Crop Growth under Extreme Environments
High and Low Temperatures

K. Raja Reddy
Mississippi State University
Mississippi State, MS
Plant Responses to Extreme Environments

High Temperature Injury
Plants lack locomotion
They should either adapt or tolerate stress
Plant Responses to Extreme Temperatures

• Few plant species can survive a steady high temperatures above 45 °C

✓ Actively growing tissues can rarely survive over 45°C

✓ However, non-growing cells or organs (Pollen and seed) can survive much higher temperatures.

  - some pollen up to 70 °C
  - some seed up to 120 °C.

• Heat stress is also a major problem in greenhouses, where low air speed and high humidity decreases leaf cooling and thus affecting leaf/canopy temperatures.
Plant Responses to High Temperatures

• Plants do adapt to high temperature:
  ✓ Reflective leaf hairs and waxes
  ✓ Leaf rolling, and vertical leaf orientation
  ✓ Small leaves and dissected (okra) leaf morphology
  ✓ Synthesis of heat-shock proteins (HSPs)

  ⇒ Help cells withstand heat stress

  ⇒ However, the functions of all HSPs are not yet fully known, but many act as molecular chaperons, help stabilize and fold proteins, assist in polypeptide transport across membranes, protect enzymes, etc.
Plant Critical Processes at High Temperatures

- Photosynthesis and respiration, and conductivity will be affected by high temperatures.
- However, photosynthesis declines faster than respiration and conductivity at high temperatures.
- The point when the amount of CO$_2$ fixed equals to the amount of CO$_2$ released by respiration is called temperature compensation point. At this point and beyond, the carbon is not replaced, and carbohydrate reserves will be used for cellular functions.
- Therefore, the imbalance between photosynthesis and respiration causes deleterious effects at high temperatures.
Plant Critical Processes at High Temperatures

- The question is how do plant groups respond to high temperatures?
- Enhanced temperatures are more detrimental in $C_3$ plants than in $C_4$ or CAM plants because of rates of both dark and photorespiration are increased more in $C_3$ plants.
- What happens to $C_3$ plants under elevated CO$_2$ conditions?
Climatic Zones and Temperature Conditions

Tropical zone, Djibol, Senegal
- Daily maximum
- Monthly mean
- Daily minimum

Subtropical zone, Gainesville, Florida
- Daily maximum
- Monthly mean
- Daily minimum

Temperate zone, Spokane, Washington
- Daily maximum
- Mean
- Daily minimum

Boreal zone, Fairbanks, Alaska
- Daily maximum
- Mean
- Daily minimum
Long-Term Average Temperatures

Day of the Year

Temperature, °C

0 50 100 150 200 250 300 350

Phoenix, AZ

Maros, Indonesia

Stoneville, MS

Long-Term Average Temperatures for Phoenix, AZ, Maros, Indonesia, and Stoneville, MS, showing temperature variations throughout the year.
Long-term Average Temperatures for Four US Cotton Producing Areas

- Corpus Christi, Texas: Days above Optimum = 85
- Phoenix, Arizona: Days above Optimum = 111
- Stoneville, Mississippi: Days above Optimum = 0
- Bakersfield, California: Days above Optimum = 36
Hourly Temperatures for July 1995
Mississippi State, MS
Diurnal temperature data recorded in June 1989 at Fatehpur, Rajasthan, India, (Latitude 27ºC 37'N).

5 cm depth of soil (▲)
0.5 cm depth of soil (●)
150 cm above the soil surface (■)

Howarth, 1991
Climate Change and Crop Production

- Past changes in greenhouse gases has resulted about 0.6 °C increase in global average temperature during the last century.

- If current and future rates of changes in greenhouse gases and other land-use changes continue, then, these changes will exacerbate the natural climate changes and may result in:
  - 2 to 6 °C warmer temperatures
  - More frequent episodes of extreme events (heat, cold, drought, excessive rainfall resulting in floods, severe hurricanes, etc.).
Second green revolution to overcome environmental stresses
5 bolls per plant with 6 g per boll will yield 1.98 bales per acre
Pima Cotton Responses to Temperatures

The next 3 video clips show cotton responses to optimum (30/22°C, day/night), higher (35/27°C) and super-optimum (40/32°C) temperatures.

Notice that the plants grown in optimum temperatures are producing both vegetative and reproductive structures continuously and there is no abscission of squares or fruiting structures. Plants grown in 35/27°C are producing luxuriant vegetative growth, but some of the squares are being abscised due to excessive heat. If plants are grown in 40/32°C, the vegetative growth is reduced to certain extent compared to plants grown in other temperatures, but there is a complete reproductive failure (no flower-bud initiation and even fruiting branch production) due to excessive heat.
Optimum Temperature
No Injury to Reproductive Parts
Higher Temperature Injury
Partial Injury to Reproductive Parts
Super High Temperature Injury
Total Reproductive Failure, Including Fruiting Branch Production
High Temperature Effects on Cotton – Upland Cotton

![Graph showing the effects of temperature on bolls and squares produced and retained in cotton plants.](attachment:image.png)

- **Produced**: The number of bolls and squares produced increases with temperature up to 30°C and then decreases sharply at 35°C.
- **Retained**: The number of bolls and squares retained increases with temperature up to 30°C and then decreases sharply at 35°C.

**Temperature, °C**: 15, 20, 25, 30, 35

**Bolls and Squares, no. plant⁻¹**: 0, 10, 20, 30, 40, 50, 60, 70, 80
High Temperature Effects on Cotton – Pima Cotton

![Graph showing the effect of temperature on the number of bolls and squares per plant. The x-axis represents temperature in °C, ranging from 15 to 35. The y-axis represents the number of bolls and squares per plant, ranging from 0 to 100. Two lines are shown, one for CO₂ concentration of 700 µl l⁻¹ and the other for 350 µl l⁻¹. The graph illustrates that as temperature increases, the number of bolls and squares decreases, with a peak at approximately 25 °C.]
Table 1. Effect of temperature on cotton growth, cv. Stoneville 825, harvested 49 days after initiation of temperature treatments. Treatments are imposed at first flower. Standard error of the mean values are shown.

<table>
<thead>
<tr>
<th>Day/Night Temperature, °C</th>
<th>Grams per Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/12</td>
<td>242</td>
</tr>
<tr>
<td>25/15</td>
<td>320</td>
</tr>
<tr>
<td>30/20</td>
<td>330</td>
</tr>
<tr>
<td>35/25</td>
<td>293</td>
</tr>
<tr>
<td>40/30</td>
<td>225</td>
</tr>
</tbody>
</table>

Total Wt.  
% of Optimum  
Bolls  
% of Optimum
Environment - Crop Growth – High Temperatures
Injury to Reproductive Parts

![Graph showing the relationship between temperature and boll production and retention.](image-url)
### Projected Temperatures and Cotton Development

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Days to the Event</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Square</td>
<td>Flower</td>
<td>Open Boll</td>
</tr>
<tr>
<td>1995 minus 2°C</td>
<td>33</td>
<td>65</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>1995 plus 0°C</td>
<td>26</td>
<td>51</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>1995 plus 2°C</td>
<td>24</td>
<td>48</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>1995 plus 5°C</td>
<td>21</td>
<td>42</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>1995 plus 7°C</td>
<td>19</td>
<td>39</td>
<td>No Fruit</td>
<td></td>
</tr>
</tbody>
</table>

No significant differences were observed between CO₂ levels
High Temperature Injury
Temperature and CO2 Interactions

Vegetative Biomass

Temperature Deviation from 1995, °C

Vegetative Weight, g plant$^{-1}$

- **360 CO$_2$ µL L$^{-1}$**
- **720 CO$_2$ µL L$^{-1}$**

Temperature Deviation from 1995, °C:
- 1995-2
- 1995
- 1995+2
- 1995+5
- 1995+7
High Temperature Injury

Temperature and CO2 Interactions – Cotton

Fruiting Sites

- 360 CO2 µl l⁻¹
- 720 CO2 µl l⁻¹

Bolls and Squares, no plant⁻¹

Temperature Deviation from 1995, °C

High Temperature Injury
Temperature and CO2 Interactions – Cotton

Retained Bolls

- 360 CO₂ µl l⁻¹
- 720 CO₂ µl l⁻¹

Temperature Deviation from 1995, °C

- 1995-2
- 1995
- 1995+2
- 1995+5
- 1995+7

Retained Bolls, no plant⁻¹
High Temperature Injury
Temperature and CO2 Interactions – Cotton

Boll weight

![Graph showing the relationship between temperature deviation from 1995, °C, and boll weight with CO2 levels.

- **360 CO2 µL L⁻¹**
- **720 CO2 µL L⁻¹**

**Temperature Deviation from 1995, °C:**

**Boll Weight, g plant⁻¹:**
0, 50, 100, 150, 200, 250, 300, 350, 400

- **1995-2**
- **1995**
- **1995+2**
- **1995+5**
- **1995+7**
High Temperature Injury
Temperature and CO2 Interactions – Cotton

Fruit Production Efficiency

Fruit Production Efficiency (g kg\(^{-1}\) Dry Weight)

Temperature, °C

- 700 µL L\(^{-1}\)
- 350 µL L\(^{-1}\)
High Temperature Injury
Using Simulation Models – Cotton Lint Yield

Cotton Lint Yield and Climate Scenarios

- Current + Ambient CO₂
- Current + Elevated CO₂
- Future + Elevated CO₂

Climate Change Scenario:
- Hot Dry
- Hot Wet
- Cold Dry
- Cold Wet
- Normal

Reddy et al. 2002
High Temperature Effects on Cotton
Heat-blasted Squares – San Joaquin Valley, California, USA

Figure 7. Heat-blasted squares in California’s San Joaquin Valley. (Photo: R. Vargas)
High Temperature Effects on Cotton
Heat-blasted Flowers – San Joaquin Valley, California, USA
High Temperature Effects on Cotton

The high temperature injury in cotton to reproductive growth and development is not fully understood so far.

High temperature causes some heat-sensitive cultivars/species (Pima cotton) to be vegetative (total reproductive failure and the reproductive induction process is sensitive). Not much is known why plants stay vegetative at those high temperature conditions.

Once the flower-buds (squares) are formed, exposure to extremely high temperatures (35/27°C) will result in abscission of squares.
High Temperature Effects on Cotton

- Nutrient starvation is not the factor that causes that square abortion because plants grown in elevated or twice ambient CO₂ and under optimum nutrient conditions also drop those squares, and the nutrient demand for squares is minimal.

- The evidence suggest that the 2 weeks prior to and 1 week post flower is the most sensitive stage in cotton.

- Systematic evaluation is needed to quantify the effects of high temperature on both the male (anther, pollen growth and development) and female (ovule growth and development).
High Temperature Effects on Cotton

• Breeders need simple and quantitative methods to screen genotypic variability and to find or breed a genotype to a niche environment for optimum crop production.

• Biotechnology may play a role in developing cultivars that are more heat-tolerant.

• Heat-tolerance will be beneficial even in today’s environment, and will be needed more in a warmer future climatic conditions.
High Temperature Injury
Temperature and CO2 – Rice Growth

Biomass, g plant$^{-1}$

Temperature, °C

20\% more at 660 than at 330

Baker and Allen, 1993
High Temperature Injury
Temperature and CO2 – Rice

Baker and Allen, 1993
Cooling degree days are calculated based on air temperatures and with a base temperature of 22 °C. 22 – mean temperature

Fig. 4.5. Relation between cooling degree-days and percentage spikelet (γ) sterility of the variety Eiko between booting and flowering stages (Horie, 1988 constructed from data of Shibota et al., 1990).
High Temperature Effects on Rice Fertility

Fig. 4.6. Relation between average daily maximum temperature during the flowering period and spikelet fertility in the variety Akihikari acclimated to different CO$_2$ concentrations (Horie, 1993).
High Temperature Effects on Rice Yields

Baker et al., 1993

CO$_2$, µl l$^{-1}$
- 300
- 700

Grain Yield, Mg ha$^{-1}$

Temperature, °C
Rice Growing Areas – Weather Stations (67 locations)

Fig. 2.1. Locations of the weather stations used in the study.
Growing season temperatures from those locations listed in the previous slide and with an additional 5°C added to those temperatures relative to optimum and marginal conditions.

From the data presented in Slide 16, we can estimate:
- Ambient temperature: 25.36°C = 8.26 Mg/ha
- Ambient plus 5°C: 30.36°C = 5.51 Mg/ha, 33%

Sites

Temperature, °C
High Temperature Injury
Temperature and CO₂ Interactions – Sorghum

Seed Weight and Seed-set

- Seed weight, g plant⁻¹
- Seed-set, %

Air temperature (°C)

- 700 µmol CO₂ mol⁻¹
- 350 µmol CO₂ mol⁻¹
High Temperature Injury
Temperature and CO2 Interactions – Sorghum

Pollen Germination

- Elevated temperature decreased pollen longevity.
- Elevated CO2 had no effect.

Prasad et al. 2005
High Temperature Injury
Temperature and CO2 Interactions – Dry Beans

Total Weight and Seed Weight

- Elevated temperatures decreased total dry weights and seed yields.
- Elevated CO$_2$ increased seed yields but to a lesser extent at high temperatures.

Prasad et al. 2005
Harvest, index, seed size, shelling percentage, seed-set, pollen viability and seed number did not change between CO2 levels, but drastically reduced with increase in temperatures.

Prasad et al. 2005
High Temperature Injury
Temperature and CO2 – Rangeland C4 Grass – Big Bluestem

Vegetative Weight and Seed Weight

Kakani and Reddy, 2006
# Temperature Effects on Crop Yield
## Several Major Crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Topt, °C</th>
<th>Tmax, °C</th>
<th>Yield at Topt, t/ha</th>
<th>Yield at 28 °C, t/ha</th>
<th>Yield at 32°C t/ha</th>
<th>% decrease (28 to 32 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>25</td>
<td>36</td>
<td>7.55</td>
<td>6.31</td>
<td>2.93</td>
<td>54</td>
</tr>
<tr>
<td>Soybean</td>
<td>28</td>
<td>39</td>
<td>3.41</td>
<td>3.41</td>
<td>3.06</td>
<td>10</td>
</tr>
<tr>
<td>Dry bean</td>
<td>22</td>
<td>32</td>
<td>2.87</td>
<td>1.39</td>
<td>0.00</td>
<td>100</td>
</tr>
<tr>
<td>Peanut</td>
<td>25</td>
<td>40</td>
<td>3.38</td>
<td>3.22</td>
<td>2.58</td>
<td>20</td>
</tr>
<tr>
<td>Grain sorghum</td>
<td>26</td>
<td>35</td>
<td>12.24</td>
<td>11.75</td>
<td>6.95</td>
<td>41</td>
</tr>
</tbody>
</table>

Allen et al., 2000
# High Temperature Effects on Growth Stages of Major Crops

Table 3.4 High temperature effects on growth stages of major crops (from Acock and Acock, 1993)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Temperature $&gt;30^\circ$C for $&gt;8$ h, can reverse vernalization</td>
</tr>
<tr>
<td>Rice</td>
<td>Temperature $&gt;35^\circ$C for $&gt;1$ h at anthesis causes spikelet sterility</td>
</tr>
<tr>
<td>Maize</td>
<td>Temperature $&gt;36^\circ$C causes pollen to lose viability</td>
</tr>
<tr>
<td>Soybean</td>
<td>Great ability to recover from stress. No especially critical period in its development</td>
</tr>
<tr>
<td>Potato</td>
<td>Temperature $&gt;20^\circ$C depresses tuber initiation and bulking</td>
</tr>
<tr>
<td>Cotton</td>
<td>Temperature $&gt;40^\circ$C for $&gt;6$ h causes bolls to abort</td>
</tr>
</tbody>
</table>
There are no beneficial effects of elevated CO₂ on reproductive processes.

There are no beneficial interaction of CO₂ on temperature effects on reproductive processes and yield.

Negative effects of elevated temperature on seed set, seed yield and harvest index were greater at elevated CO₂ (grain sorghum, dry bean and big blue stem).
Plant Responses to Extreme Environments
Chilling and Freezing Temperature Injury
There are no beneficial effects of elevated CO$_2$ on reproductive processes in the crops investigated (cotton, soybean, rice, sorghum and beans).

There are no beneficial interaction of temperature on UV-B effects on reproductive processes.

High temperatures and higher UV-B aggravated the damaging effect on many reproductive processes.

Elevated CO$_2$ did not ameliorate the damaging effects of either higher temperatures or elevated UV-B levels.
• Sensitive plant species are injured by chilling at temperatures (10 to 15°C) that are too low for normal growth but not low enough for ice to form.
• Typically, tropical or subtropical species (crops such as maize, beans, rice, tomato, cucumber, sweet potato, cotton, and ornamental such as *Coleus, Pasiflora* etc.) are susceptible to chilling injury.
• Typical symptoms include:
  - Growth is slowed
  - Discoloration on foliage
  - Leaves appear as if they are soaked in water
  - If roots are chilled, then plants may wilt.
Low Temperature Injury
Chilling and Freezing stress

- Physiological changes: Membrane properties change in response to chilling injury:
  - Inhibition of photosynthesis
  - Inhibition of carbohydrate translocation
  - Slower respiration rates
  - Inhibition protein synthesis
  - Increased degradation of existing proteins
  - Solutes leak

- Plants will synthesize more unsaturated fatty acids (more double bonds), at least, in the chill-resistant plants. Also, more of the simple sugars such as sucrose will be formed under chilling.
### Percent weight of total fatty acid content

<table>
<thead>
<tr>
<th>Major fatty acid</th>
<th>Chill-resistant species - Cauliflower</th>
<th>Chill-sensitive species - maize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palmitic (16:0)</td>
<td>21.3</td>
<td>28.3</td>
</tr>
<tr>
<td>Steric (18:0)</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Oleic (18:0)</td>
<td>7.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Linoleic (18:2)</td>
<td>16.4</td>
<td>54.6</td>
</tr>
<tr>
<td>Linolenic (18:3)</td>
<td>49.4</td>
<td>6.8</td>
</tr>
<tr>
<td>Ratio of unsaturated to saturated fatty acids</td>
<td>3.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Freezing (<0°C) kills plants by forming intracellular ice crystals or by dehydrating the protoplast.

The ability of plants to tolerate freezing temperatures under natural conditions varies greatly among chill-resistant plants.

Continued exposure to freezing temperatures may lead to death of the plants.

Some freeze-resistant plants may synthesize antifreeze proteins, which will bind to the surfaces of ice crystals and prevent or slow down further crystal growth.
Multiple Abiotic Factors and Crop Productivity

Effects of Multiple Abiotic Factors
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

Photosynthesis, µmol m⁻² s⁻¹

24/16 °C
30/22 °C
36/28 °C

30/22

36/28
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

Bolls and Squares

<table>
<thead>
<tr>
<th>UV-B Radiation, kJ m^-2 d^-1</th>
<th>0</th>
<th>7</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>24/16 °C</td>
<td>60</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>30/22 °C</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>36/28 °C</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

30/22

36/28
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

Bolls Produced

- 30/22 °C
- 36/28 °C

UV-B Radiation, kJ m⁻² d⁻¹

Bolls produced, no. plant⁻¹

0 7 14

0 10 20 30 40
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

Retained Bolls

30/22

36/28

UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

Retained Bolls

Retained bolls, no. plant⁻¹

0 10 20 30 40

UV-B Radiation, kJ m⁻² d⁻¹

24/16 °C
30/22 °C
36/28 °C
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pollen no. anther(^{-1})</th>
<th>Pollen germination %</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/22</td>
<td>180-210</td>
<td>70</td>
</tr>
<tr>
<td>36/28</td>
<td>50-80</td>
<td>1</td>
</tr>
</tbody>
</table>
## Treatments

**Growing Conditions and Treatments:**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>CO₂ (ppm)</th>
<th>UV-B (kJ m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/22</td>
<td>360</td>
<td>0</td>
</tr>
<tr>
<td>38/30</td>
<td>720</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>
UV-B and Temperature

Soybean Reproductive Development – Sensitive Cultivar

Control

+T

+UV-B

+T+UV-B
Crop Traits and Genetic Variability to Abiotic Stresses

- **Morphological parameters:**
  - Leaf shape and lobation
  - Leaf angle
  - Root growth – length and density

- **Biophysical parameters:**
  - Canopy temperatures, canopy temperature depression, canopy and air temperature differential, crop water stress index, etc.

- **Remote sensing parameters:**
  - Looking at biophysical parameters (temperature) and crop chemistry and physiology (Water, pigment and chemical signals)
Crop Traits and Genetic Variability to Abiotic Stresses

- **Physiological parameters:**
  - ✓ Stomata conductance
  - ✓ Photosynthesis, respiration, and fluorescence
  - ✓ Specific leaf area/weight
  - ✓ Cell membrane thermostability (CMT)
  - ✓ Chlorophyll stability index (CSI)
  - ✓ Carbon isotope discrimination ($^{13}$C:$^{12}$C ratio)

- **Seed-based parameters:**
  - ✓ Seed germination percentage and germination rate
  - ✓ Cardinal temperatures – seed germination and seed germination rate
Crop Traits and Genetic Variability to Abiotic Stresses

- **Reproductive parameters:**
  - ☑ Pollen viability, pollen germination, pollen tube length responses to abiotic factors.
  - ☑ Cardinal temperatures – pollen germination and pollen tube length responses.
  - ☑ Fruit and seed set
  - ☑ Yield

- **Molecular tools:**
  - ☑ Currently whole host of molecular tools are available for breeding purposes, QTL’s and marked assisted breeding strategies.
Traits and Abiotic Stress Tolerance
Physiological Parameters - Stomata Conductance and Yield

(A) Pima cotton (Arizona)

(B) Bread wheat (Ciudad Obregón, Mexico)
Traits and Abiotic Stress Tolerance
Physiological Parameters – Cell Membrane Thermostability
Genotypic Variability - Ornamental Pepper Cultivars

- Black Pearl
- Calico
- Chilly Chili
- Explosive Ember
- Medusa
- Purple Flash
- Red Missile
- Salsa Yellow
- Sangria
- Thai Hot
- Treasures Red
- Variegata
Traits and Abiotic Stress Tolerance
Physiological Parameters – Canopy Temperature Depression
Genotypic Variability - Ornamental Pepper Cultivars

- Black Pearl
- Calico
- Chilly Chili
- Explosive Ember
- Medusa
- Purple Flash
- Red Missile
- Salsa Yellow
- Sangria
- Thai Hot
- Treasures Red
- Variegata
Traits and Abiotic Stress Tolerance
Physiological Parameters – Chlorophyll Stability Index
Genotypic Variability - Ornamental Pepper Cultivars

![Graph showing Chlorophyll stability index for different cultivars.](image)
• Greater variability for cardinal temperatures among ornamental pepper cultivars.

<table>
<thead>
<tr>
<th>Cardinal Temperature</th>
<th>MSG (mean)</th>
<th>SGR (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{min}}$</td>
<td>10.1</td>
<td>15.3</td>
</tr>
<tr>
<td>$T_{\text{opt}}$</td>
<td>24.0</td>
<td>27.7</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>42.5</td>
<td>43.0</td>
</tr>
</tbody>
</table>
Traits and Abiotic Stress Tolerance
Seed-based Parameters – Genotypic Variability
Switchgrass Genotypes

- Greater variability for cardinal temperatures among switch grass genotypes.

<table>
<thead>
<tr>
<th>Cardinal Temperature</th>
<th>MSG (mean)</th>
<th>SGR (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_min</td>
<td>8.08</td>
<td>11.3</td>
</tr>
<tr>
<td>T_opt</td>
<td>26.58</td>
<td>33.12</td>
</tr>
<tr>
<td>T_max</td>
<td>45.09</td>
<td>46.01</td>
</tr>
</tbody>
</table>
Traits and Abiotic Stress Tolerance
Reproductive Parameters – Pollen Germination
Genotypic Variability - Cotton

Kakani et al., 2005
Traits and Abiotic Stress Tolerance
Reproductive parameters – Pollen Germination
Genotypic Variability - Soybean

Soybean

Germination, %

Temperature, °C

STALWART
PI471938
DG 5630RR

Salem et al., 2006
Effect of temperature on percentage pollen germination of susceptible (Topt < mean-LSD), moderately tolerant (Topt = mean±LSD) and tolerant (Topt > mean+LSD) genotypes. Symbols are observed values and lines are fitted values.

Kakani et al., 2002
Temperature – Pollen Tube Growth - Groundnut

Kakani et al., 2002

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Length $T_b$</th>
<th>$T_{opt}$</th>
<th>$T_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1280</td>
<td>16.0</td>
<td>36.4</td>
<td>45.5</td>
</tr>
<tr>
<td>1080</td>
<td>15.3</td>
<td>30.5</td>
<td>37.7</td>
</tr>
<tr>
<td>1410</td>
<td>14.5</td>
<td>37.6</td>
<td>45.1</td>
</tr>
</tbody>
</table>
Traits and Abiotic Stress Tolerance
Reproductive parameters – Pollen Germination - Genotypic Variability

Kakani et al., 2005
Traits and Abiotic Stress Tolerance
Reproductive parameters – Pollen Germination
Genotypic Variability

Soybean

\[ \text{Tmax} = 47.2 \, ^\circ\text{C} \]
\[ \text{Topt} = 30.2 \, ^\circ\text{C} \]
\[ \text{Tmin} = 13.3 \, ^\circ\text{C} \]

Salem et al., 2006
Genotypes

Cardinal temperatures, °C

55
50
45
40
35
30
25
20
15
10
5
0

Groundnut

Tmax

43 °C

Topt

30.1 °C

Tmin

14.1 °C

Genotypes

Kakani et al. 2002

Traits and Abiotic Stress Tolerance
Reproductive parameters – Pollen Germination
Genotypic Variability
• The influence of stress factors on reproductive biology of crops/plants has not been well studied.

• Better screening tools/methods are needed to assess the genotypic variability among crop species, genotypes or lines including wild relatives of crop species.

• Molecular tools and biotechnology will play a greater role in the quest for knowledge and in developing stress tolerance.
The current rate of climate change and climate variability and projected changes in climate are unprecedented, and plants may not cope with these rapid changes.

There is an urgent need to develop crop cultivars to a variety of stresses (high and low temperatures, drought tolerance, UV-B radiation stress, ozone tolerance, flood tolerance, heavy metal tolerance, etc.).