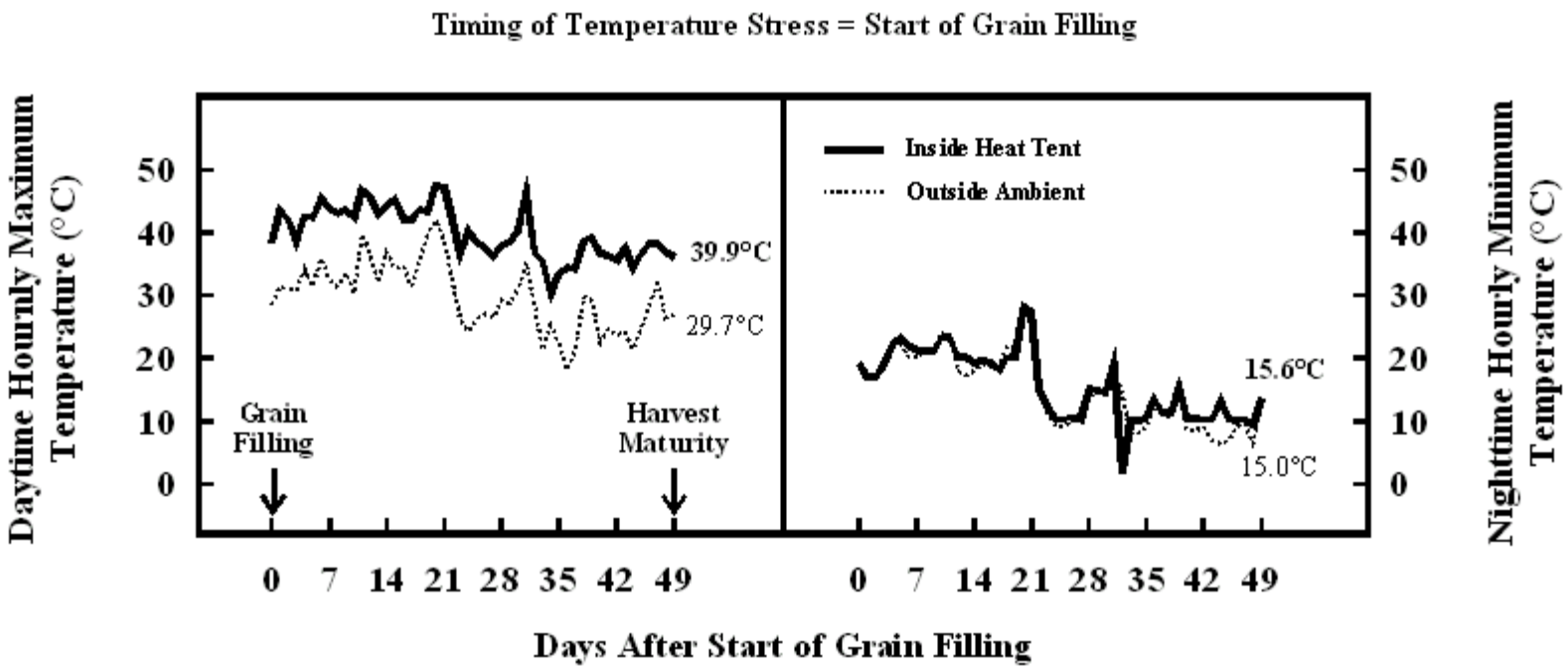
High Temperature Stress: Field (Heat Tents) – Start of Head (Panicle) Emergence – Responses



Prasad et al. (Unpublished)

Stress did not influence floret numbers or individual grain weight.
Decreased floret fertility, seeds/panicle & grain weight/ panicle.

Temperature Stress: Field (Heat Tents) – Start of Grain Filling

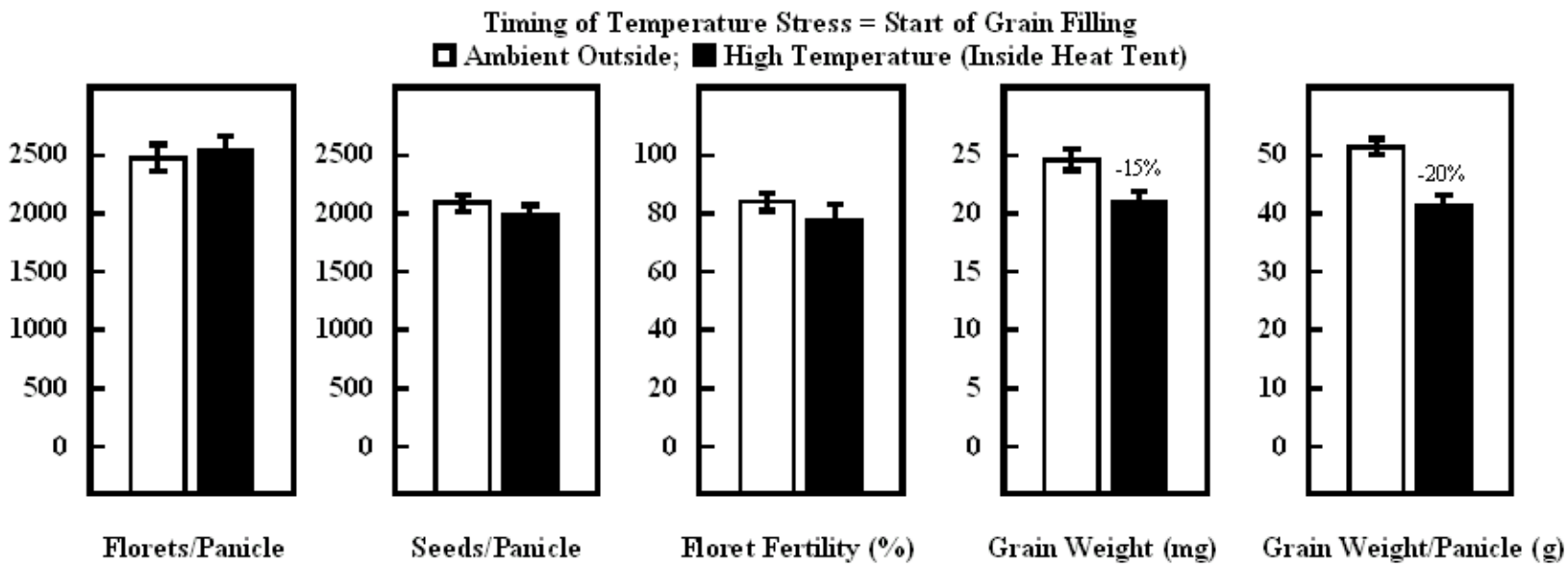


Prasad et al. (Unpublished)

Heat tent increased daytime temperatures by ~ 6 to 10°C.

Nighttime temperatures were similar outside and inside heat tents.

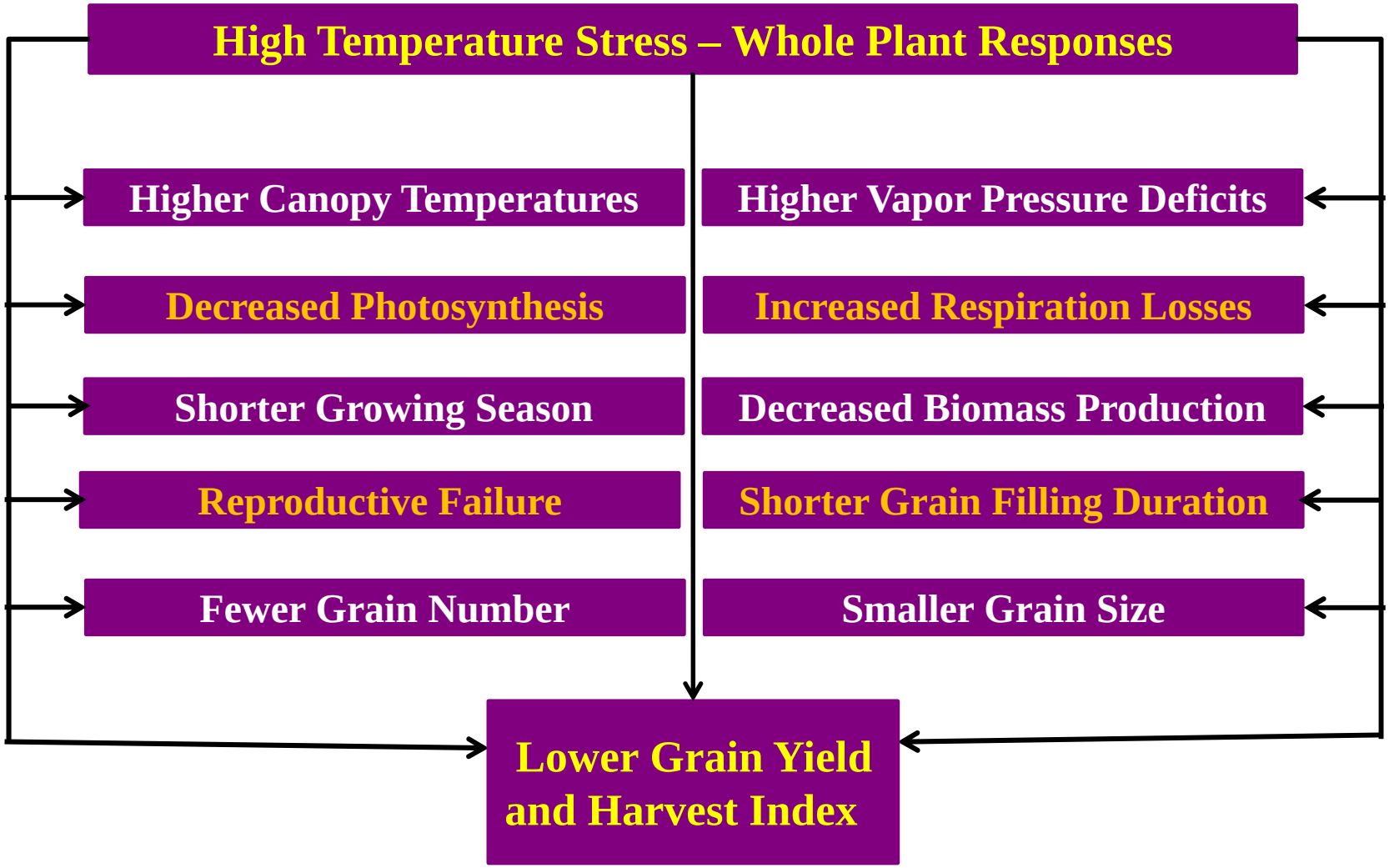
High Temperature Stress: Field (Heat Tents) – Start of Grain Filling – Responses



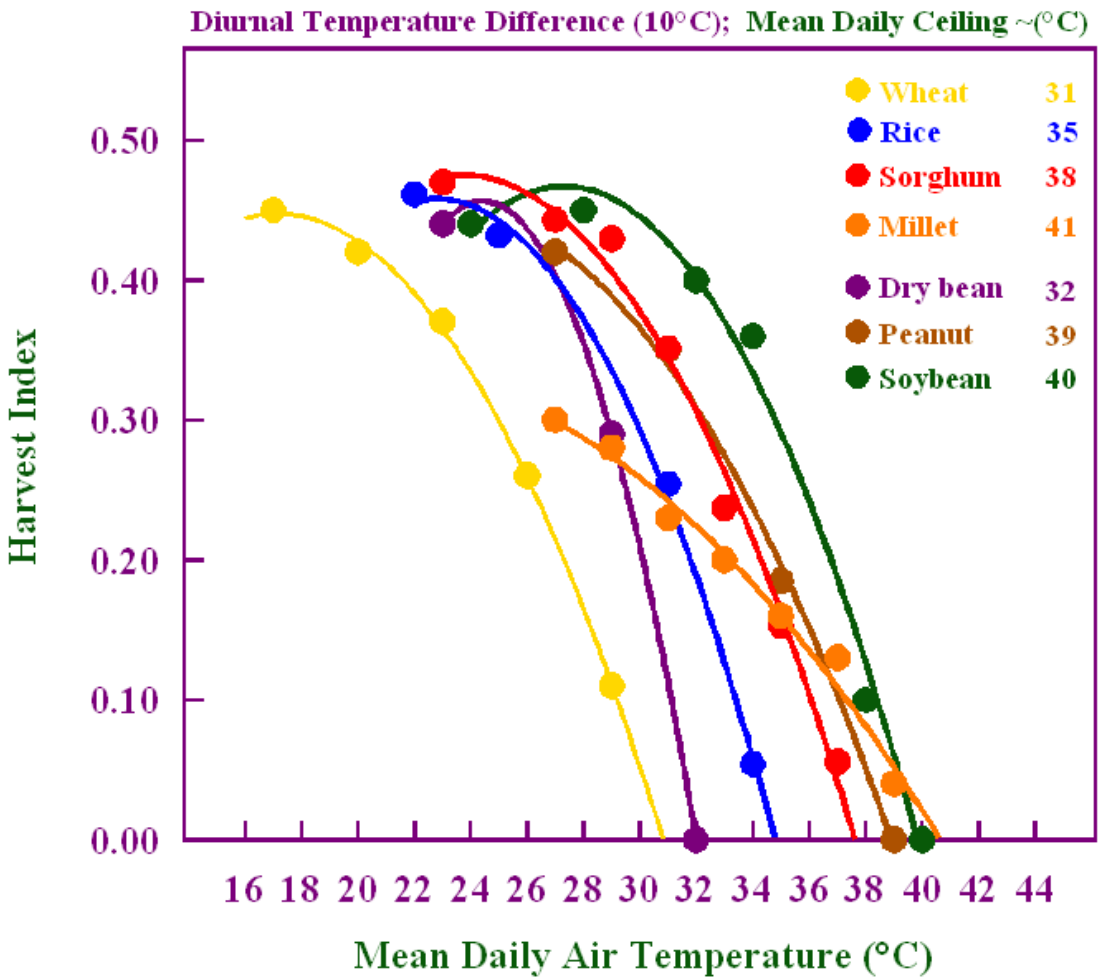
Prasad et al. (Unpublished)

Did not effect floret numbers, floret fertility or seeds/ panicle.
Decreased individual grain weight and grain weight per panicle.

High Temperature Stress: Responses – Summary



Temperature Thresholds: Summary for Crops



Season long elevated temperatures decreased harvest index due to lower seed yields caused by decreased seed-set and seed size.

Bean: Prasad et al., 2002. Global Change Biol. 8: 710-721.
Peanut: Prasad et al., 2003. Global Change Biol. 9: 1775-1787.
Sorghum : Prasad et al., 2006. Agric. For. Meterol. 139: 237-251.
Millet: Prasad (Unpublished).
Rice: Snyder, 2000. M.Sc Thesis, University of Florida.
Soybean: Pan, 1996; Thomas, 2001. PhD Thesis, Univ. Florida.
Tropical Sorghum: Prasad (Unpublished).
Wheat: Prasad (Unpublished).

Opportunities: Genetic Improvement – Traits and Opportunities

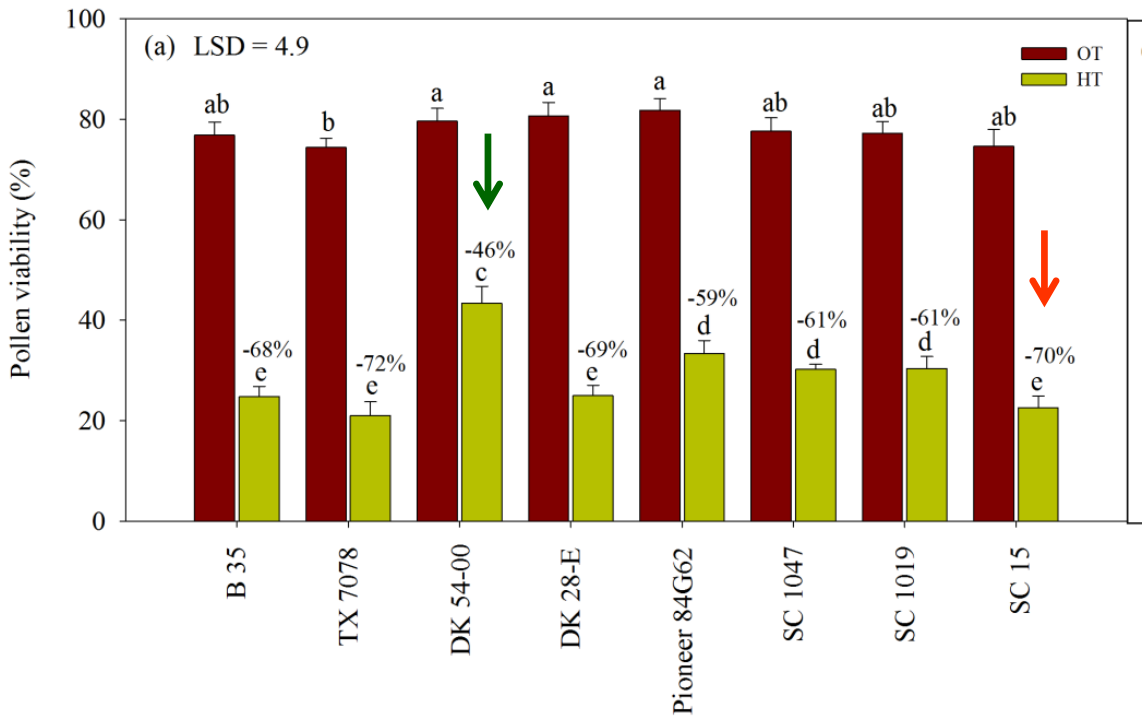
High Temperature Stress: Potential Traits

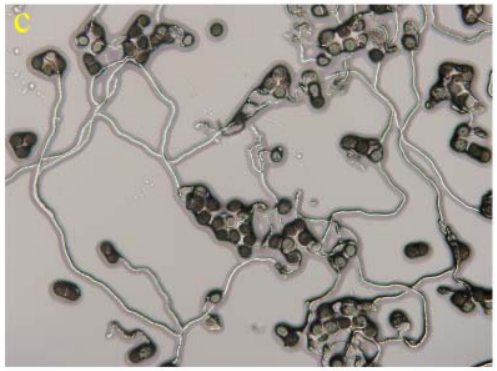
My Top Four Picks

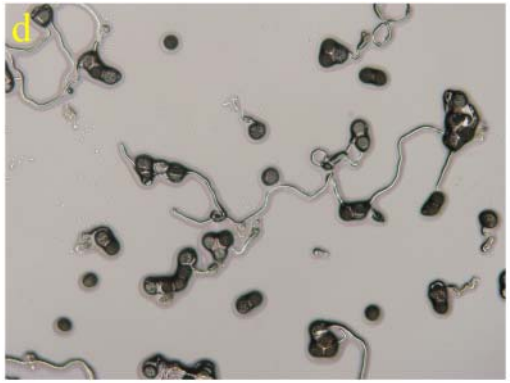
- Reproductive Success (Seed-set) – Seed Numbers
- Time of Day of Flowering – Seed Numbers
- Favorable Respiration – Increased Biomass & Partitioning
- Grain Filling Duration and Grain Filling Rate – Seed Size

Grain yield is a function of higher seed numbers, greater biomass and partitioning to grain and seed size.

Genetic Variability: Pollen Germination – Sorghum







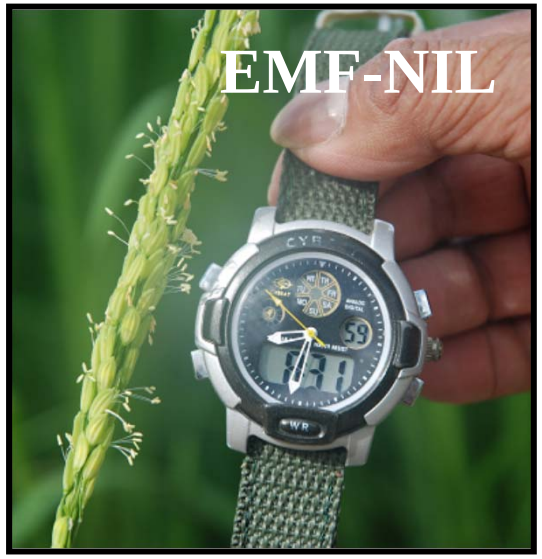
Djanaguiraman et al. (2014). Environ. Exp. Botany. 100: 43-57.

High temperatures decreased pollen viability and germination.
SC15 and TX7078 had relatively higher decrease.

Genetic Variability: Escape (Early Morning Flowering) – Rice

Prasad et al. (2006). Field Crops Research 95: 398-411

Rice Species	Time of day of flowering
Oryza sativa	9:00 am to 12:30 pm
Oryza glaberrima	7:00 am to 8:30 am
Inter-specific crosses	7:00 am to 8:30 am

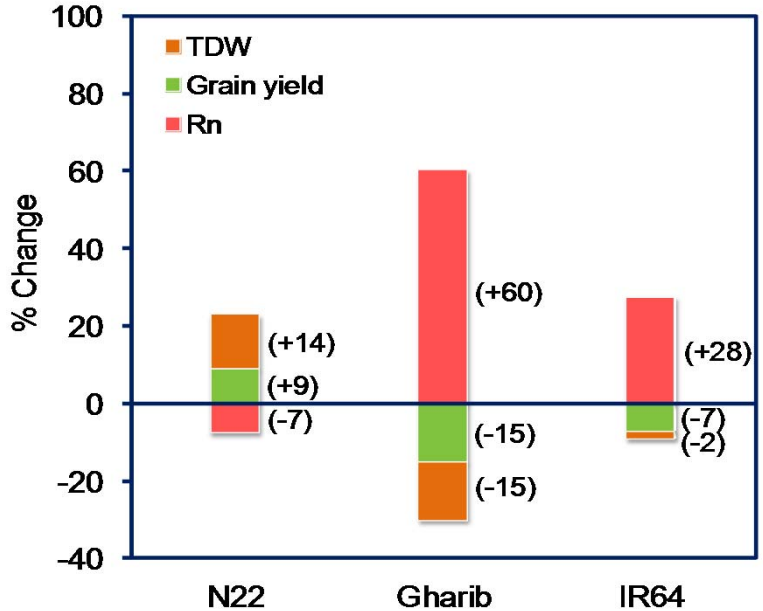


Introgression line from O. officinaris

Ishimaru et al., 2010 Ann. Bot. 106: 515–520

Rice genotypes in indica background with QTL introgressed from wild species are available.

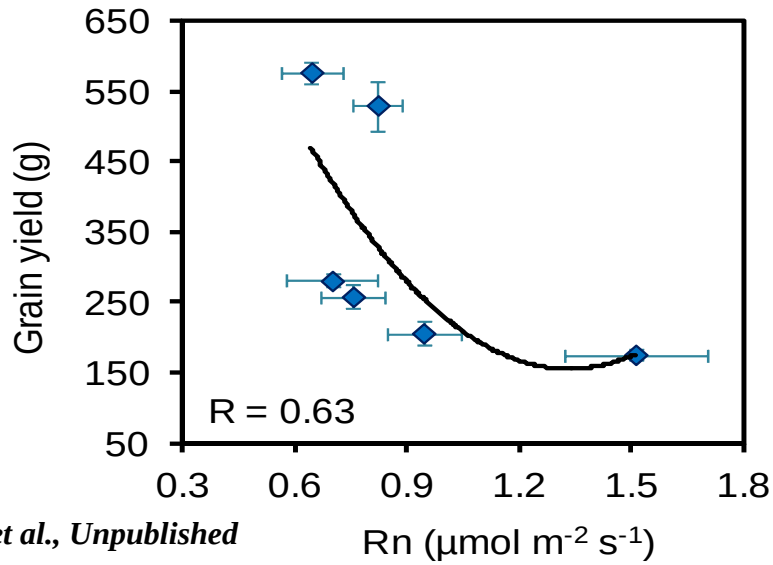
Genetic Variability: Favorable Respiration – Rice



-43 entries screened (22 vs. 28°C)

-Contrasting entries identified

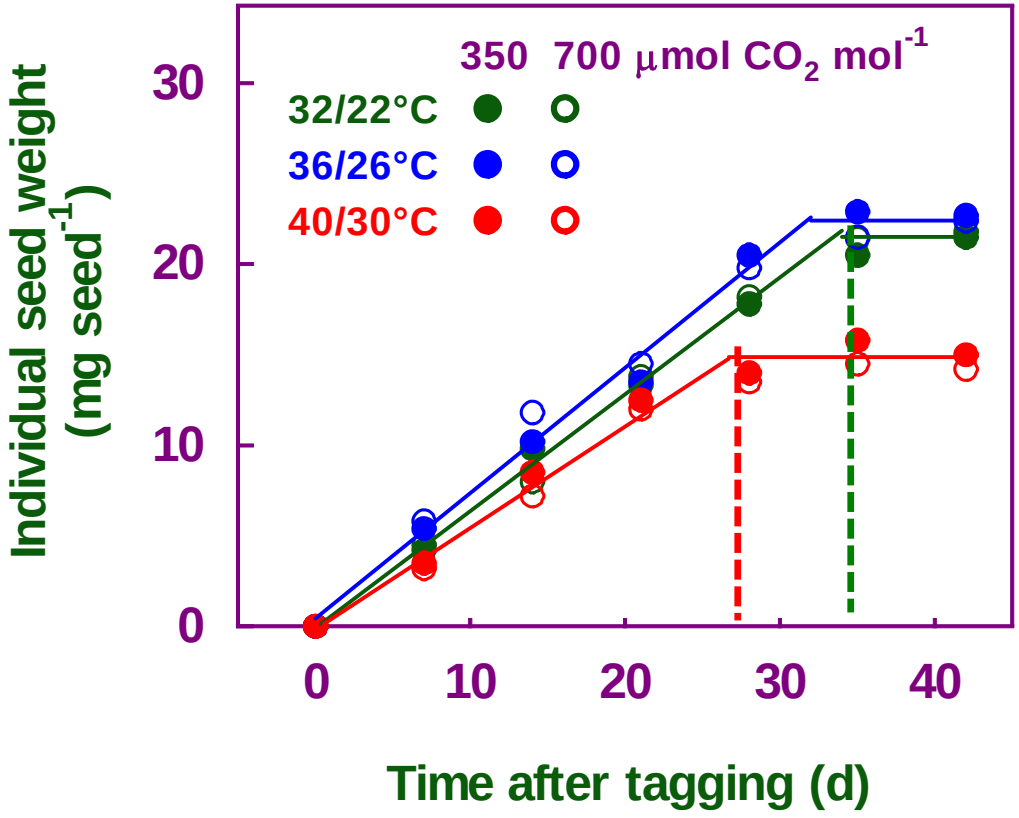
Post-anthesis Respiration Accounts for Yield Loss



W. Shi et al., 2013 New Phytologist , 197, 825–837

Bahuguna et al., Unpublished

Genetic Variability : Grain Filling Duration and Rate?



Prasad et al. (2006) Agric. Forest Meteorol. 139: 237-251.

Decreased seed size at elevated temperature was mainly due to decreased seed filling duration. Is there genetic variability?

Drought Stress: Short Episodes – Sensitive Stages

Drought Stress: Sensitive Stages

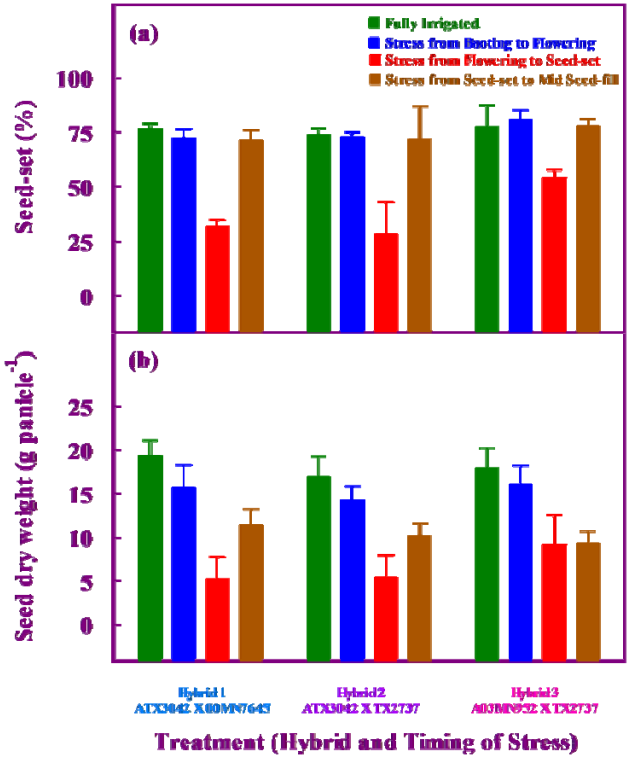


Image 2: Sorghum panicles in (a) fully irrigated; and (b) drought stress conditions during prior to and at flowering.
Photos taken at similar magnification.

Drought stress during panicle development decreased panicle size and percent seed-set.

Most sensitive stage was at flowering (anthesis).

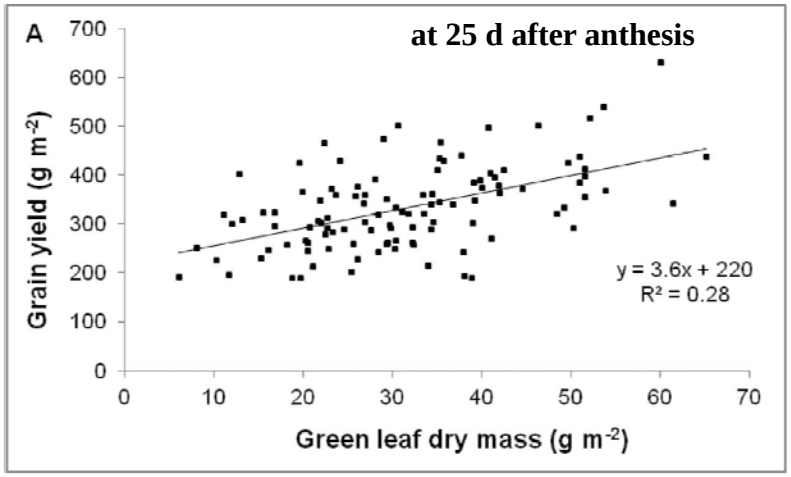
Opportunities: Genetic Improvement – Traits and Opportunities

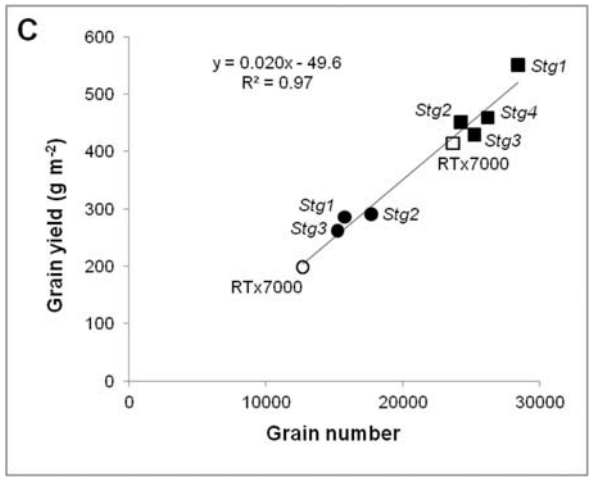
Drought Stress: Potential Traits

My Top Four Picks

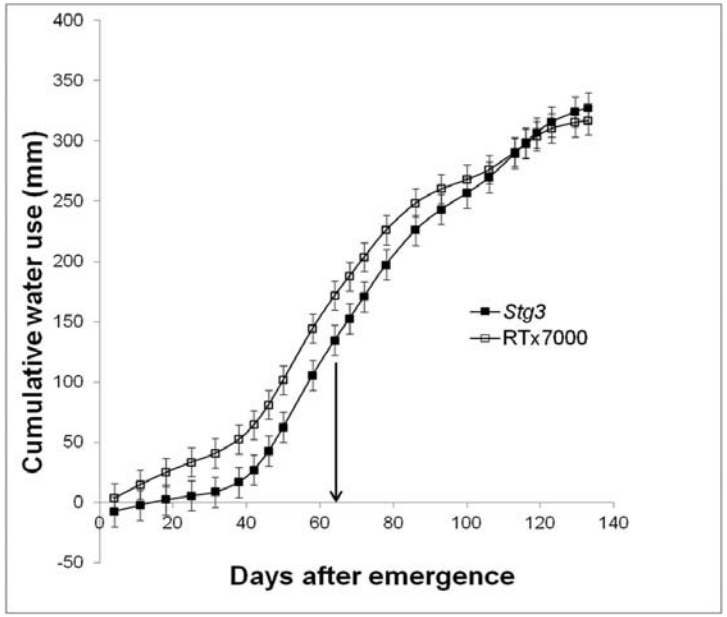
- **Stay Green (longer green leaf area duration)**
- **Limited Transpiration (water savings in early season so that water available during flowering and grain filling)**
- **Water Use Efficiency (water productivity)**
- **Efficient Root System (root angle and/or rooting depth; increased resource (water and nutrient capture)**

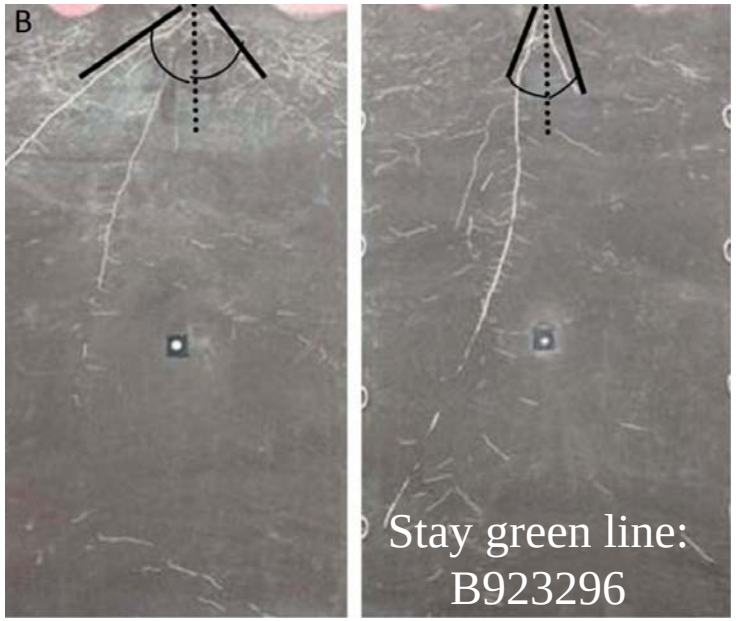
Genetic Variability: Stay Green – Physiology (Borrell et al. 2014)





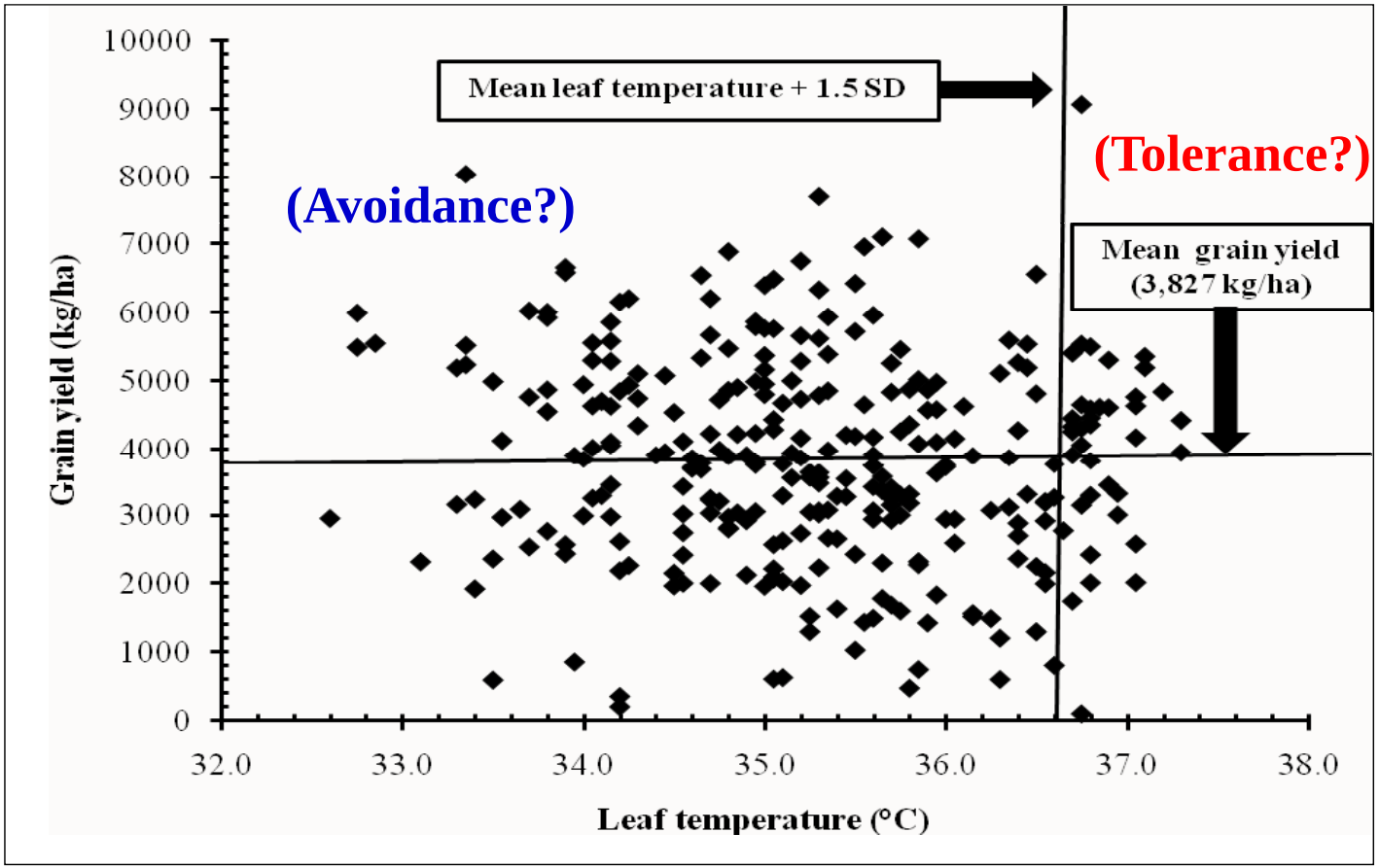
Andrew K. Borrell et al. J. Exp. Bot. 2014;jxb.ers232





Physiology Understood: Borrell et al. (2014) J. Exp. Bot: 65 (21): 6251-6263

Genetic Variability: Leaf Temperature vs. Yield



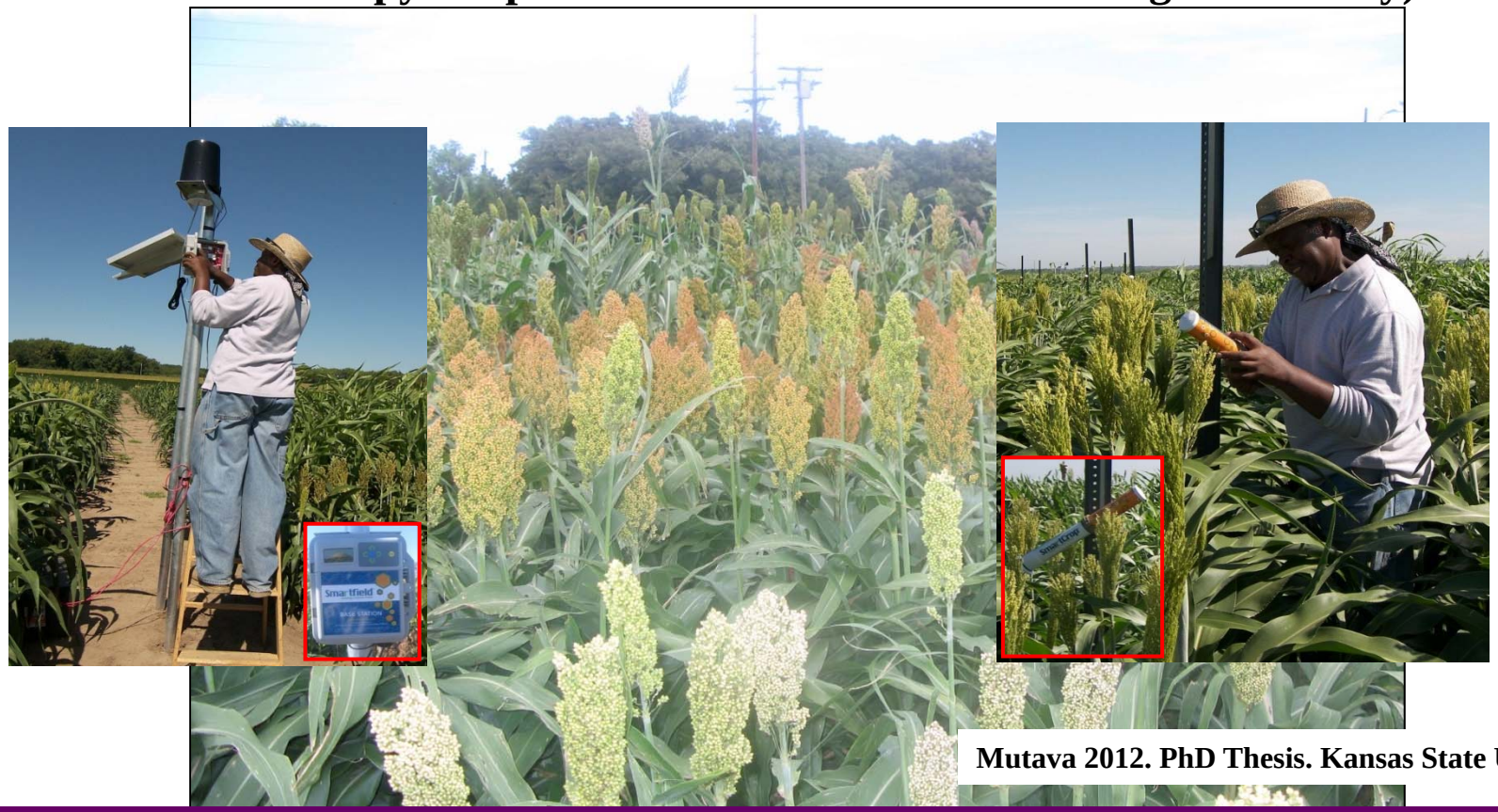
Air Temperature = 32°C

Mutava 2008. MS Thesis, KSU; Mutava et al. (2011). Field Crop Res. 123:10-18

Lines showing high leaf temperature and high yield under irrigated conditions in high vapor pressure deficit (VPD) environment may inherently conserve water without yield penalty, thus they could be drought / heat tolerant. (slow wilting trait!)

Genetic Variability: Field Evaluation – Canopy Temperature

(Search for restricted transpiration (slow wilting lines) – continuous canopy temperature measured from flowering to maturity)



Mutava 2012. PhD Thesis. Kansas State University

Quantified canopy temperature, leaf area index, biomass, yield and yield components.

Genetic Variability: Transpiration Response to VPD

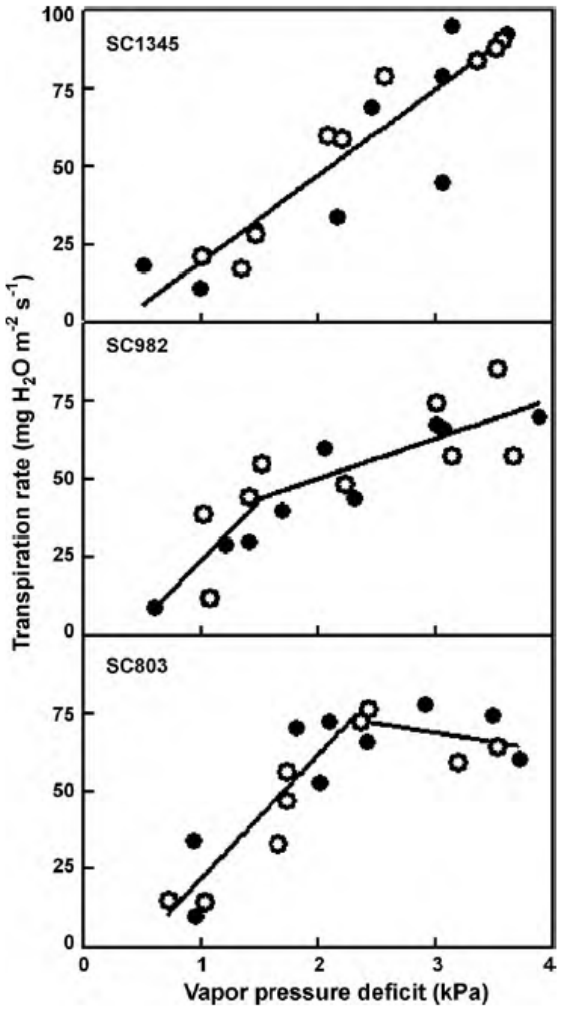


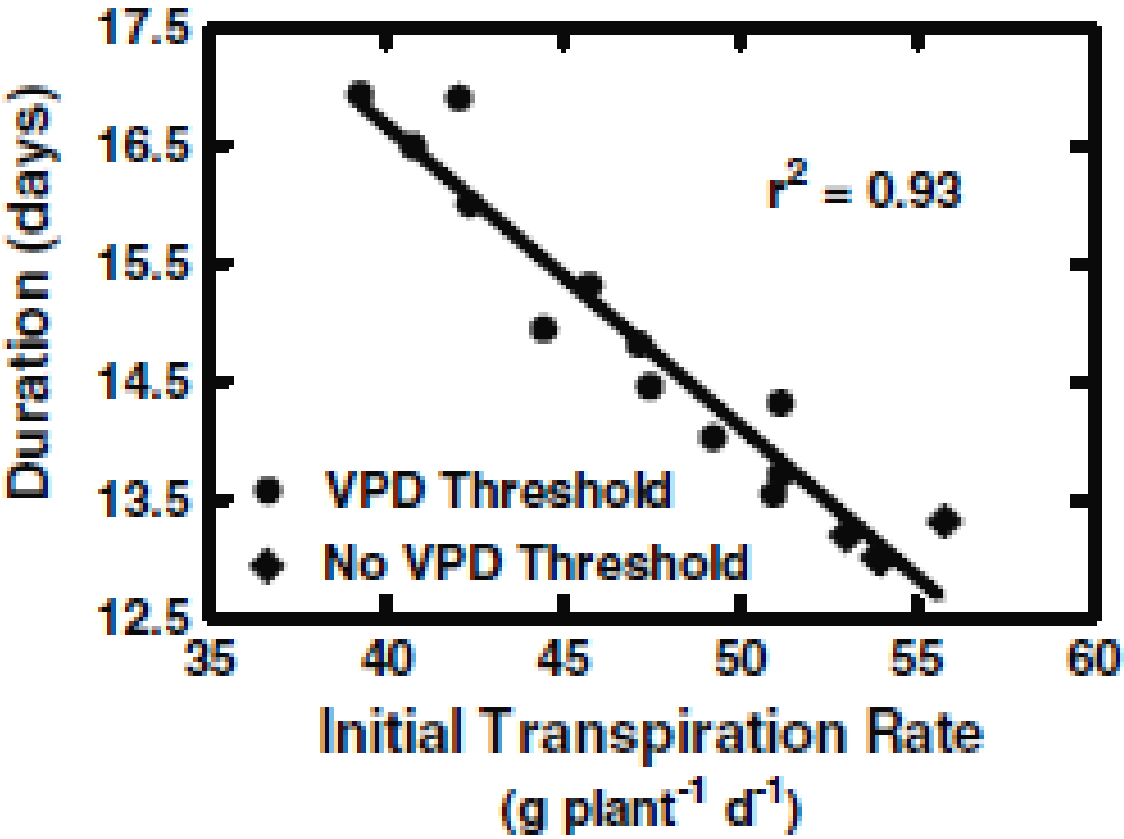
Fig. 1. Transpiration rate response of three genotypes to increasing vapor pressure deficit as three general patterns of response that was found for the tested sorghum genotypes. The two symbols indicate data recorded on 2 consecutive days

- **No break point – these genotypes will run out of water and could face drought during grain filling stages**
- **Genotypes with a high initial slope and a lower break point maximize gas exchange under low VPD and then shift to water conservation at high VPD.**
- **Genotypes with high initial slope and higher break point offer less-restrictive water conservation.**
- **Sorghum genotypes could be selected to pursue soil water conservation as a way to improve yields under water-deficit conditions.**

Gholipoor et al. (2010) Field Crops Res. 119: 85-91.

Genotypes varied in VPD response (break points and slopes).

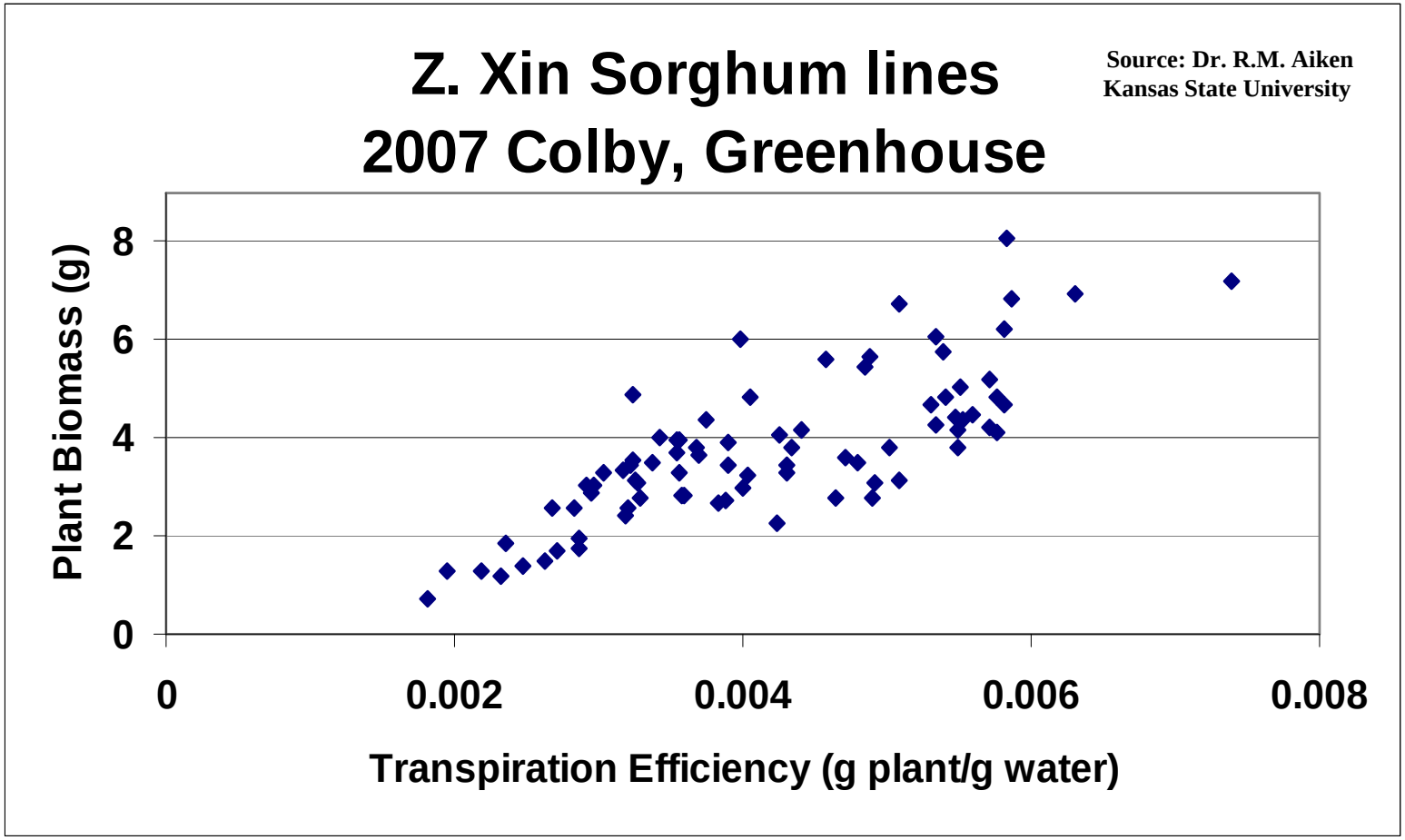
Initial Transpiration Rate: Duration for Water Extraction



Gholipoor et al. (2012): Plant and Soil 357: 35-40

Lower initial transpiration rate was associated with longer duration for complete water extraction.

Genetic Variability: Transpiration Efficiency – Increased Productivity



Higher transpiration efficiency can increase biomass production and grain yield in sorghum.

Genetic Variability: Root Traits – Root Angle and Rooting Depth

Mutava 2013. Ph,D Thesis, KSU

Turface® MVP was used as growing media with Osmocote slow release fertilizer in PVC column 20 cm ID (Inside diameter) by 1m tall.

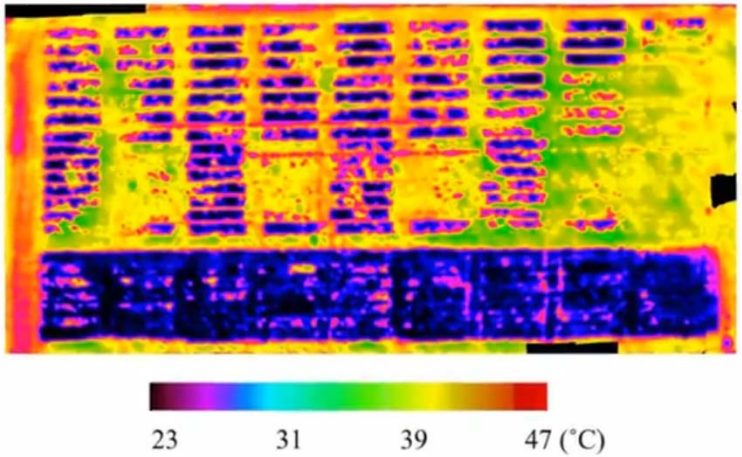
Challenges: Facilities and High Throughput Phenotyping Tools

Challenges: Field Studies – Limited Lines – Heat Tents and Rainout Shelters

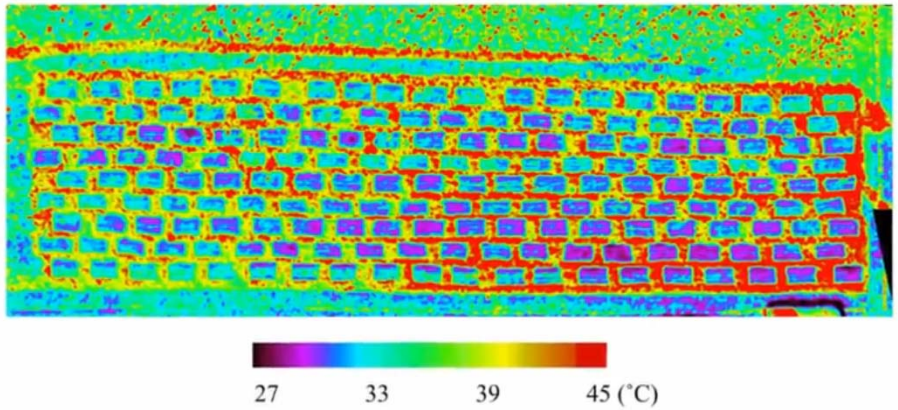
Challenges: High Throughput Phenotyping – Hand Held vs. sUAV (small unmanned aerial vehicles)

Challenges: High Throughput Phenotyping – sUAV (Federal Restrictions?)

Canola Temperature Map

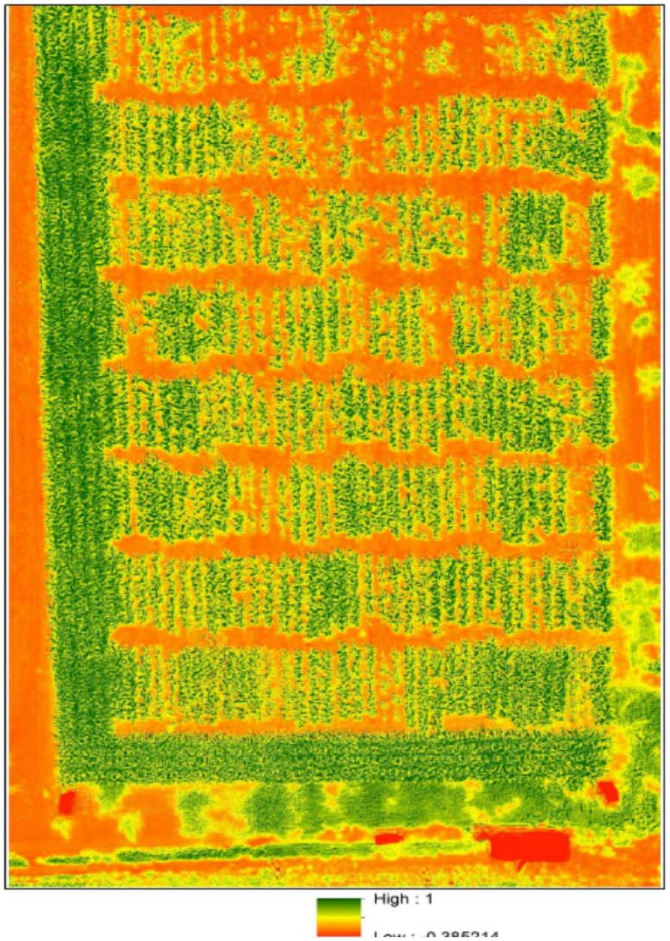


Winter Wheat Temperature Map

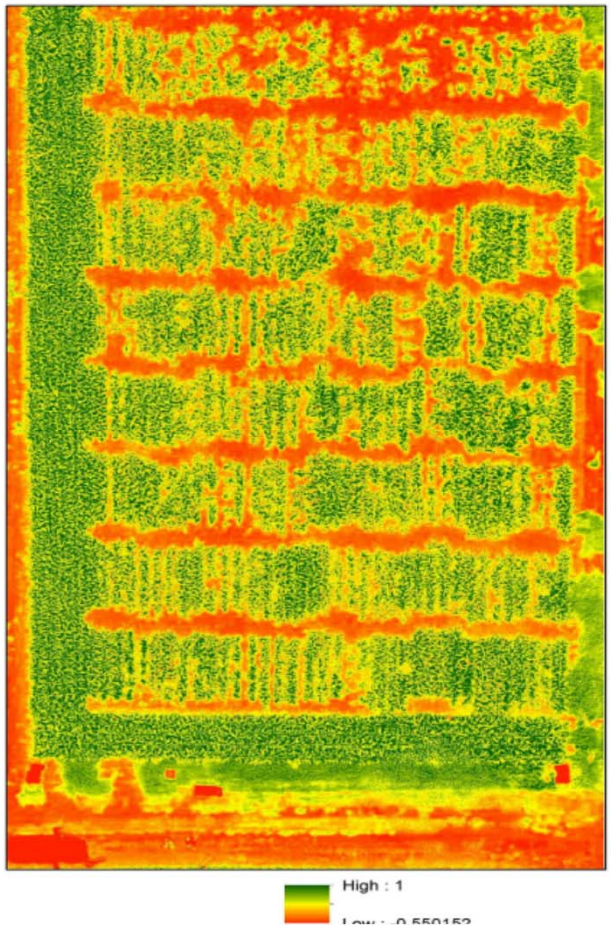


Challenges: High Throughput Phenotyping – sUAV (Federal Restrictions?)

August 20, 2014 E3NDVI (stdev 1.5)



September 16, 2014 E3NDVI (stdev 1.5)



Sorghum Field: NDVI of NAM parents – Manhattan, KS

High Temperature and Drough Stress: Conclusions

- **There were strong negative effects of high temperatures and drought stress on biomass, partitioning and reproductive processes leading to decreased seed number, seed size and grain yield.**
- **Reproductive stages of crop development (particularly flowering and grain filling) are relatively more sensitive. Good understanding of thresholds and mechanisms.**
- **Some genetic variability exists – requires systematic evaluation of germplasm resources. Targeted breeding for both drought and heat tolerance is required.**
- **Major limitations are screening facilities and accurate and fast high throughput phenotyping techniques.**

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Kansas GRAIN SORGHUM Commission

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K·STATE Research and Extension

Physiological Response of Grain Sorghum to High Temperature and Drought Stress: Understanding, Opportunities and Challenges

Presentation to SICNA Meeting – 02 September 2015

Questions and Discussion

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Thank you for your attention.