Crop Growth under Extreme Environments
High and Low Temperatures

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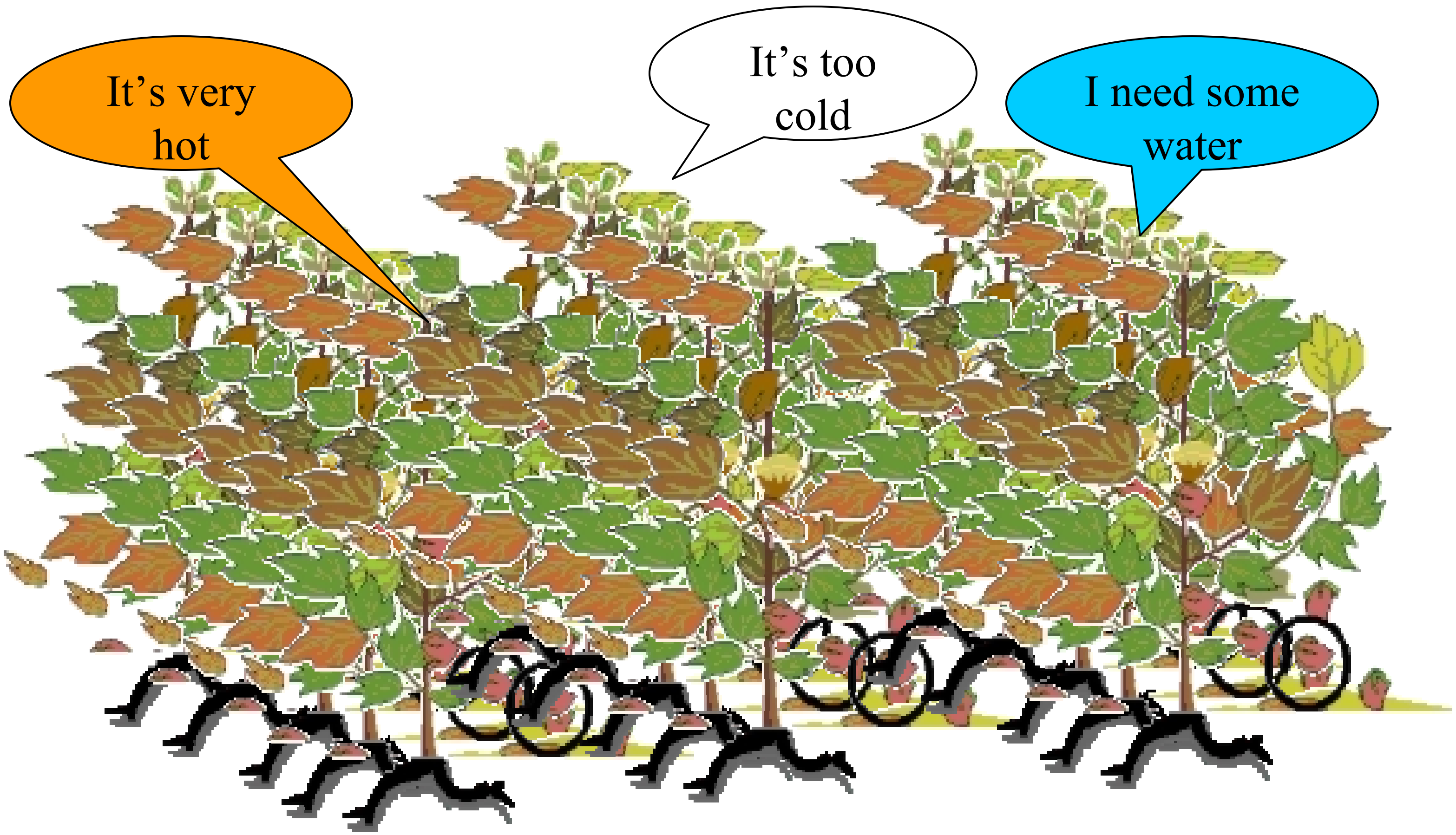
Plant Responses to Extreme Environments

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.

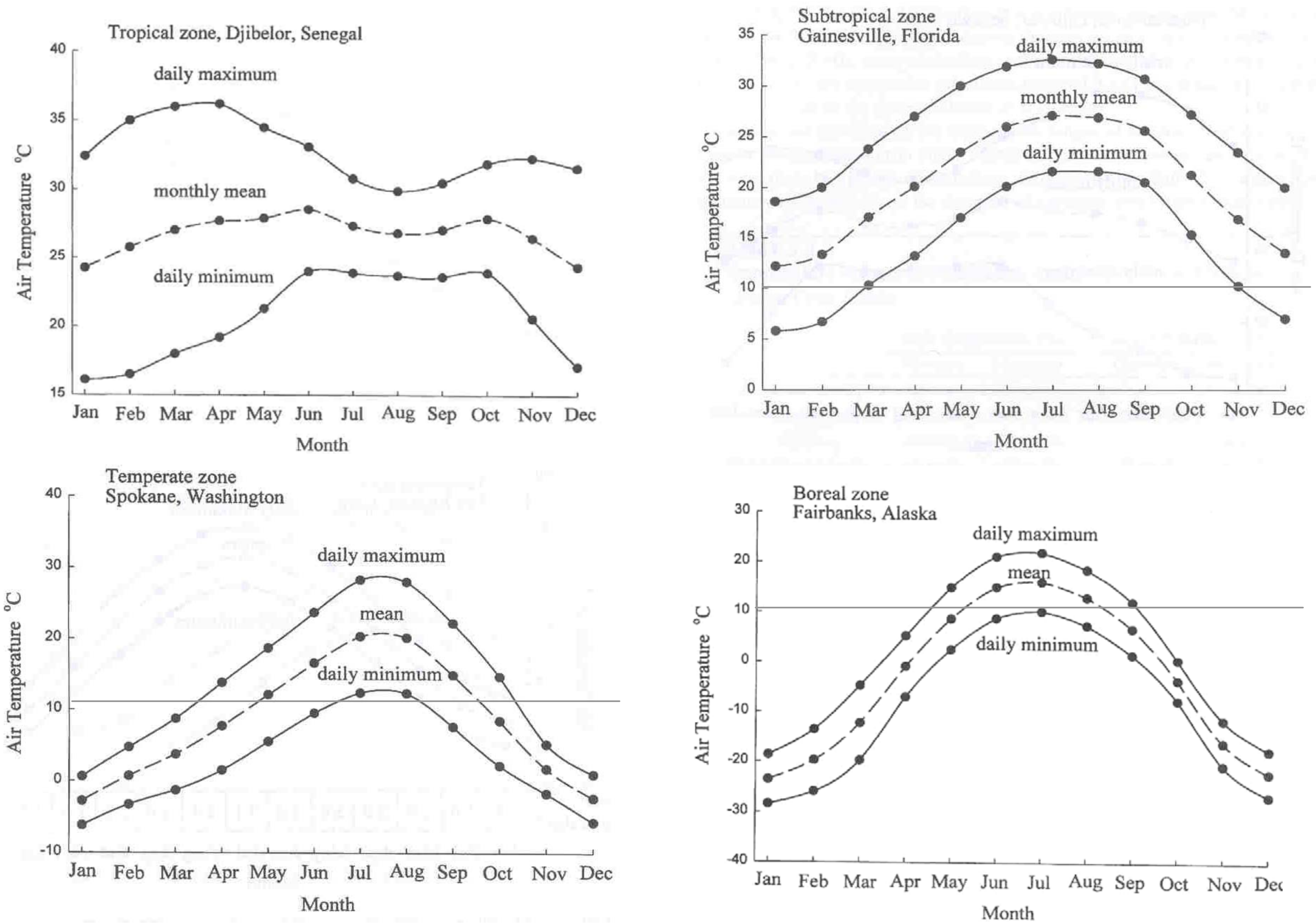
Plant Critical Processes at High Temperatures

- 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.

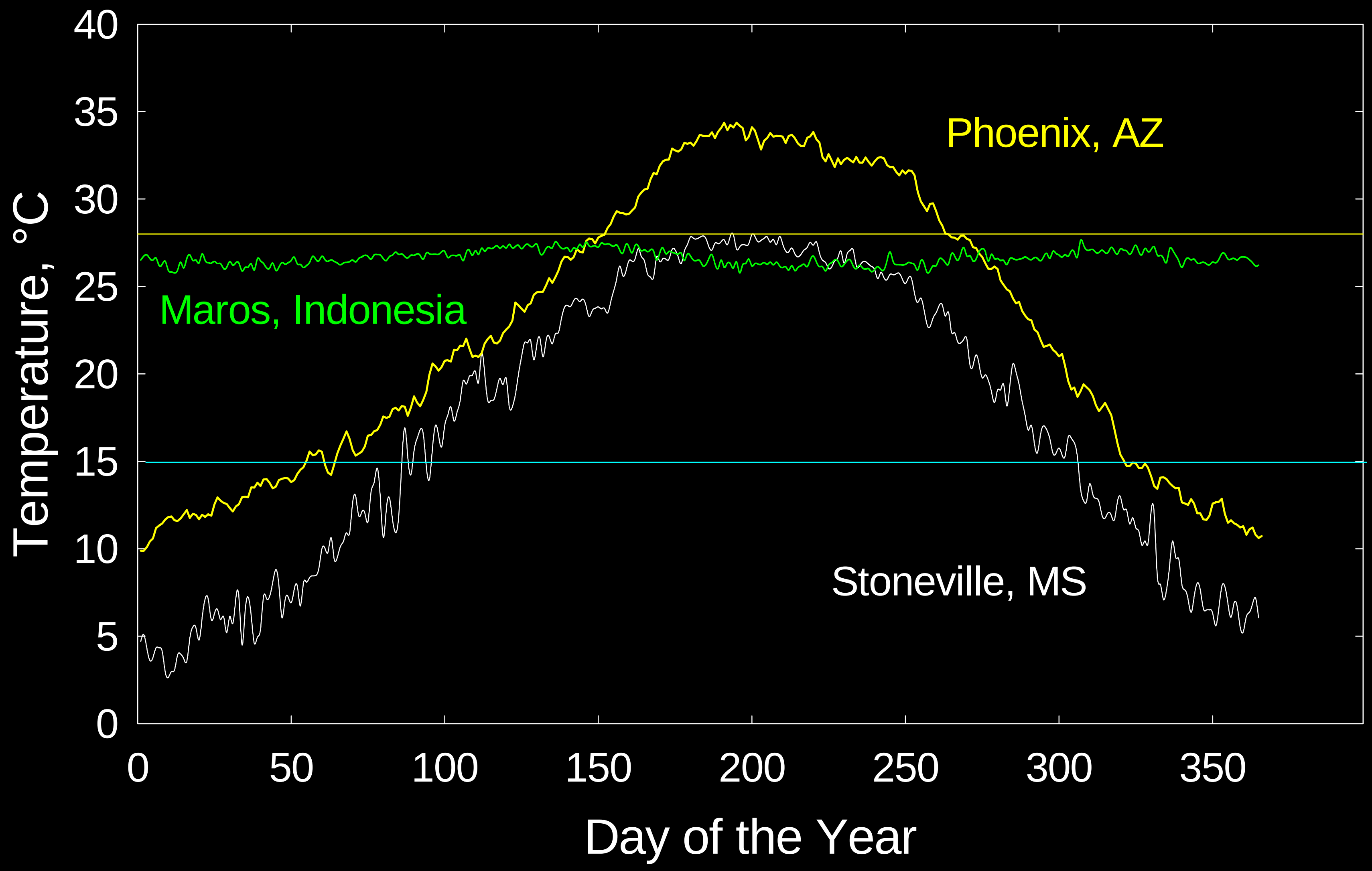
Plant Critical Processes at High Temperatures

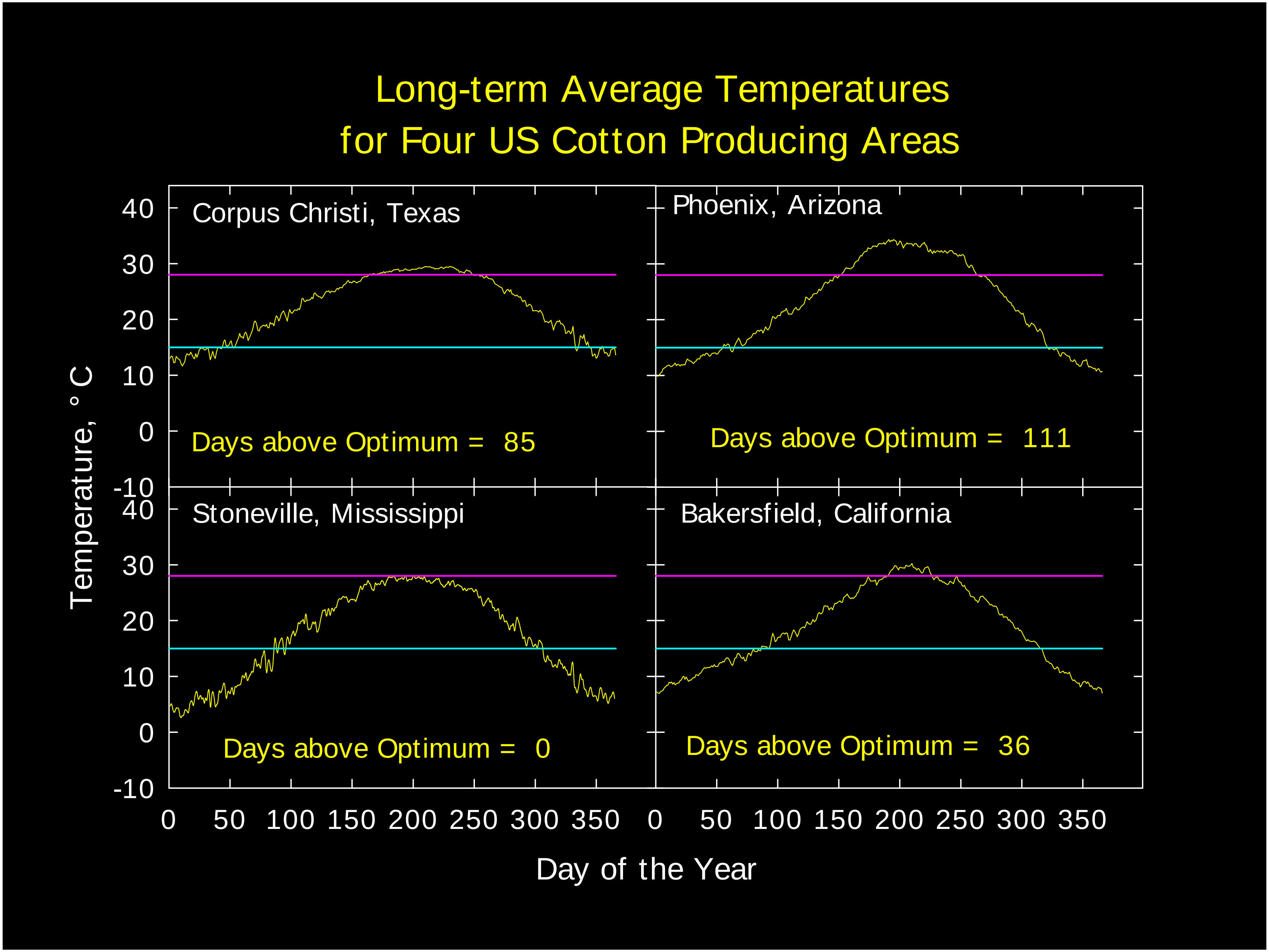
- The question is how do plant groups respond to high temperatures?
- Enhanced temperatures are more detrimental in C_3 plants than in C_4 or CAM plants because of rates of both dark and photorespiration are increased more in C_3 plants.
- What happens to C_3 plants under elevated CO_2 conditions?

Climatic Zones and Temperature Conditions

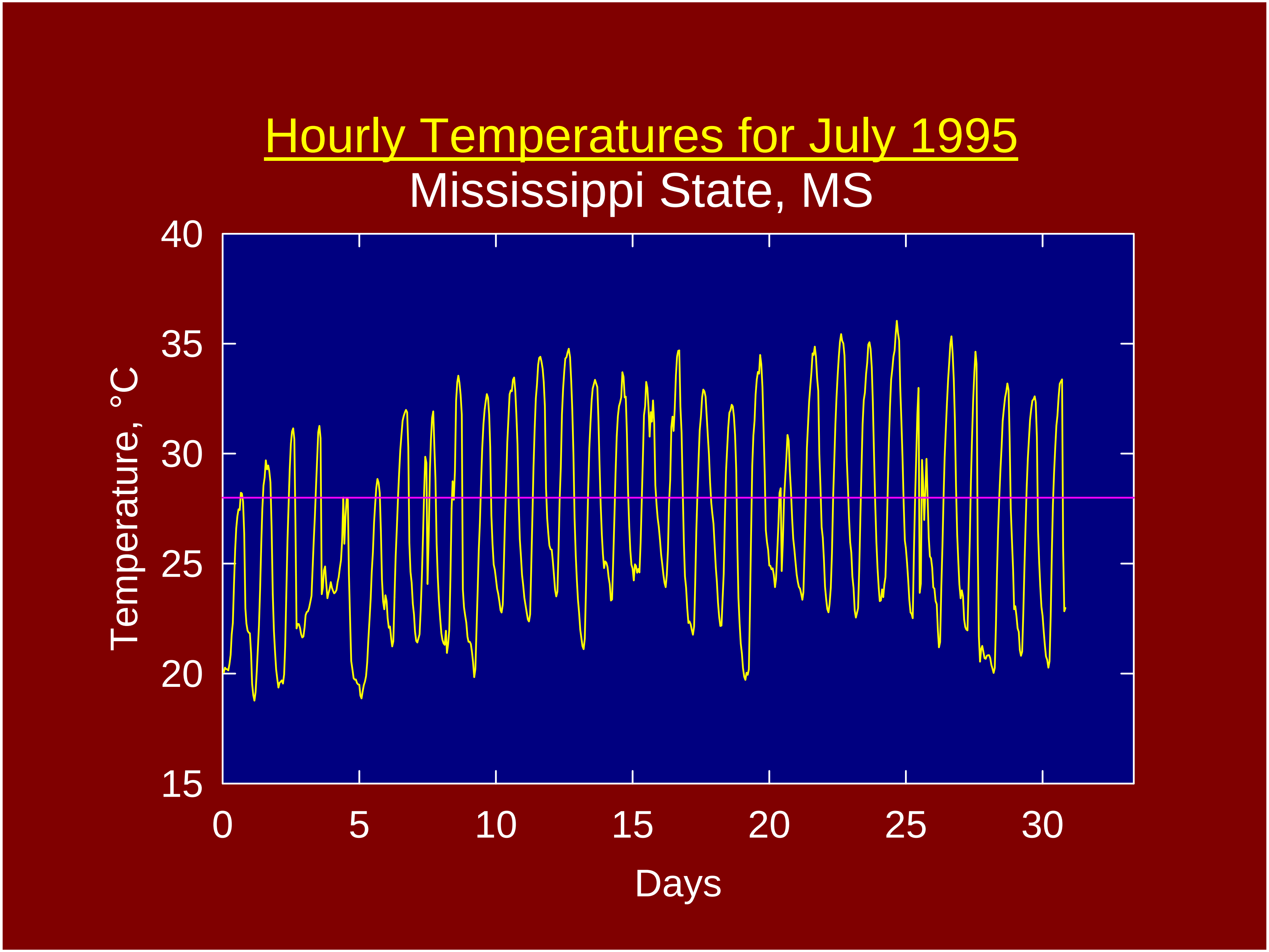


Long-Term Average Temperatures



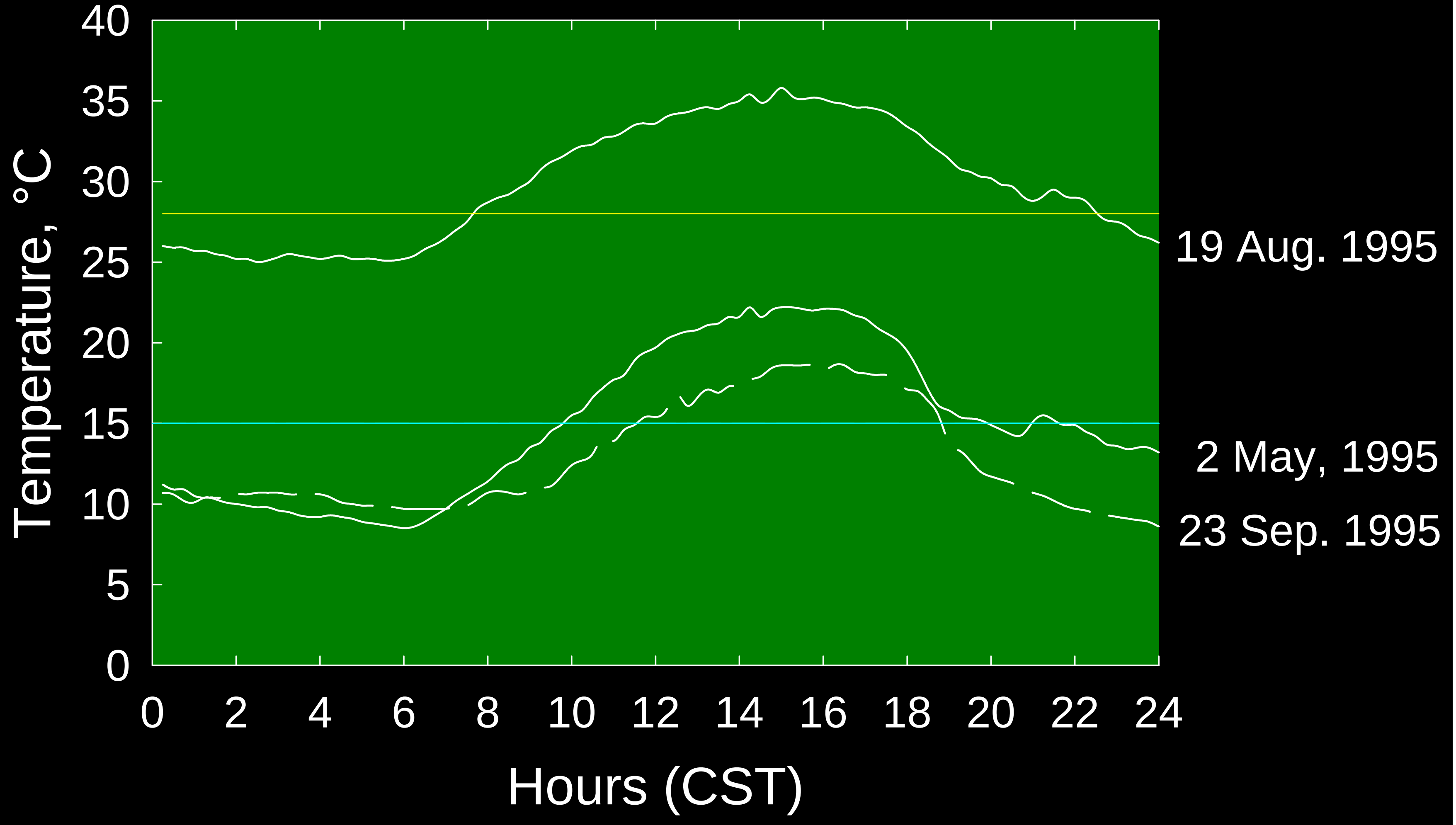


Long-term Average Temperatures
for Four US Cotton Producing Areas
Corpus Christi, Texas
Days above Optimum = 85
Phoenix, Arizona
Days above Optimum = 111
Stoneville, Mississippi
Days above Optimum = 0
Bakersfield, California
Days above Optimum = 36
Temperature, ° C
40
30
20
10
0
-10
0
50
100
150
200
250
300
350
Day of the Year



Hourly Temperatures for July 1995
Mississippi State, MS
Temperature, °C
40
35
30
25
20
15
0
5
10
15
20
25
30
Days

Temperature Conditions - Diurnal Trends
Mississippi State, MS - 1995

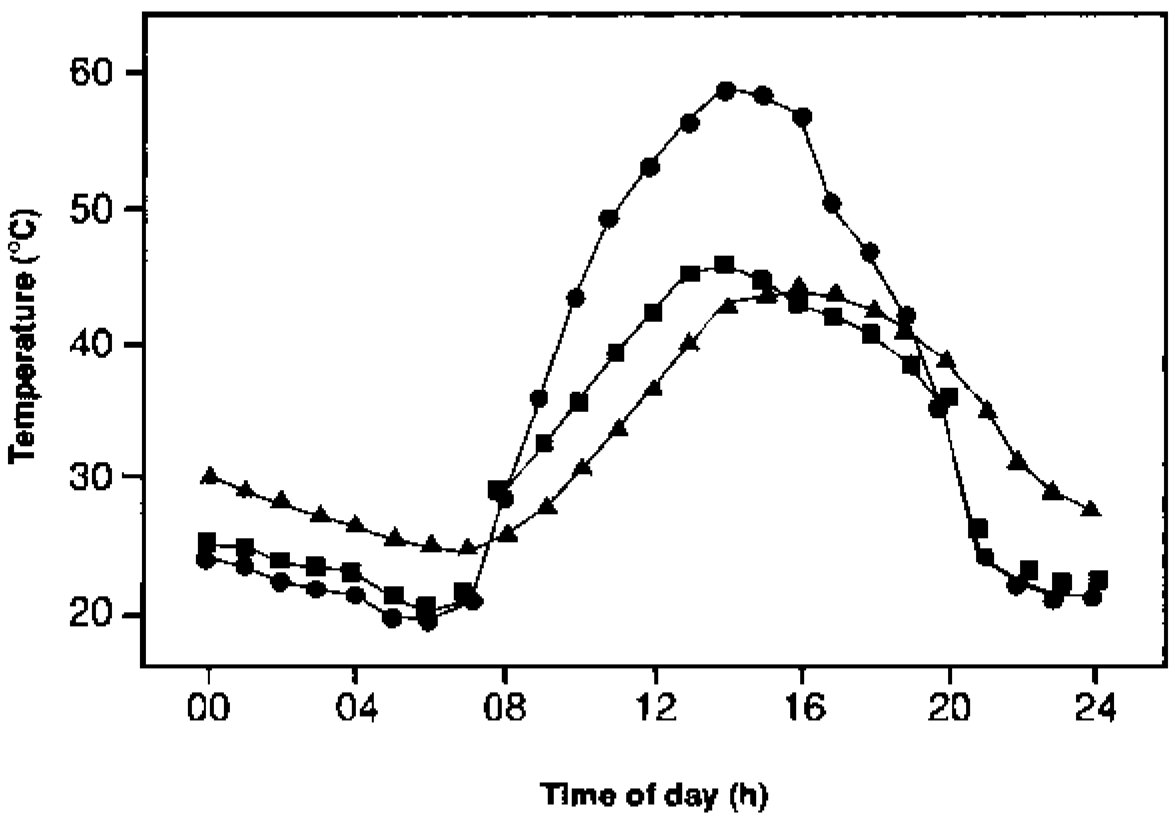


Diurnal temperature data recorded in June 1989 at Fatehpur, Rajasthan, India, (Latitude 27°C 37'N).

5 cm depth of soil (▲)

0.5 cm depth of soil (●)

150 cm above the soil surface (■)



Howarth, 1991

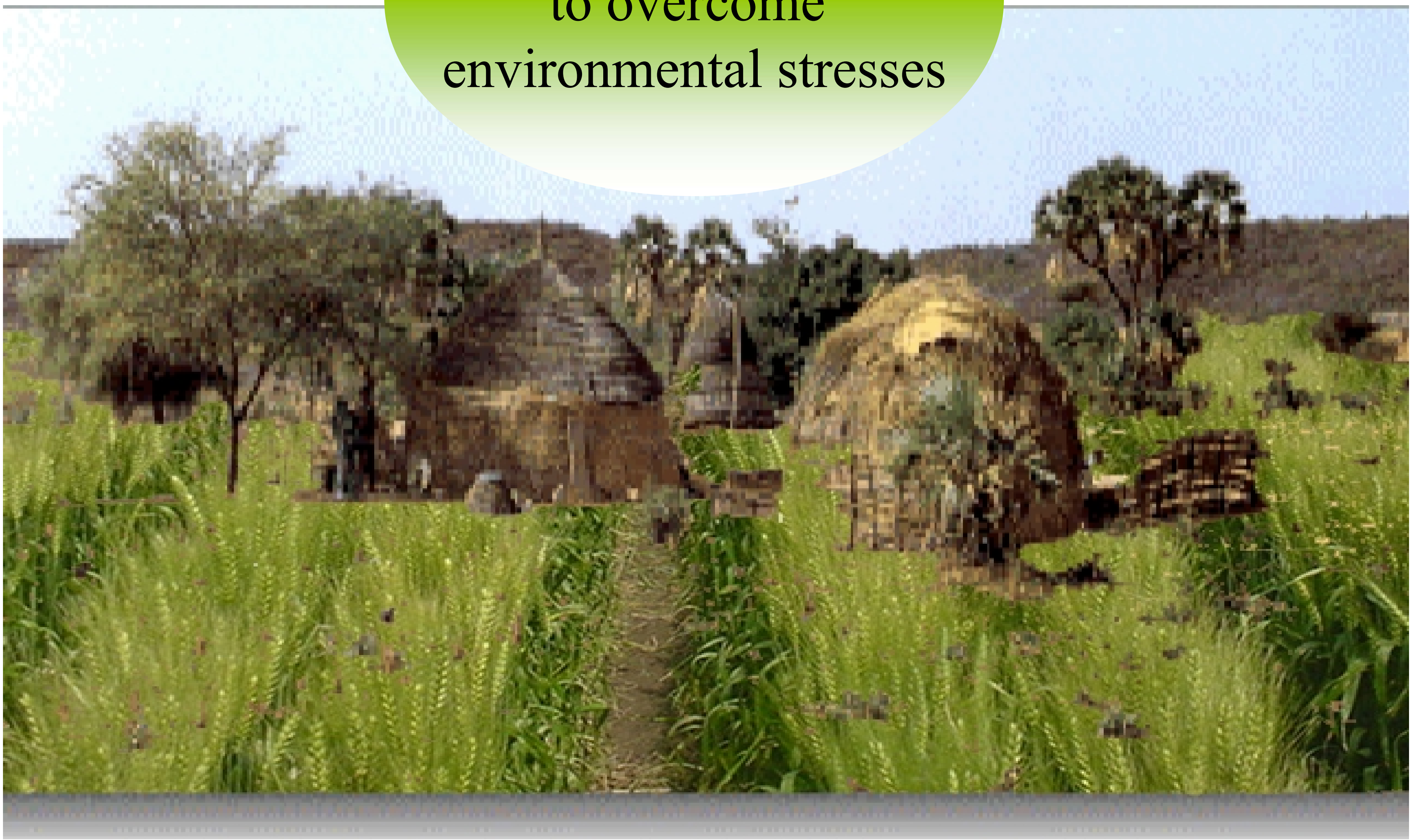
Climate Change and Crop Production

- 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

High Temperature Effects on Cotton Fruit Production and Retention

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.

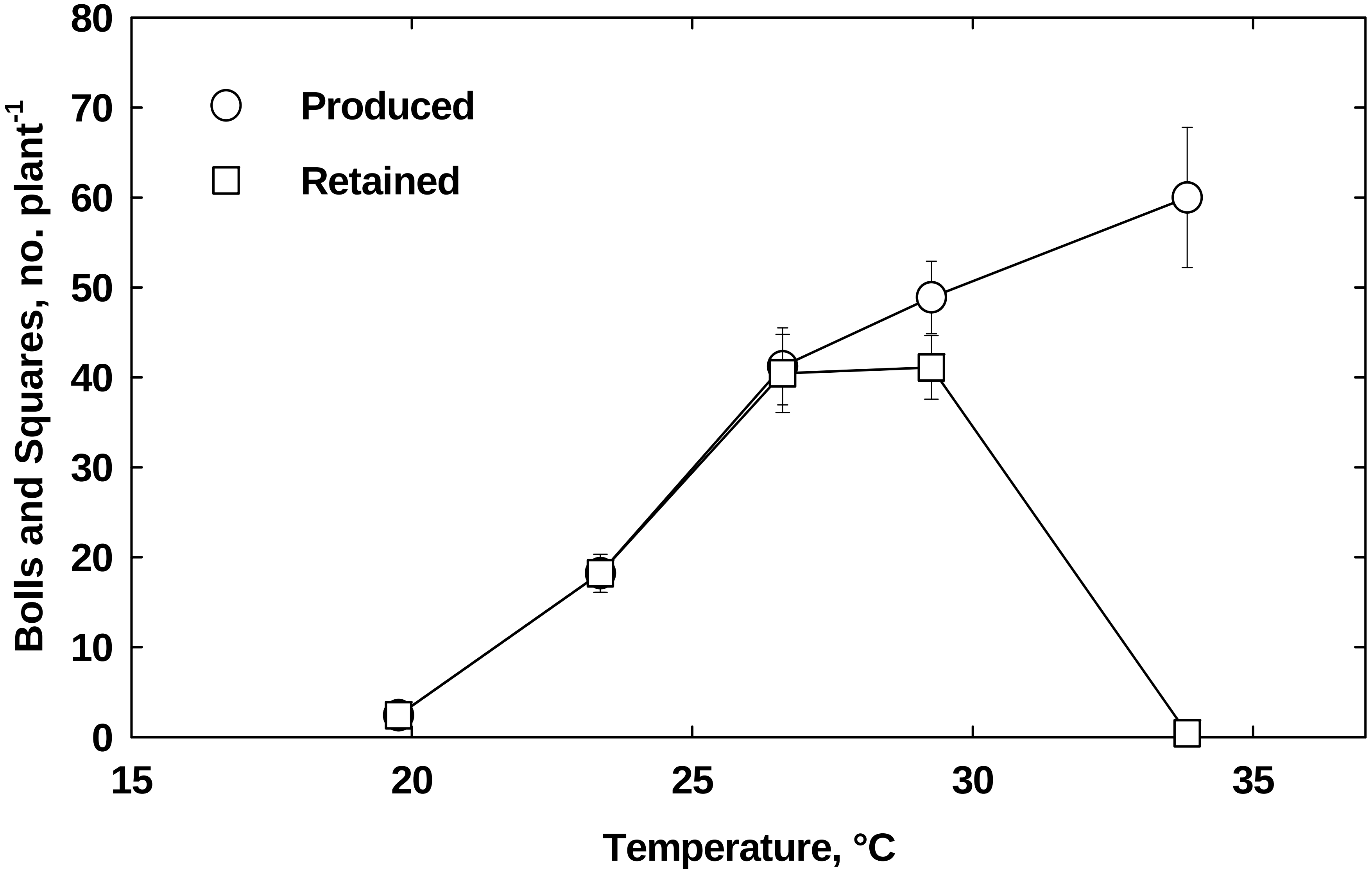
Notice that the plants grown in optimum temperatures are producing both vegetative and reproductive structures continuously and there is no abscission of squares or fruiting structures. Plants grown in 35/27°C are producing luxuriant vegetative growth, but some of the squares are being abscised due to 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

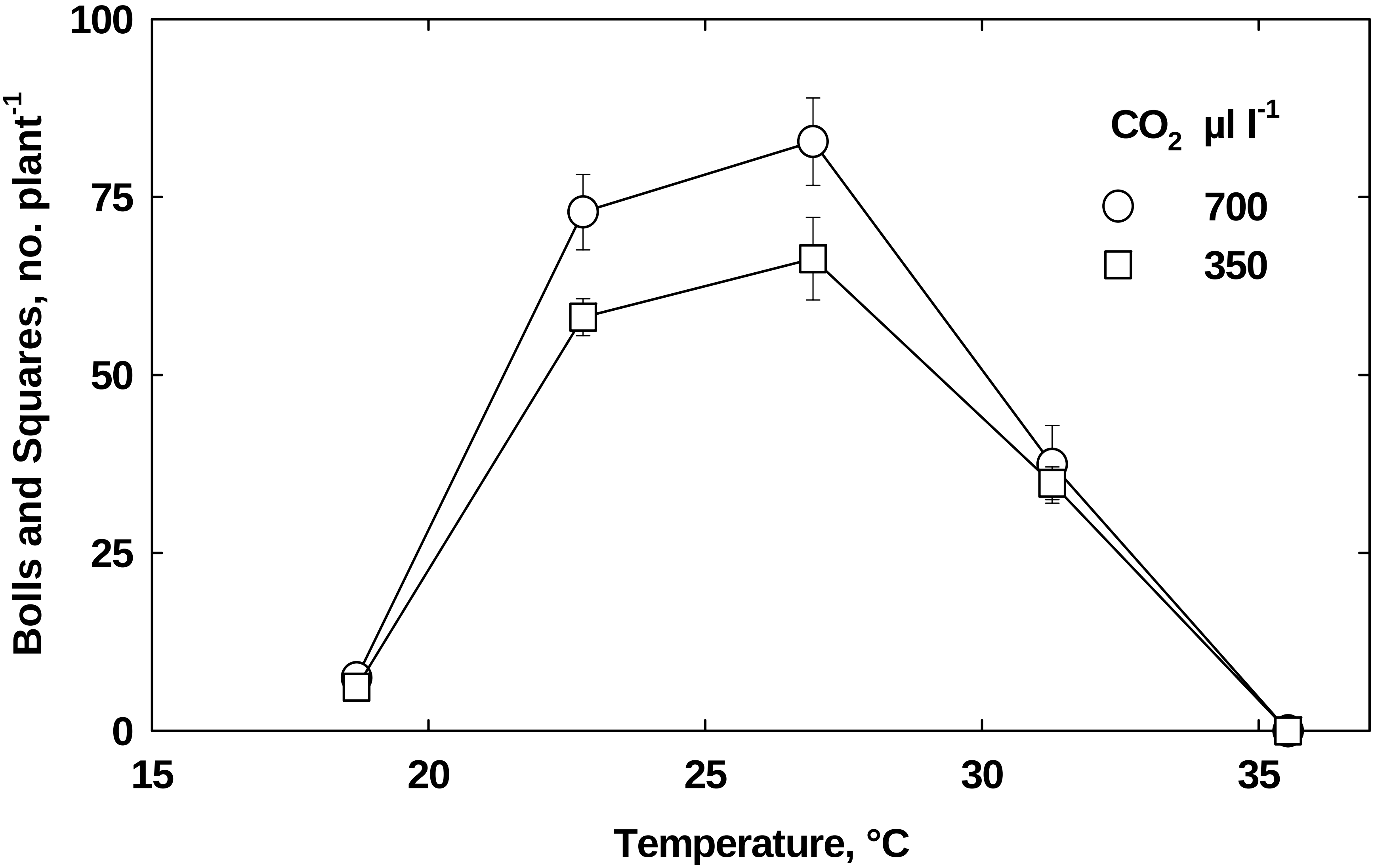
Higher Temperature Injury
Partial Injury to Reproductive Parts

Super High Temperature Injury
Total Reproductive Failure, Including Fruiting Branch Production

High Temperature Effects on Cotton – Upland Cotton



High Temperature Effects on Cotton – Pima Cotton

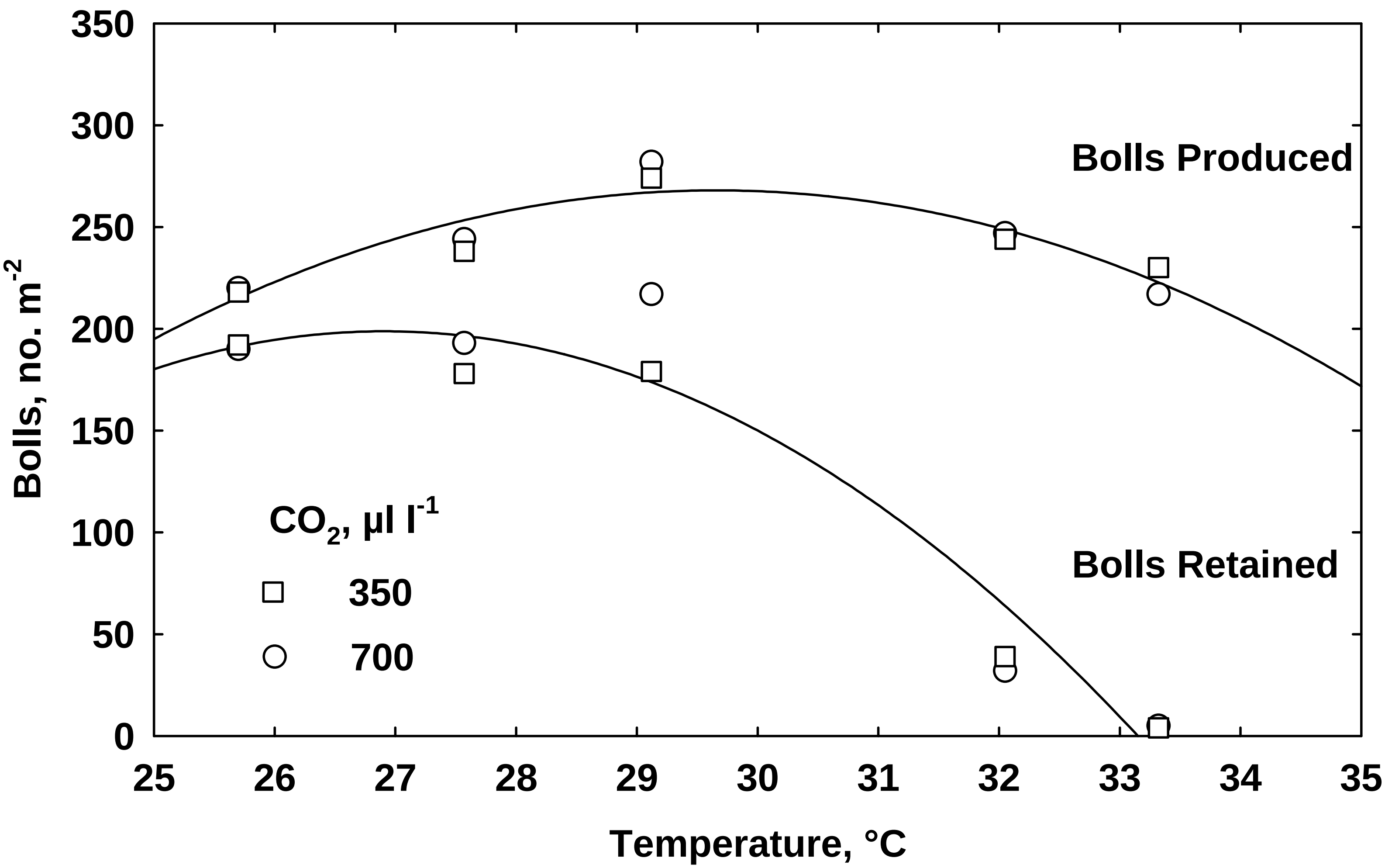


Environment - Crop Growth – High Temperature Injury to Reproductive Parts

Table 1. Effect of temperature on cotton growth, cv. Stoneville 825, harvested 49 days after initiation of temperature treatments. tretments are imposed at first flower. Standard error of the mean values are shown.

	Day/Night Temperature, °C				
	20/12	25/15	30/20	35/25	40/30
	Grams per Plant				
Total Wt.	242	320	330	293	225
% of Optimum	73	97	100	88	68
Bolls	17	63	143	17	0.8
% of Optimum	12	44	100	12	0.6

Environment - Crop Growth – High Temperatures
Injury to Reproductive Parts

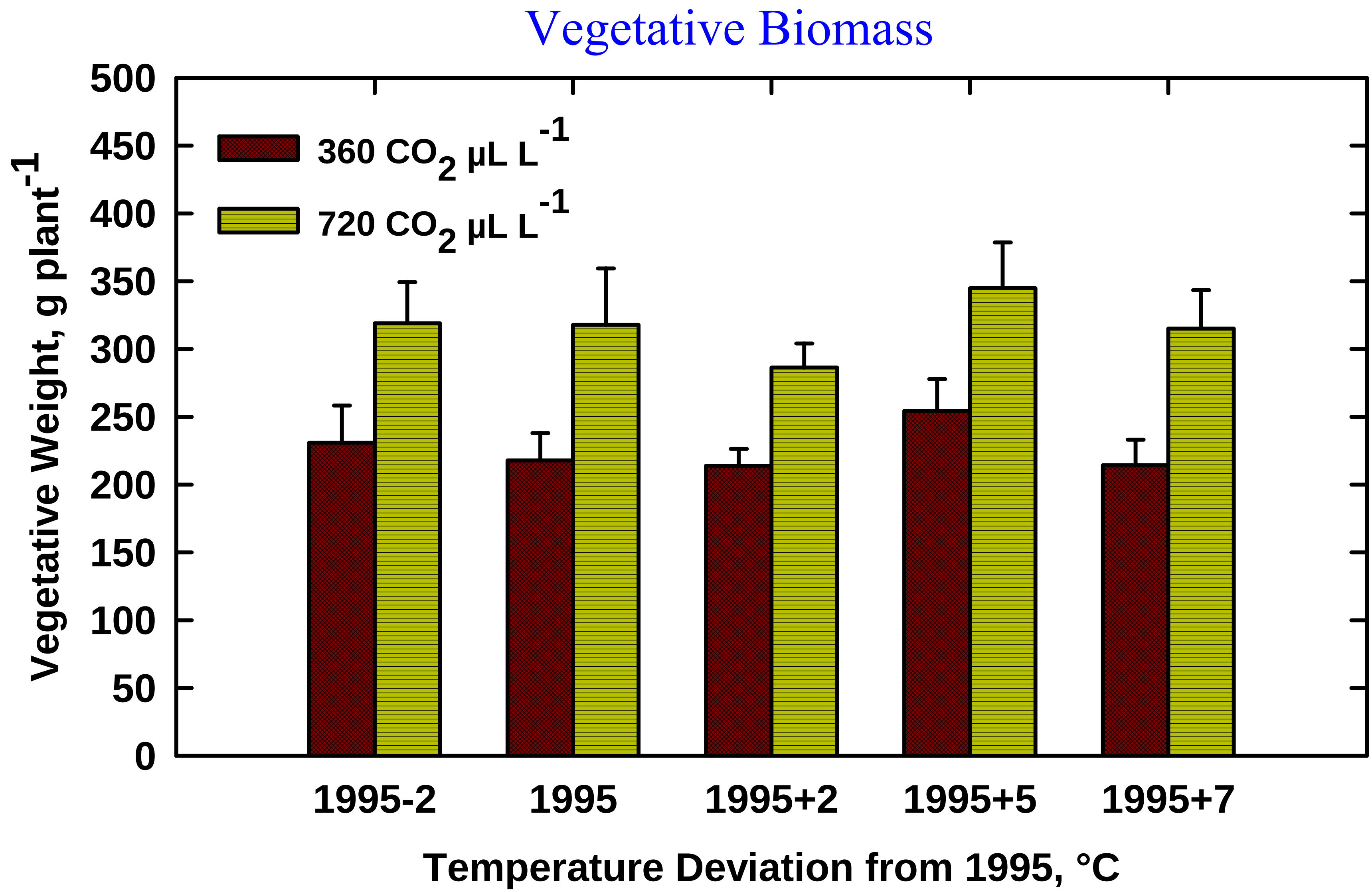


Projected Temperatures and Cotton Development

Treatment	Days to the Event		
	Square	Flower	Open Boll
1995 minus 2°C	33	65	144
1995 plus 0°C	26	51	101
1995 plus 2°C	24	48	94
1995 plus 5°C	21	42	77
1995 plus 7°C	19	39	No Fruit

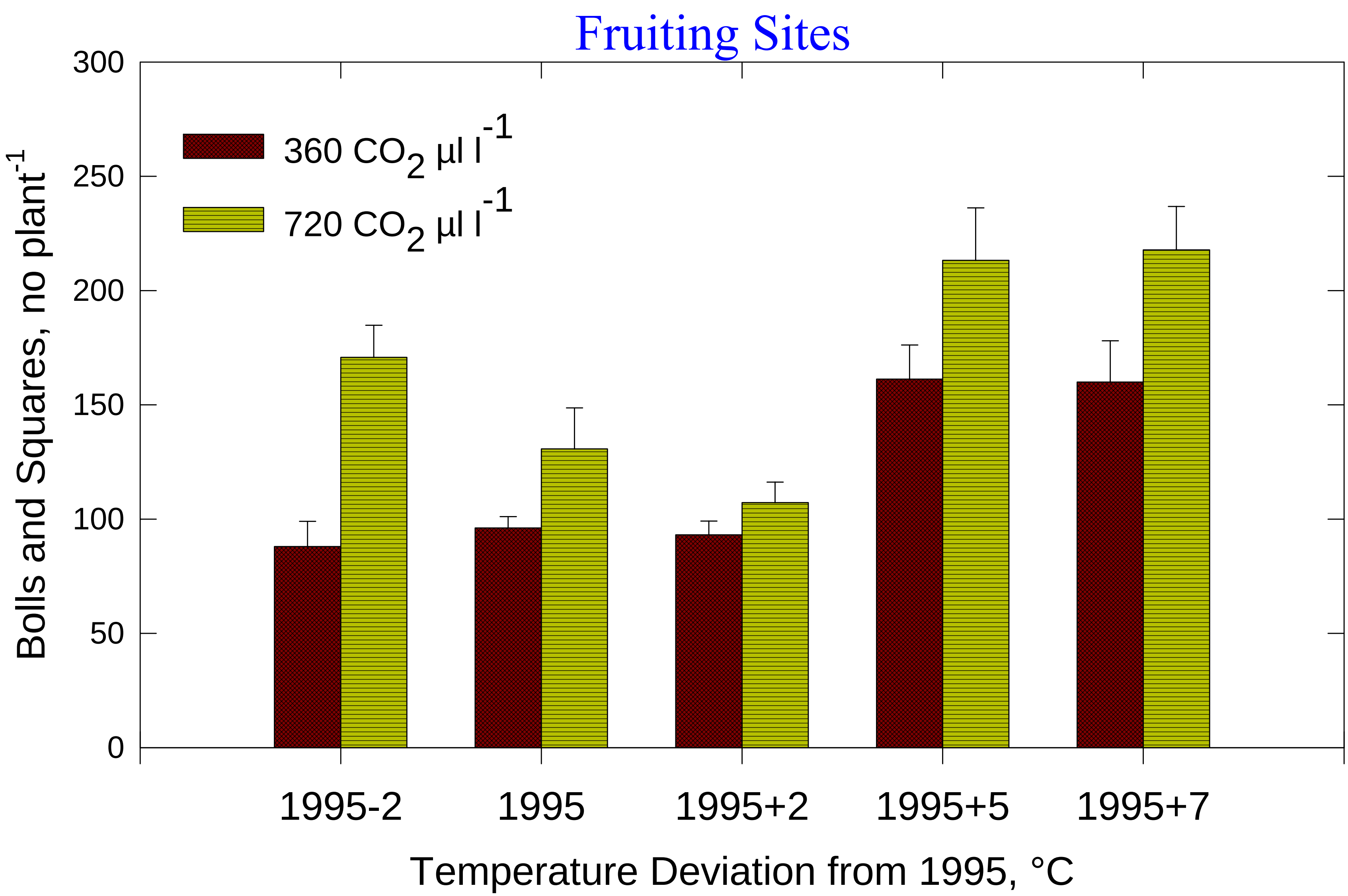
No significant differences were observed between CO_2 levels

High Temperature Injury
Temperature and CO2 Interactions

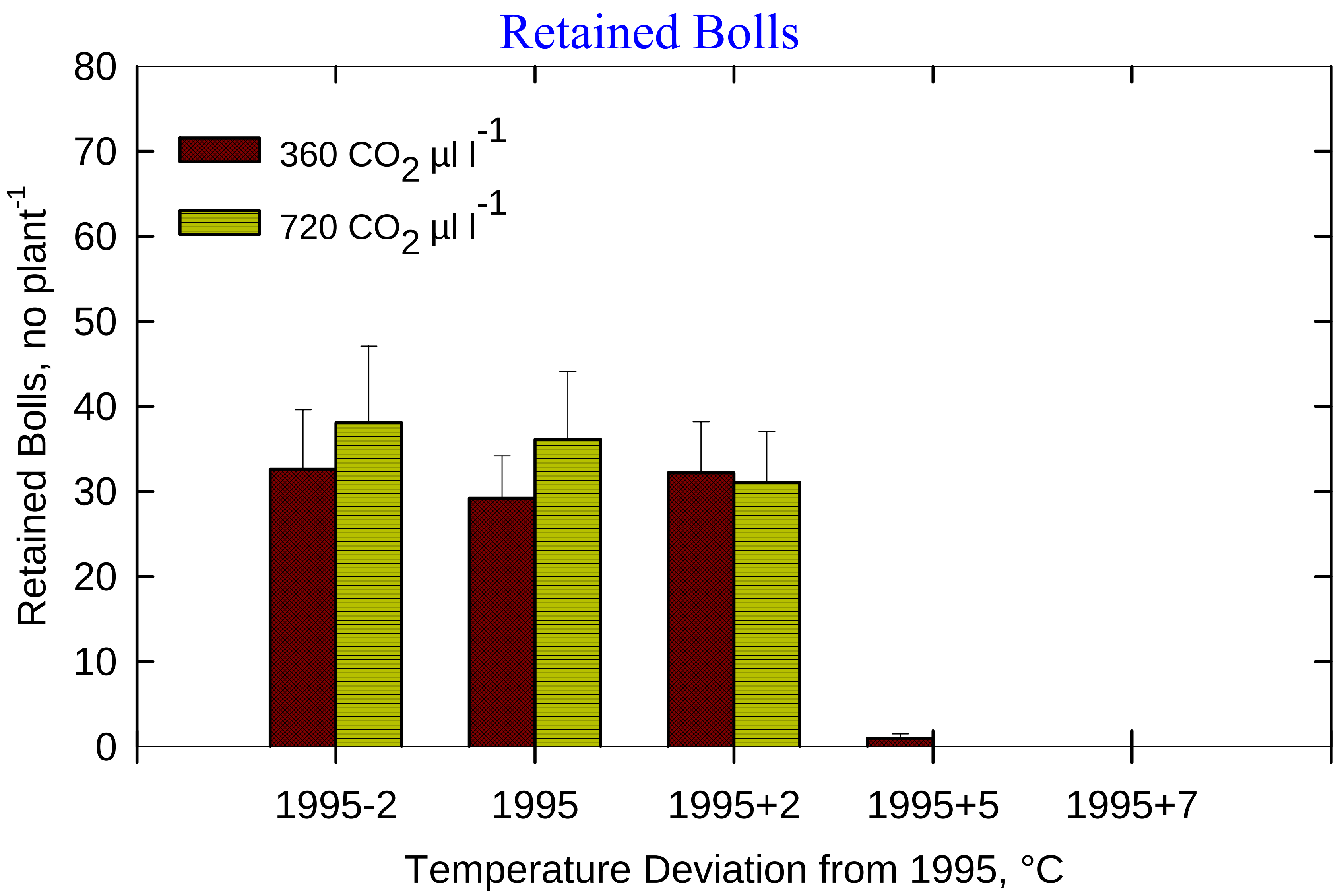


High Temperature Injury

Temperature and CO2 Interactions – Cotton

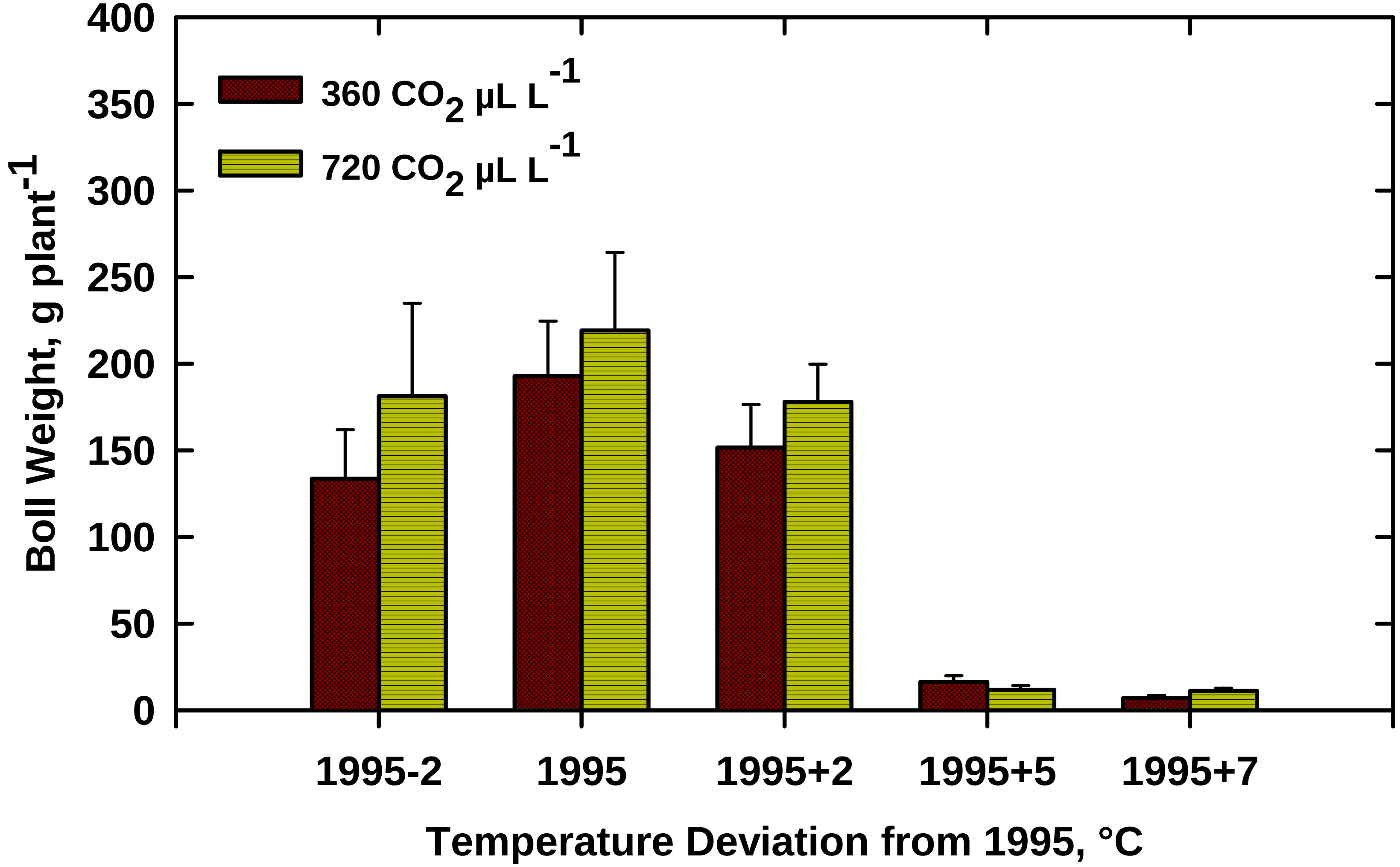


High Temperature Injury
Temperature and CO2 Interactions – Cotton



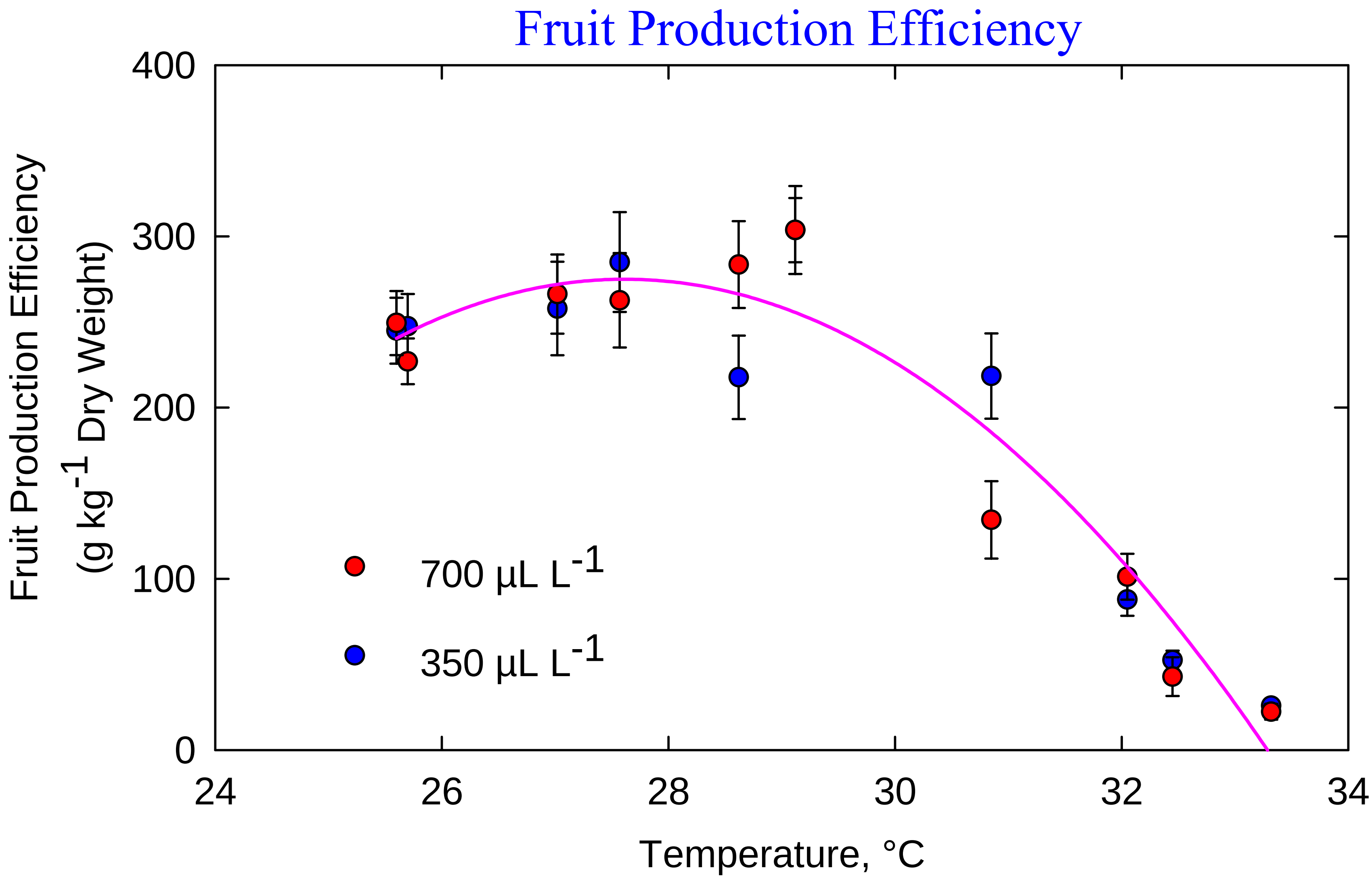
High Temperature Injury
Temperature and CO2 Interactions – Cotton

Boll weight



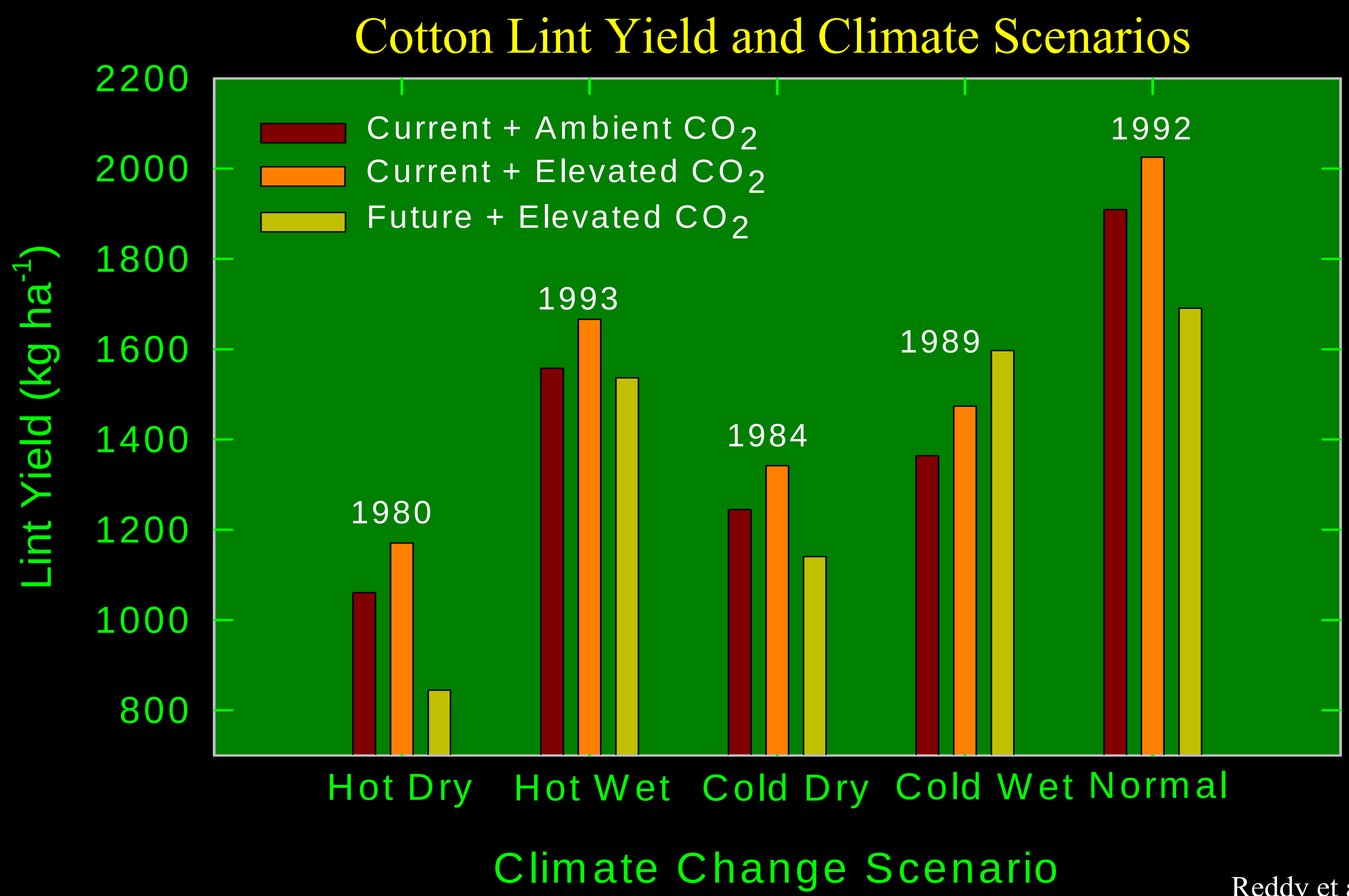
High Temperature Injury

Temperature and CO2 Interactions – Cotton



High Temperature Injury

Using Simulation Models – Cotton Lint Yield



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 for.

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^{o}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 CO_2 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).

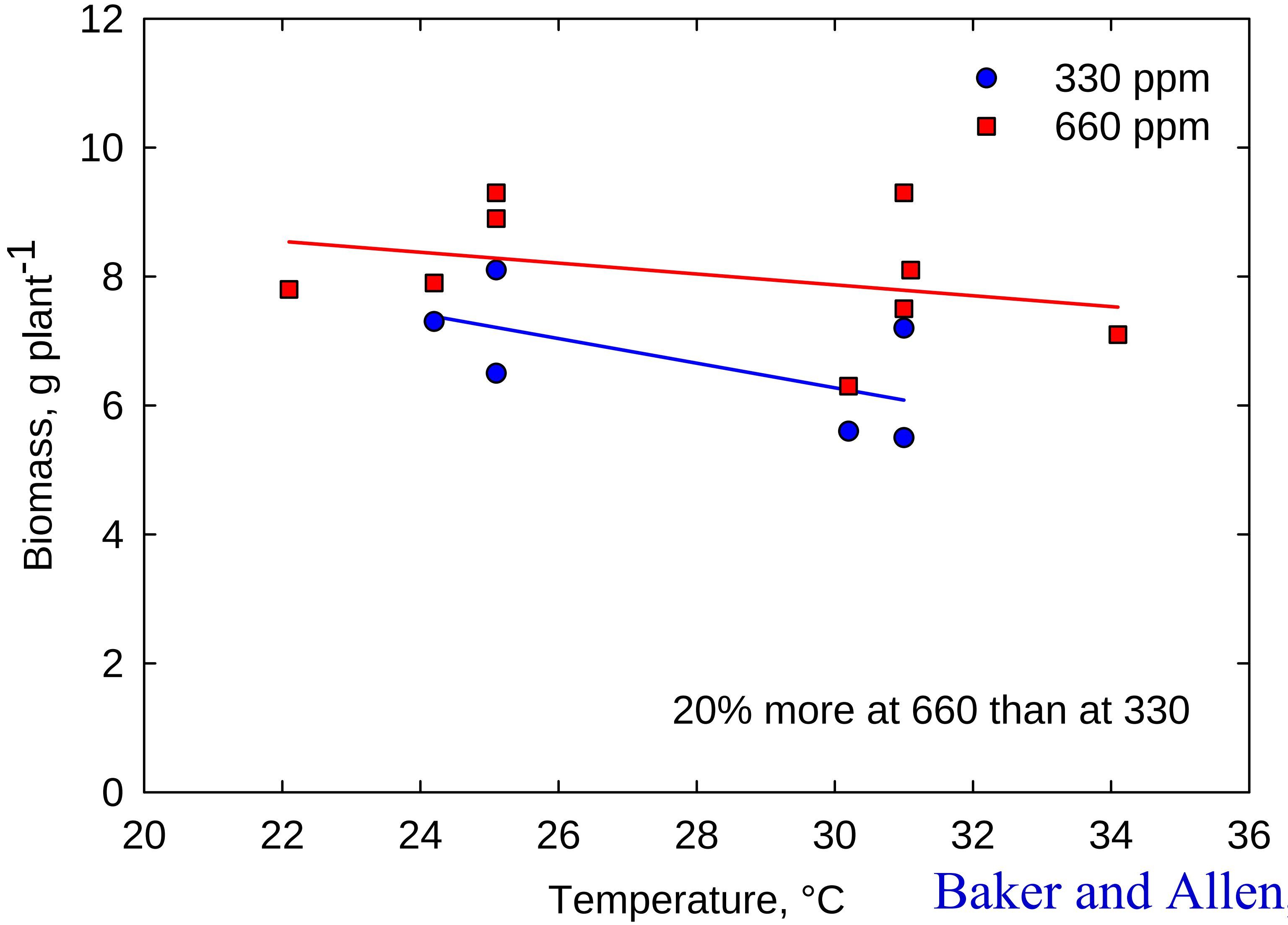
High Temperature Effects on Cotton

- 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.

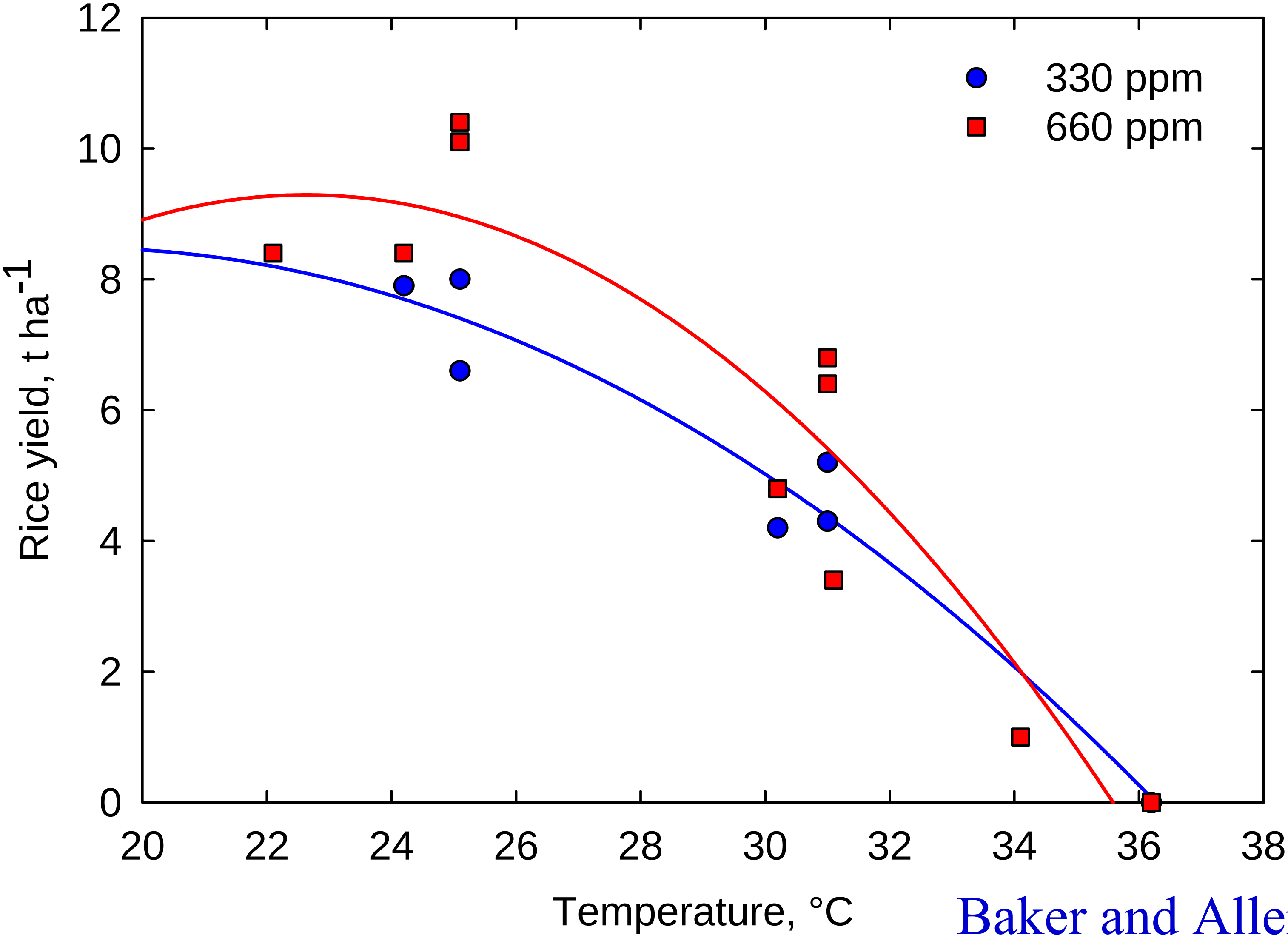
- Heat-tolerance will be beneficial even in today's environment, and will be needed more in a warmer future climatic conditions.

High Temperature Injury
Temperature and CO2 – Rice Growth



Baker and Allen, 1993

High Temperature Injury
Temperature and CO2 – Rice



Baker and Allen, 1993

Rice

High Temperature Effects on Rice Fertility

Cooling degree days are calculated based air temperatures and with a base temperature of 22 °C: 22 – mean temperature

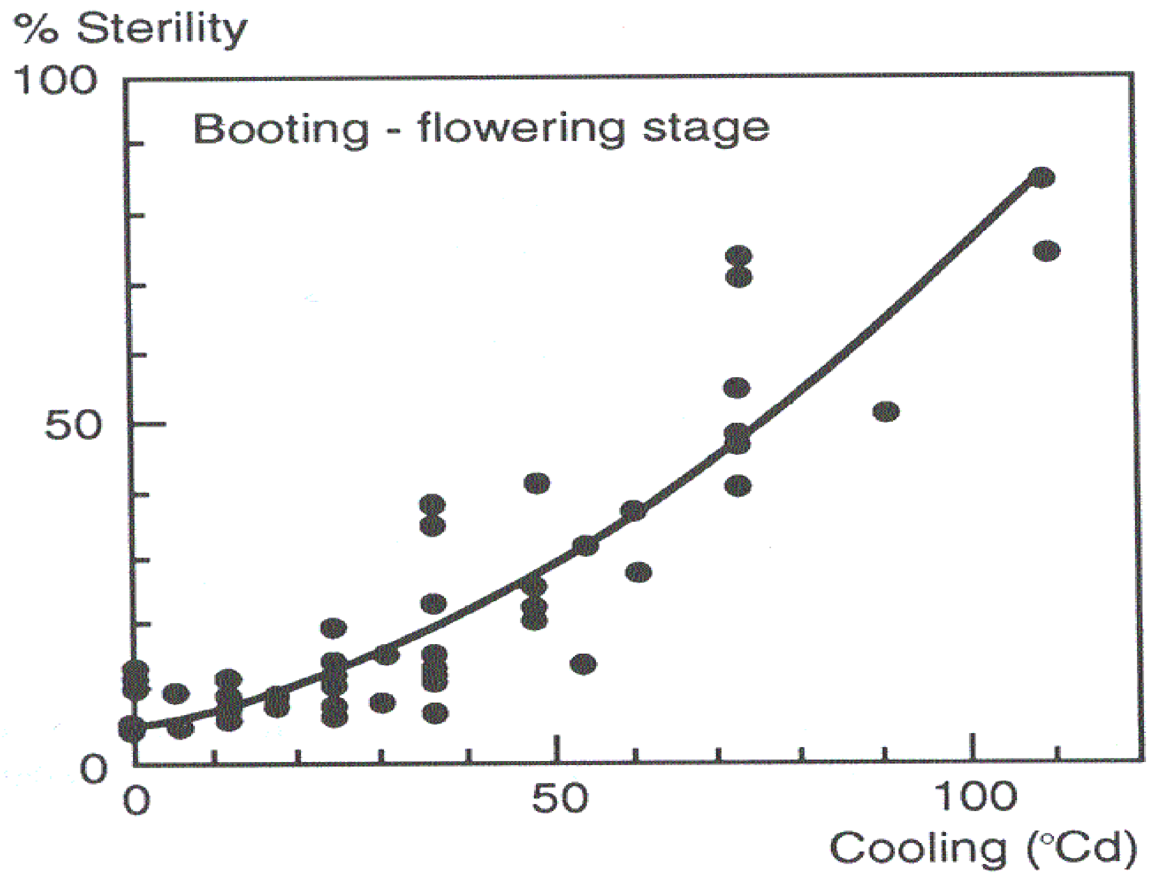


Fig. 4.5. Relation between cooling degree-days and percentage spikelet (γ) sterility of the variety Eiko between booting and flowering stages (Horie, 1988 constructed from data of Shibota *et al.*, 1990).

High Temperature Effects on Rice Fertility

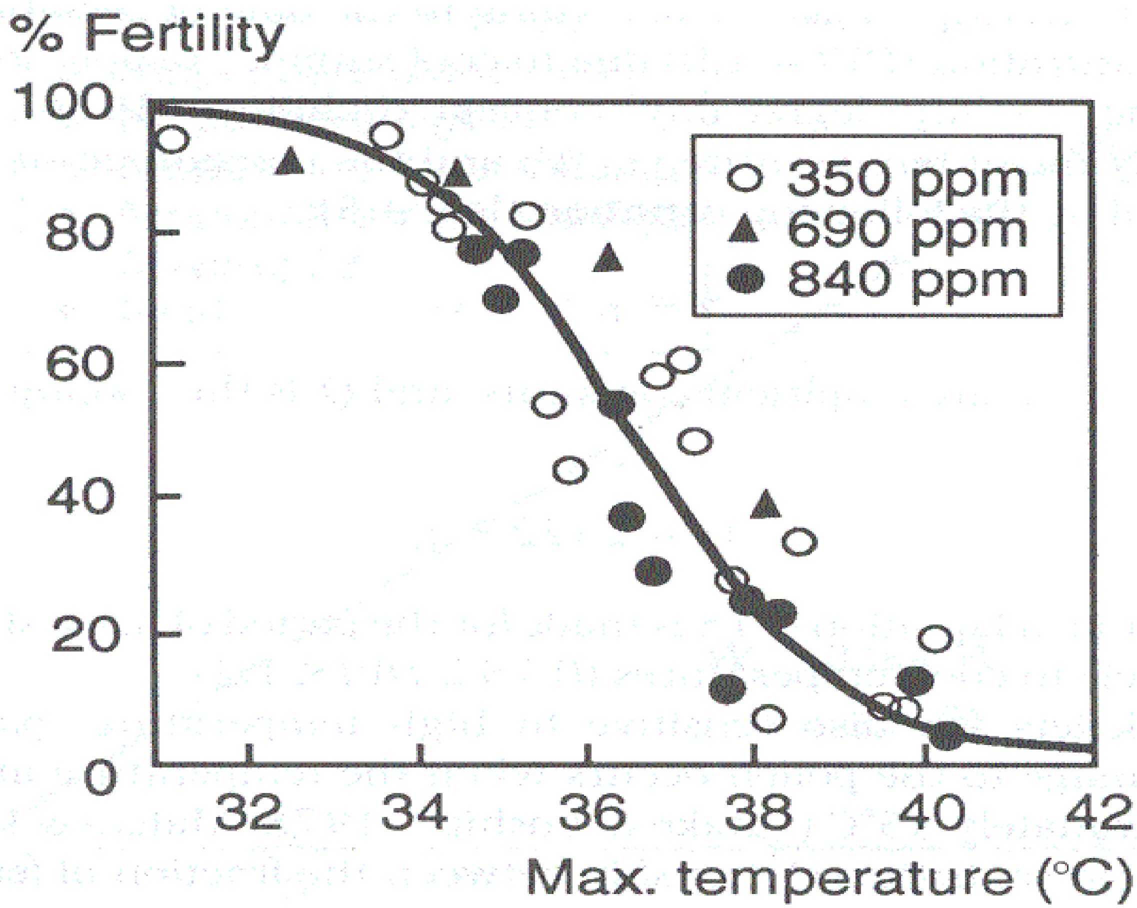
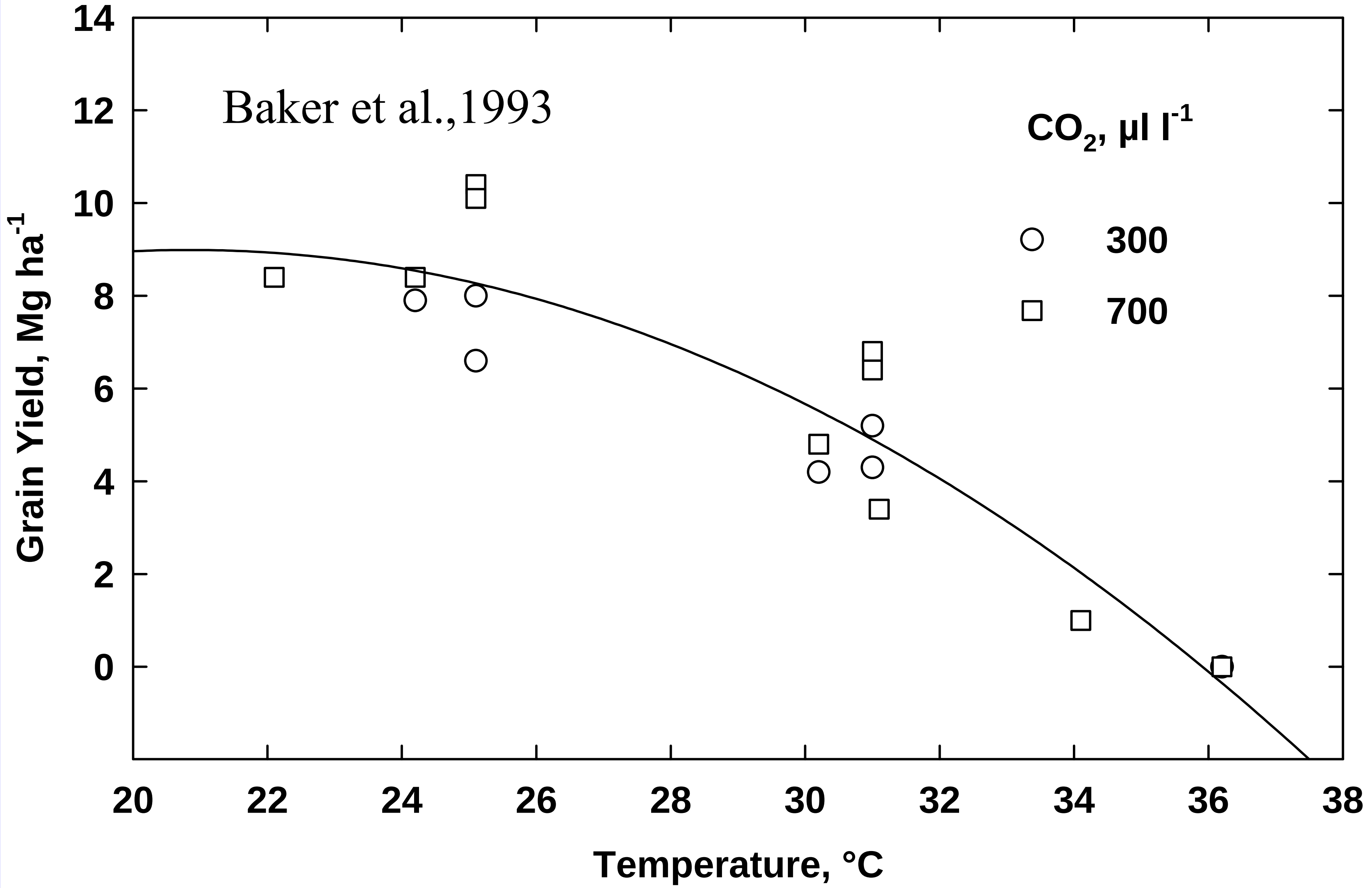


Fig. 4.6. Relation between average daily maximum temperature during the flowering period and spikelet fertility in the variety Akihikari acclimated to different CO_2 concentrations (Horie, 1993).

High Temperature Effects on Rice Yields



Rice Growing Areas – Weather Stations (67 locations)

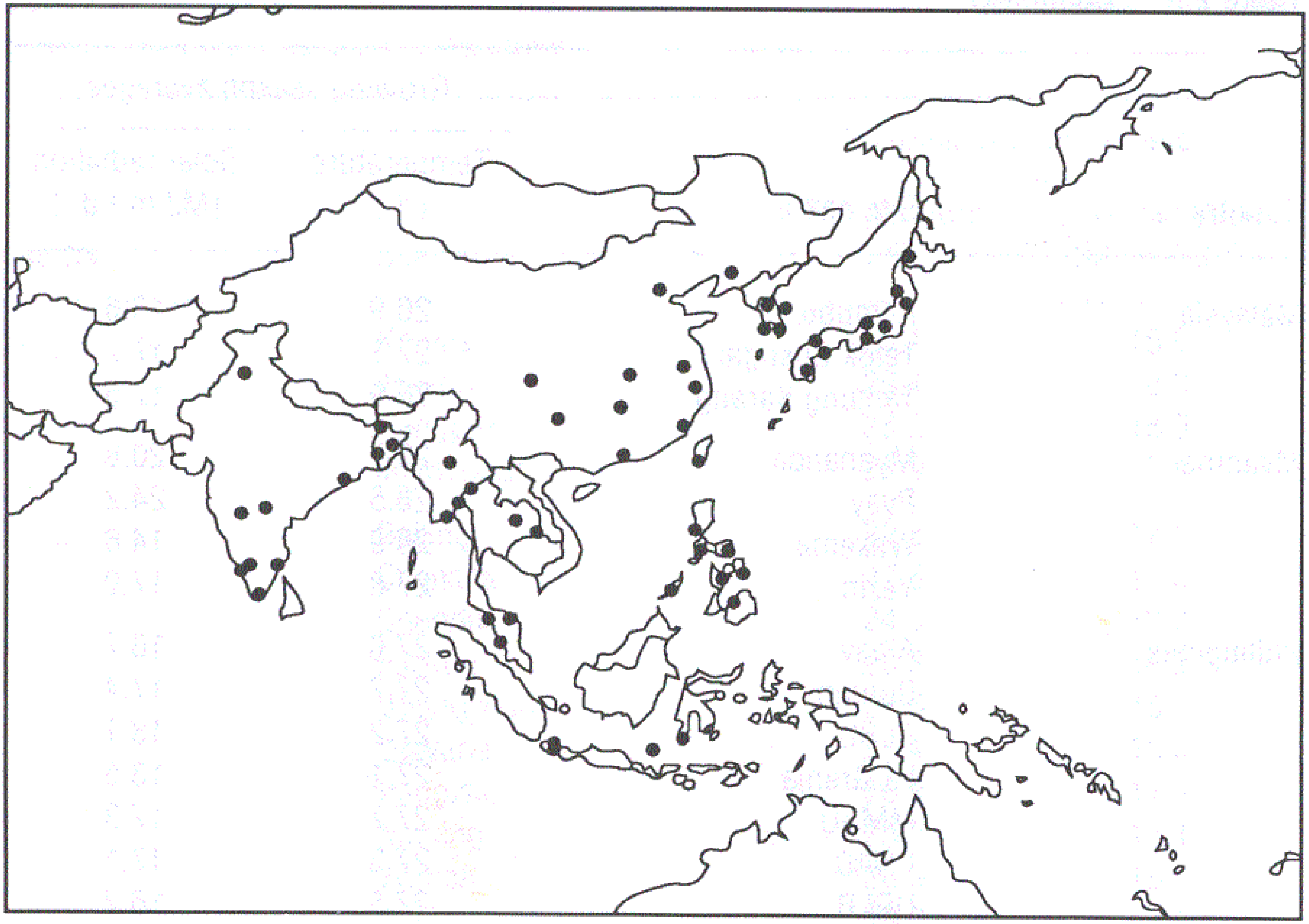
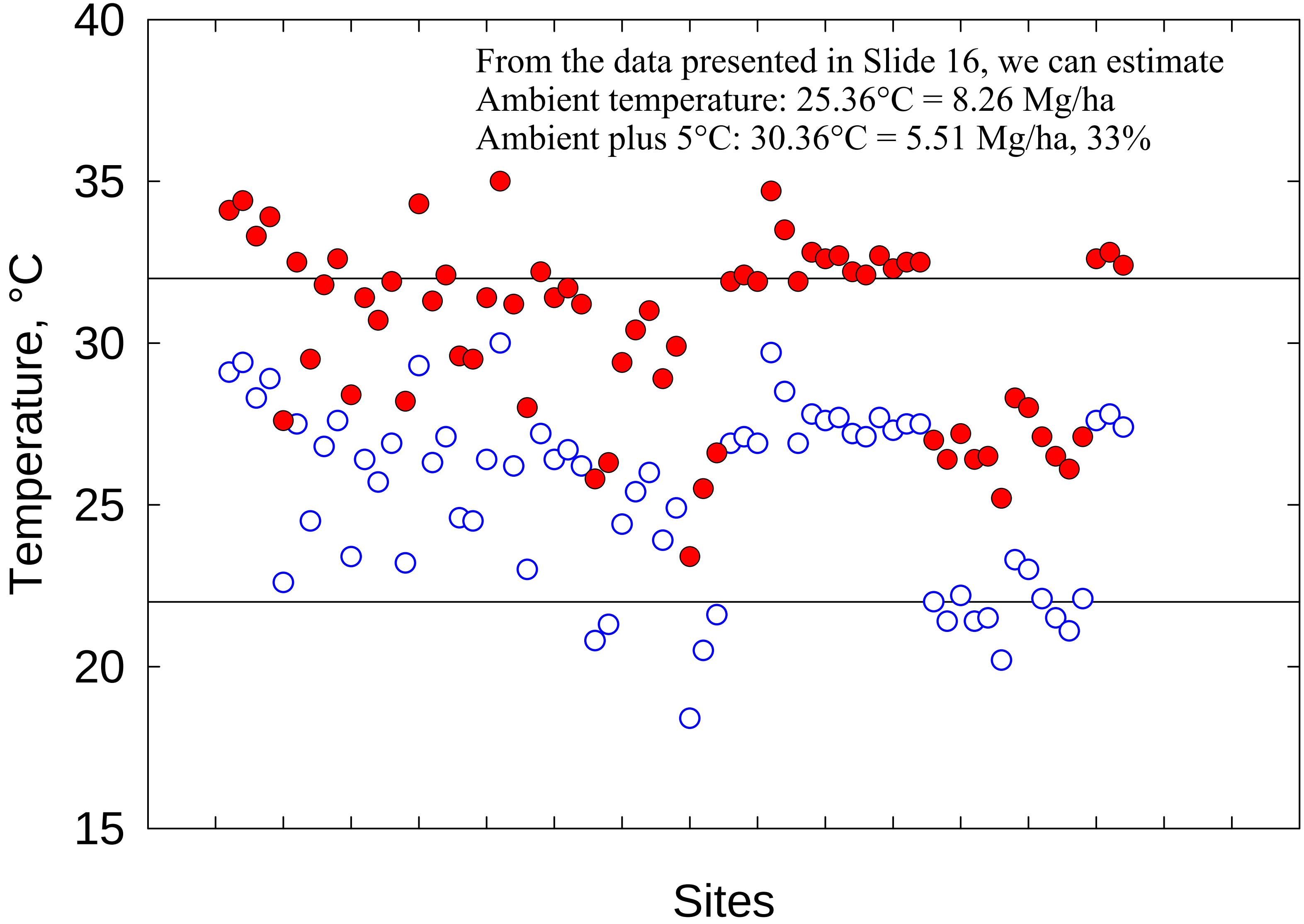


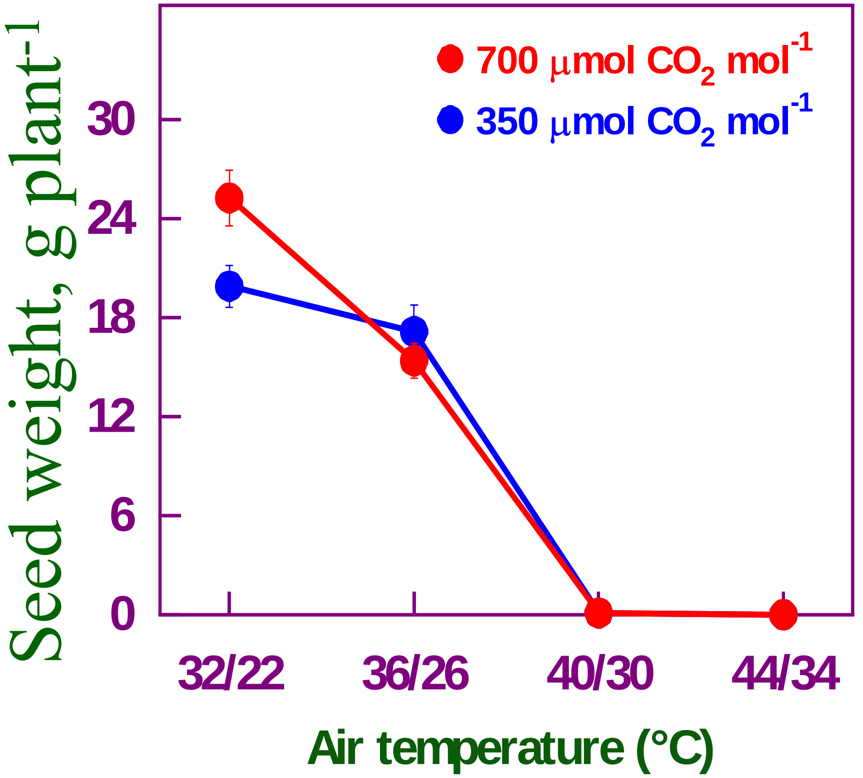
Fig. 2.1. Locations of the weather stations used in the study.

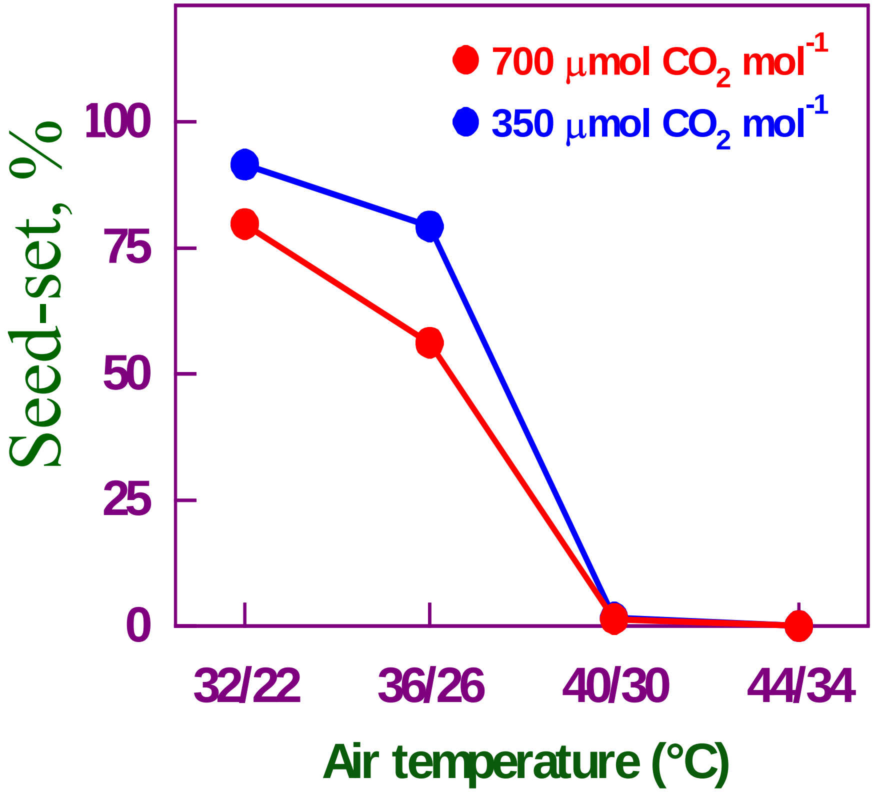
Growing season temperatures from those locations listed in the previous slide and with an additional 5°C added to those temperatures relative to optimum and marginal conditions



High Temperature Injury
Temperature and CO2 Interactions – Sorghum

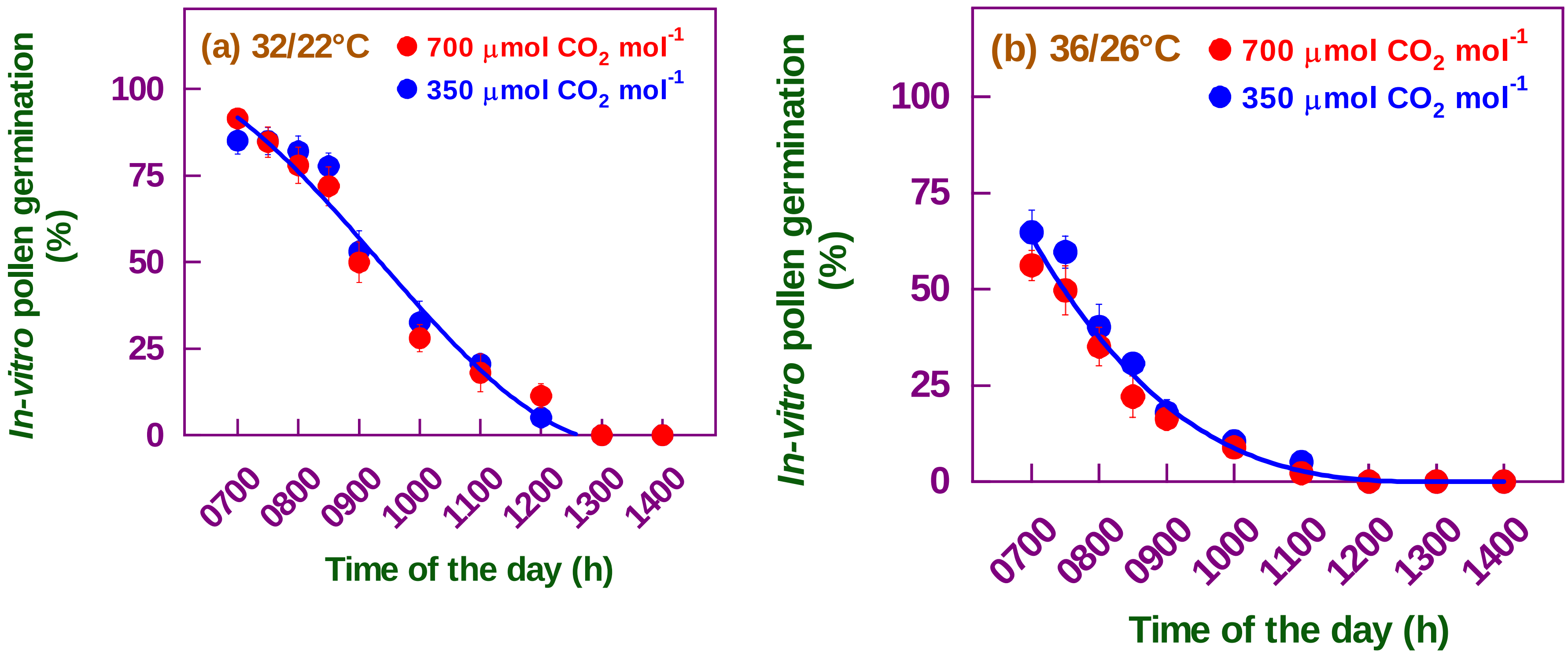
Seed Weight and Seed-set





High Temperature Injury
Temperature and CO2 Interactions – Sorghum

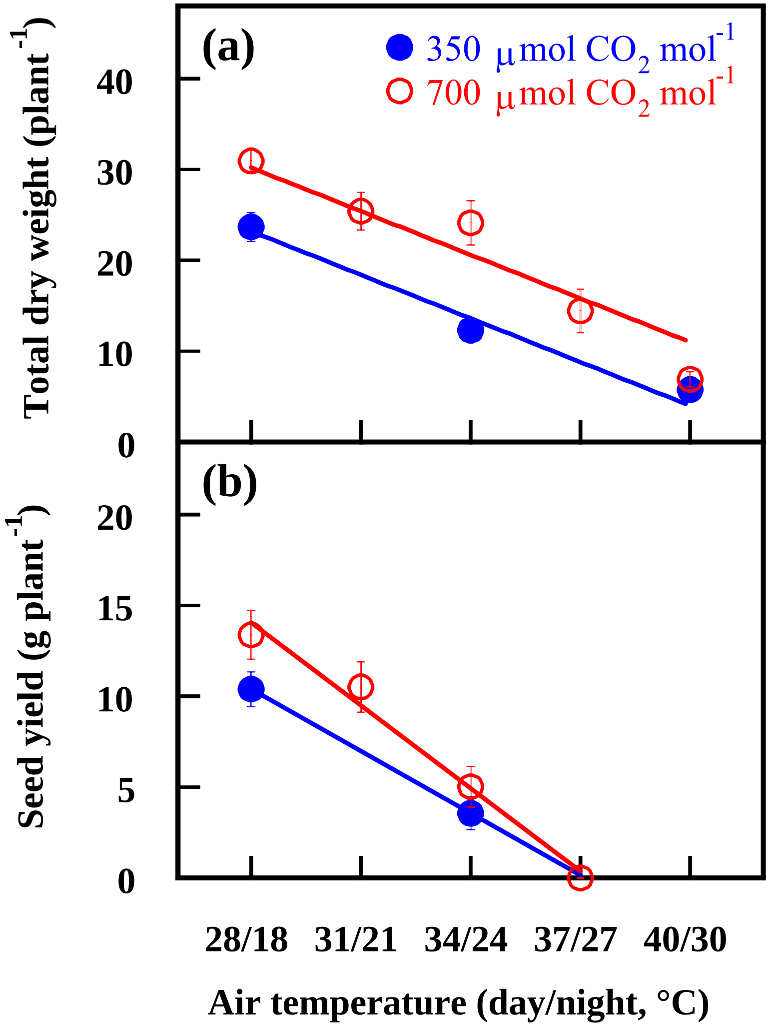
Pollen Germination



- Elevated temperature decreased pollen longevity.
- Elevated CO_2 had no effect.

Prasad et al. 2005

High Temperature Injury
Temperature and CO2 Interactions – Dry Beans



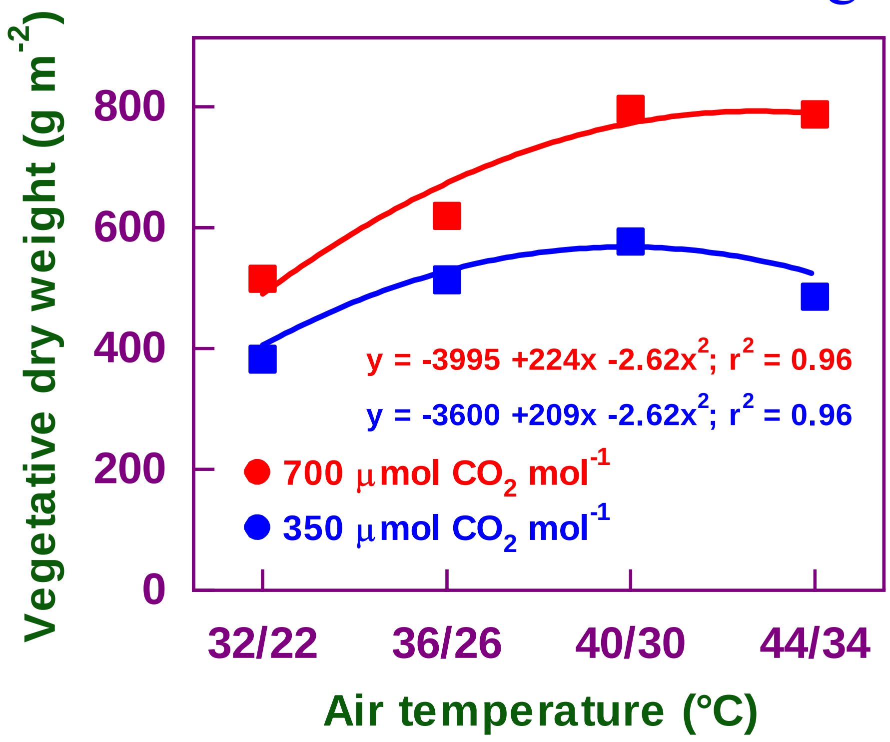
Total Weight and Seed Weight

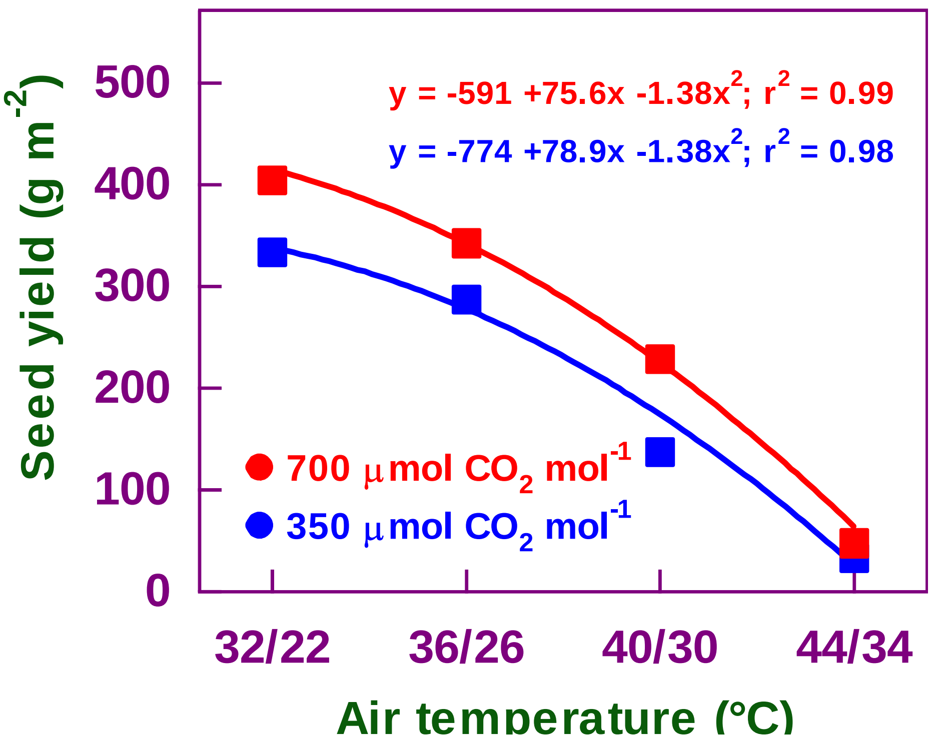
- Elevated temperatures decreased total dry weights and seed yields.
- Elevated CO_2 increased seed yields but to a lesser extent at high temperatures.

Prasad et al. 2005

High Temperature Injury
Temperature and CO2 – Groundnut

Total Weight and Seed Weight





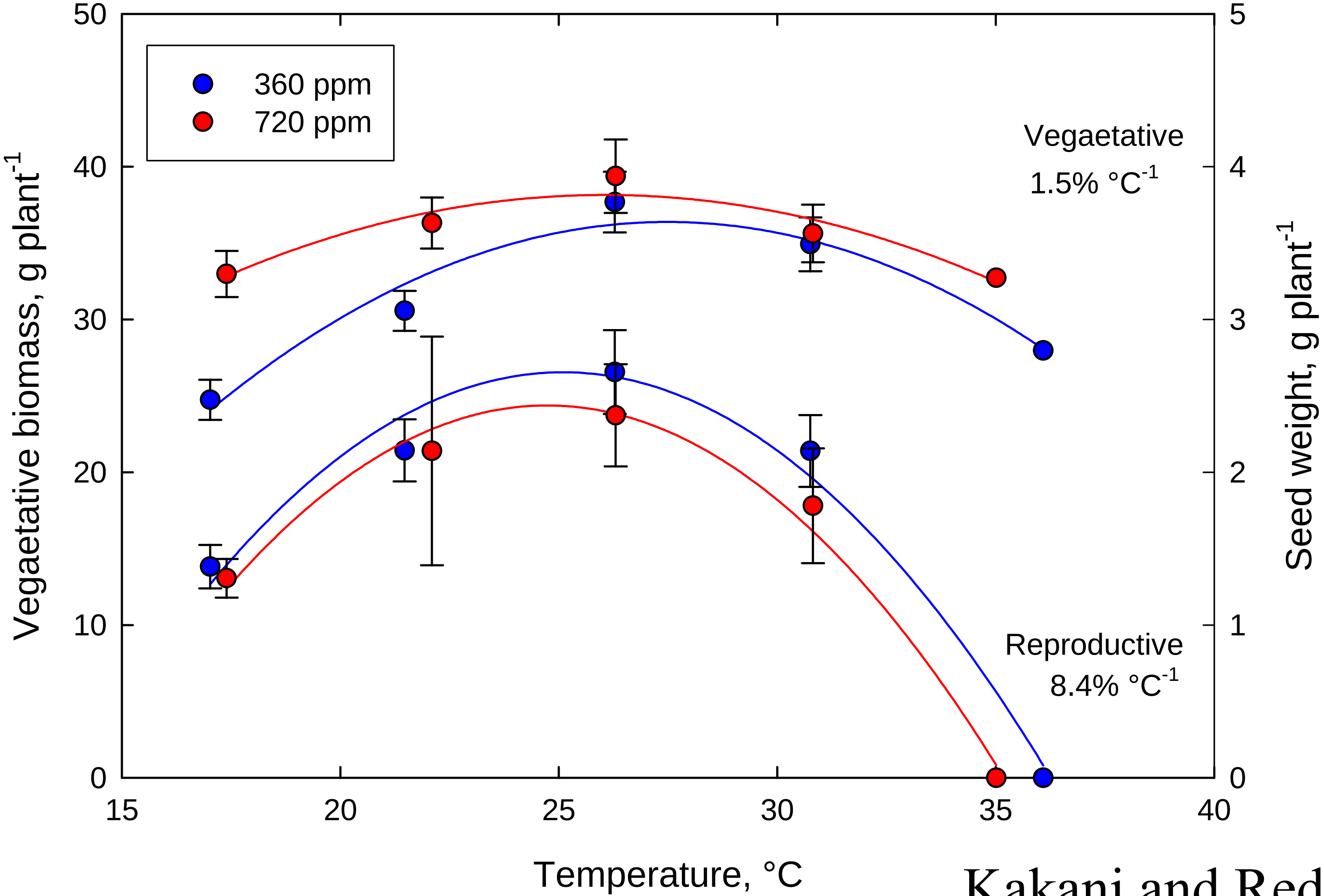
Harvest, index, seed size, shelling percentage, seed-set, pollen viability and seed number did not change between CO2 levels, but drastically reduced with increase in temperatures.

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

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

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)

Crop	Effects
Wheat	Temperature >30°C for >8 h, can reverse vernalization
Rice	Temperature >35°C for >1 h at anthesis causes spikelet sterility
Maize	Temperature >36°C causes pollen to lose viability
Soybean	Great ability to recover from stress. No especially critical period in its development
Potato	Temperature >20°C depresses tuber initiation and bulking
Cotton	Temperature >40°C for >6 h causes bolls to abort

High Temperature Injury
Conclusions – Temperature and CO2 Interactions

- There are no beneficial effects of elevated CO_2 on reproductive processes.
- There are no beneficial interaction of CO_2 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 CO_2 (grain sorghum, dry bean and big blue stem).

Plant Responses to Extreme Environments

Chilling and Freezing Temperature Injury

Climate Change and Crop Productivity

Conclusions – Temperature and CO_2 Interactions

- 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.

Low Temperature Injury
Chilling and Freezing stress

- Sensitive plant species are injured by chilling at temperatures (10 to15°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.

Low Temperature Injury
Chilling and Freezing stress

Percent weight of total fatty acid content

Major fatty acid	Chill-resistant species - Cauliflower	Chill-sensitive species - maize
Palmitic (16:0)	21.3	28.3
Steric (18:0)	1.9	1.6
Oleic (18:0)	7.0	4.6
Linoleic (18:2)	16.4	54.6
Linolenic (18:3)	49.4	6.8
Ratio of unsaturated to saturated fatty acids	3.2	2.1

Low Temperature Injury
Freezing stress

- 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.

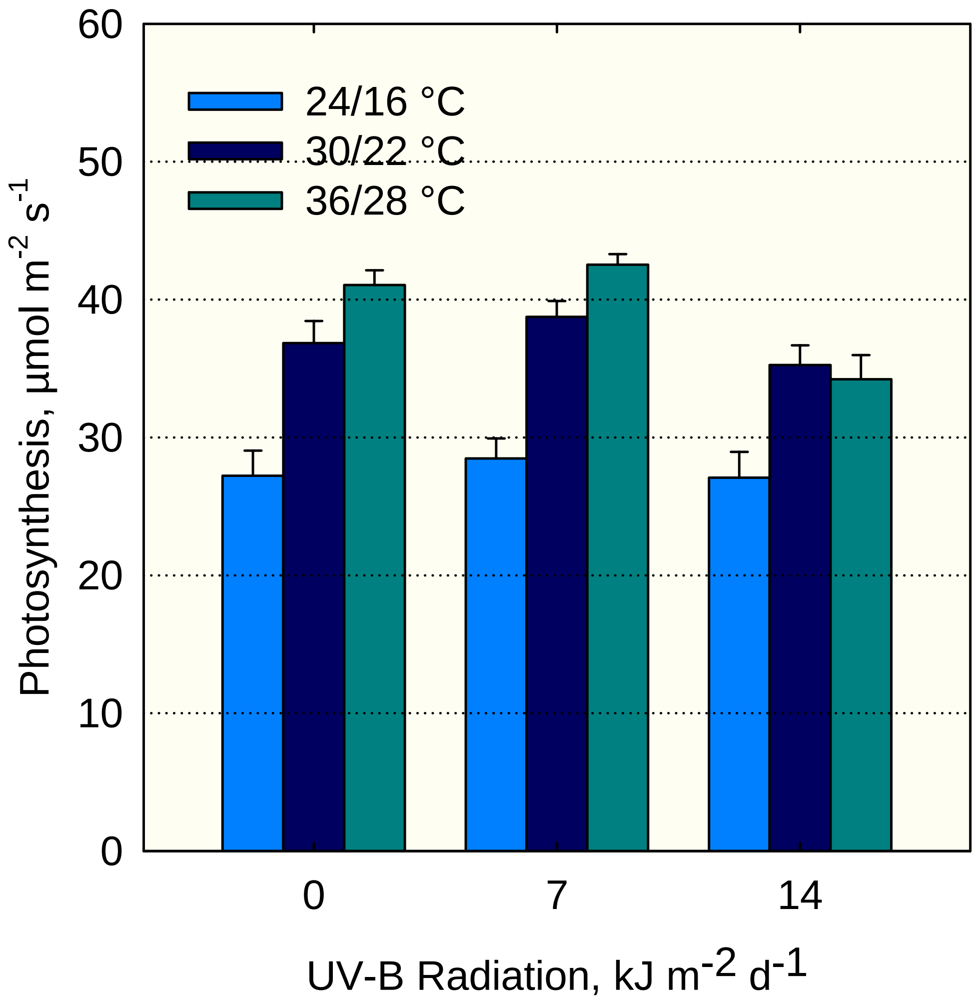
Multiple Abiotic Factors and Crop Productivity

Effects of Multiple Abiotic Factors

UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

30/22

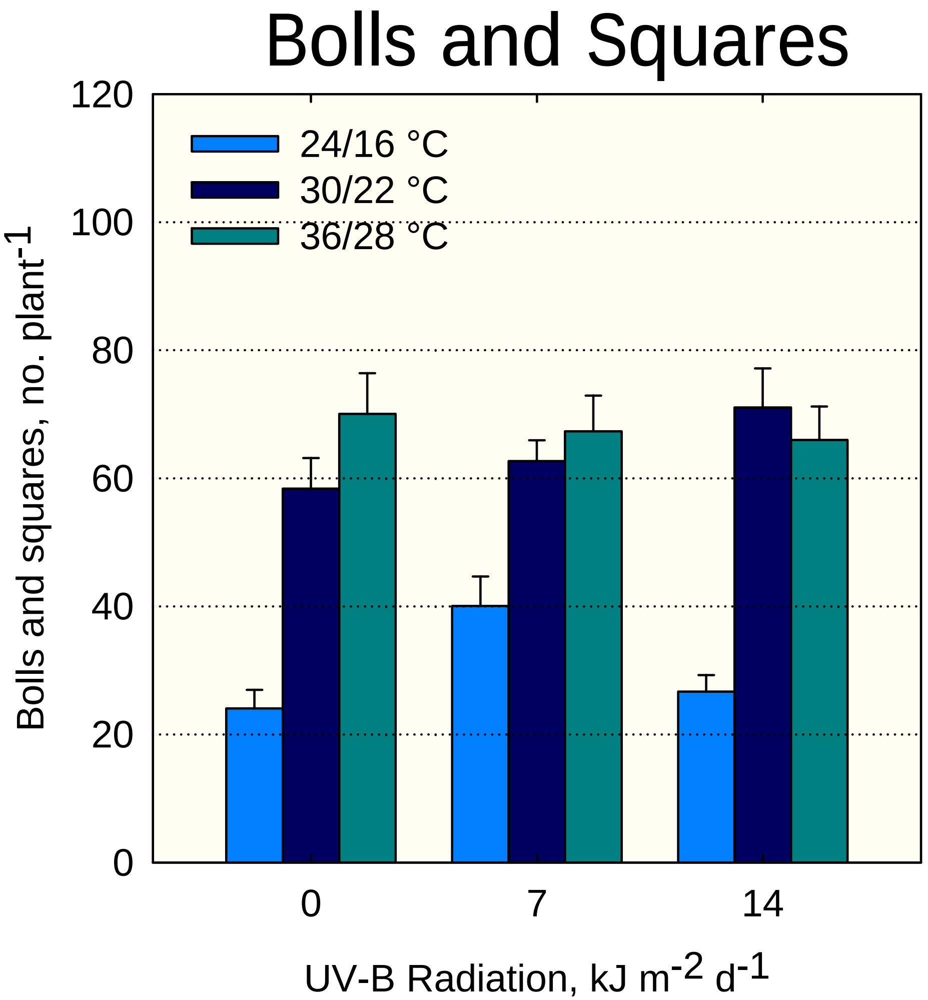
36/28



UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

30/22

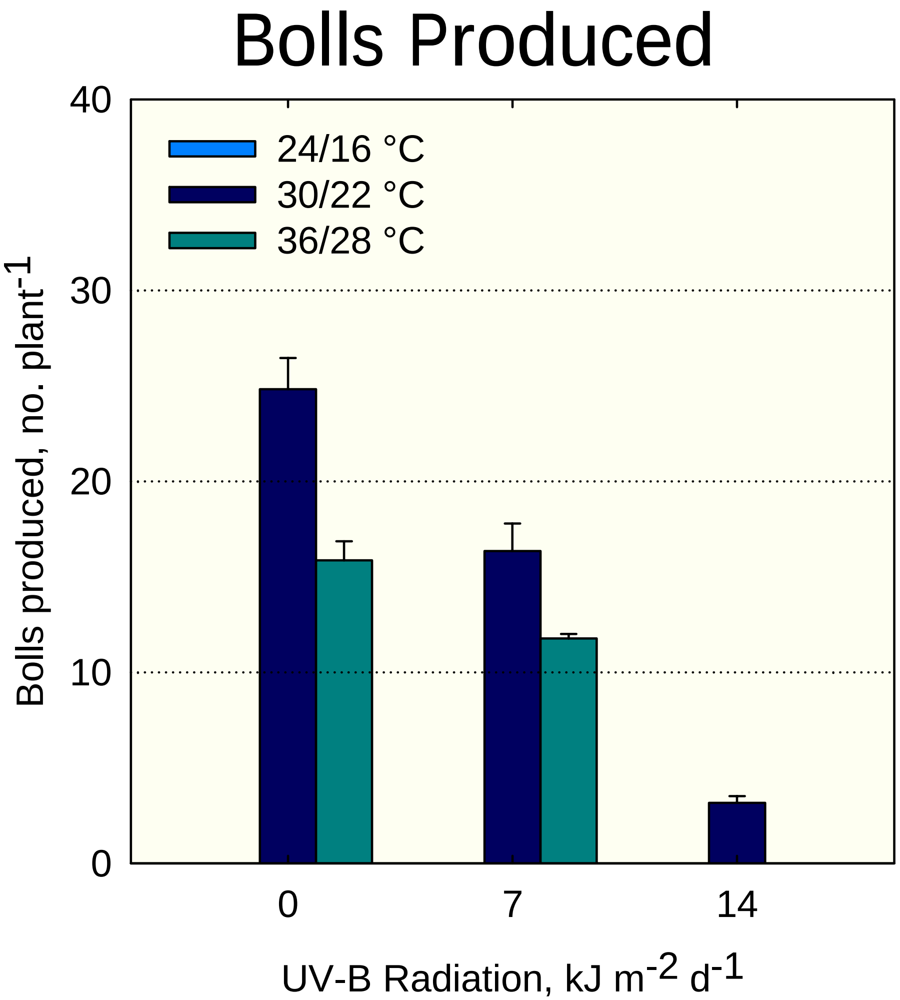
36/28



UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

30/22

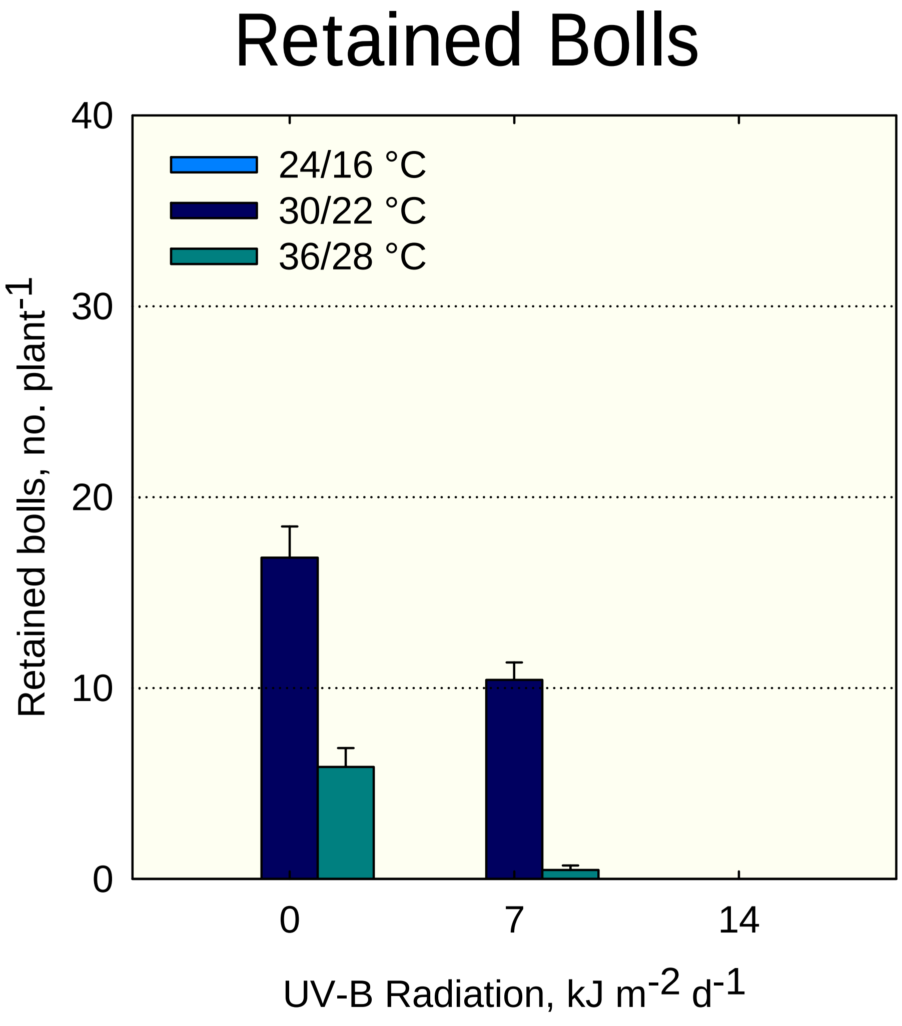
36/28



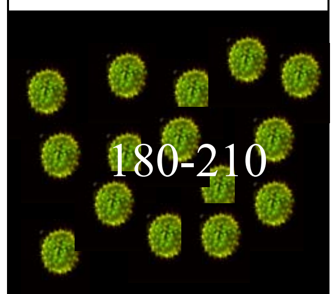
UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

30/22

36/28



UV-B Radiation and Temperature
Cotton Reproductive Growth and Development

		Pollen no. anther^{-1}	Pollen germination %
30/22		 180-210	70
36/28		 50-80	1

UV-B Radiation and Soybean Genotypes
Reproductive Growth and Development

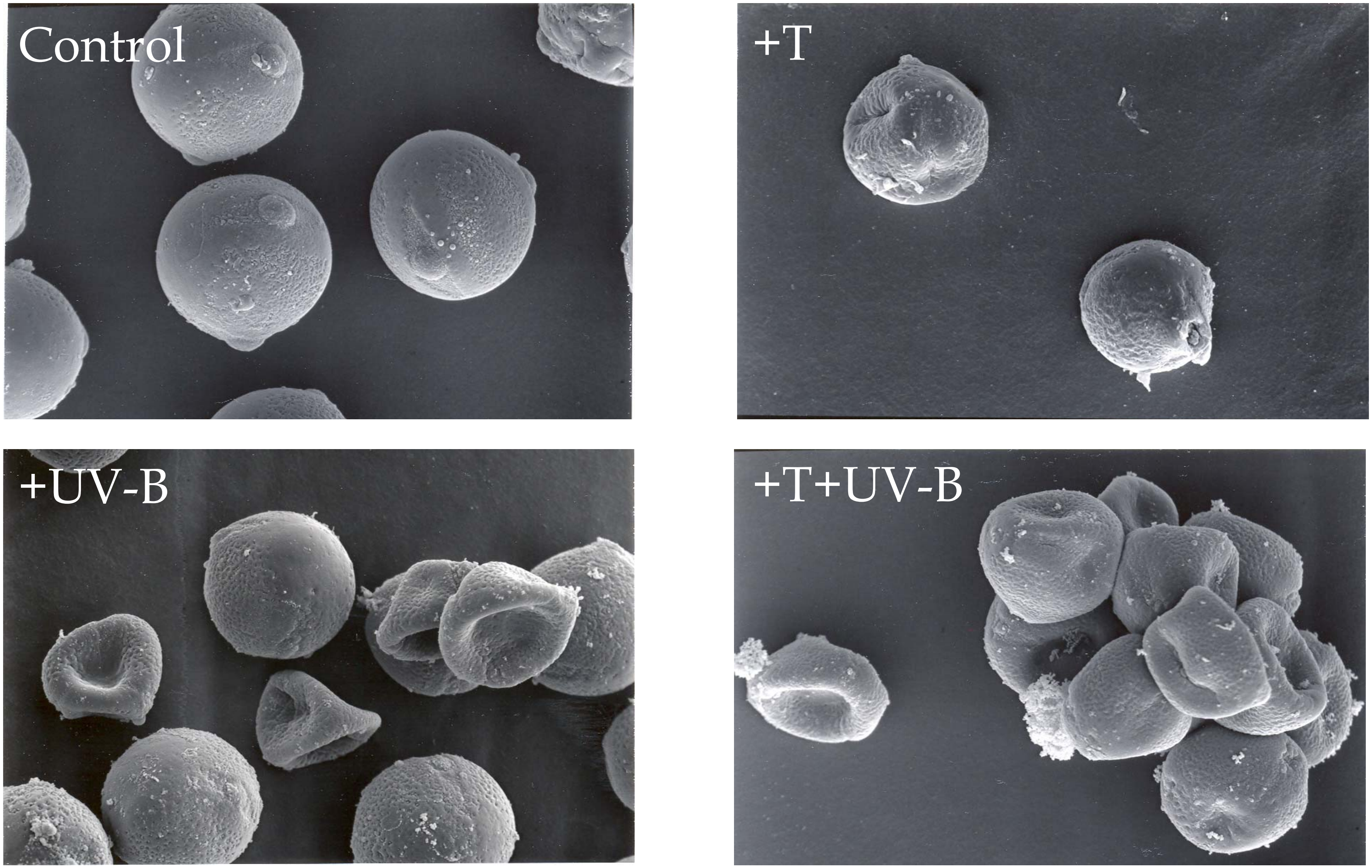
Treatments

Growing Conditions and Treatments:

Temperature (°C)	CO_2 (ppm)	UV-B (kJ m^{-2} d^{-1})
30/22	360	0
		5
38/30	720	10
		15

UV-B and Temperature

Soybean Reproductive Development – Sensitive Cultivar



Crop Traits and Genetic Variability to Abiotc Stresses

Genotypic Variability to Abiotic Stresses

Crop Traits and Genetic Variability to Abiotc 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 Abiotc 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

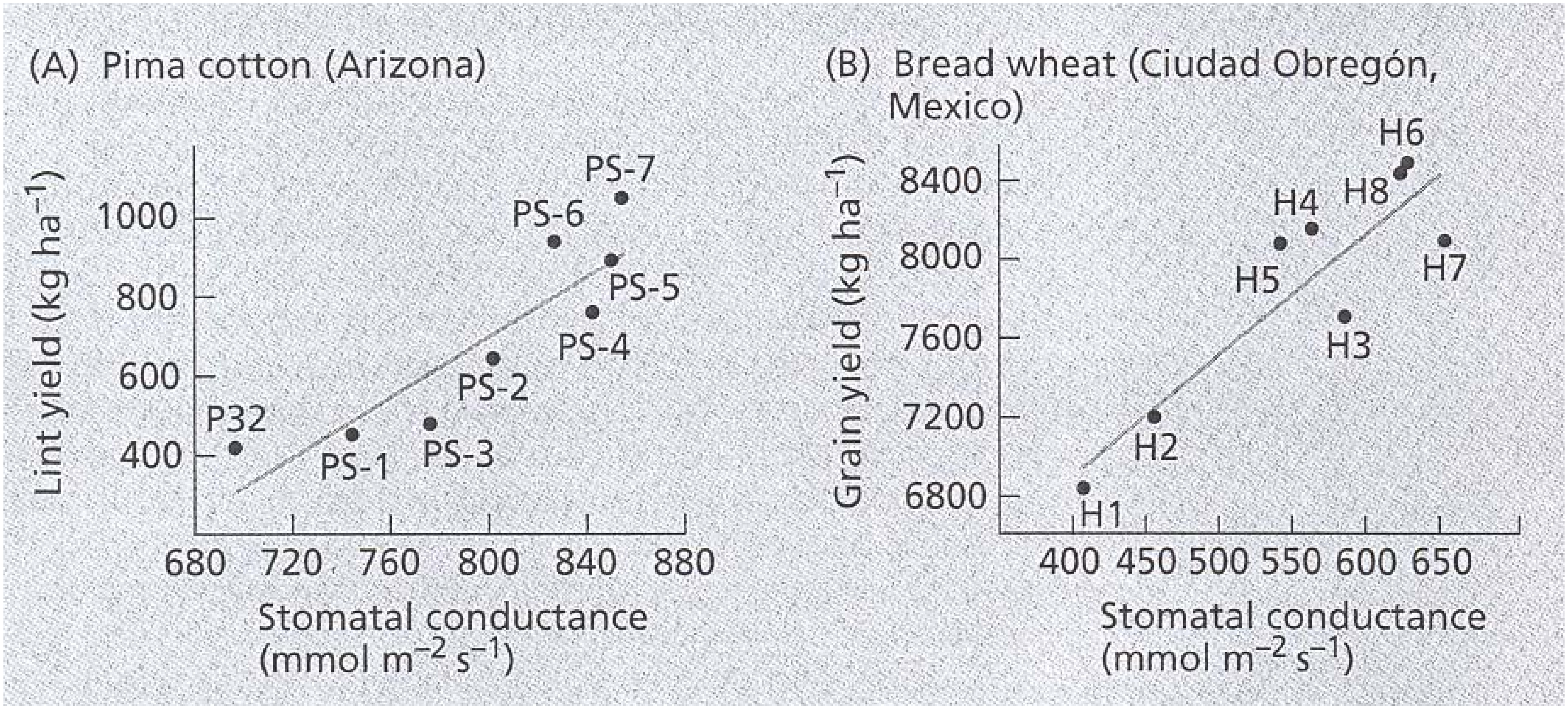
Crop Traits and Genetic Variability to Abiotc Stresses

- 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

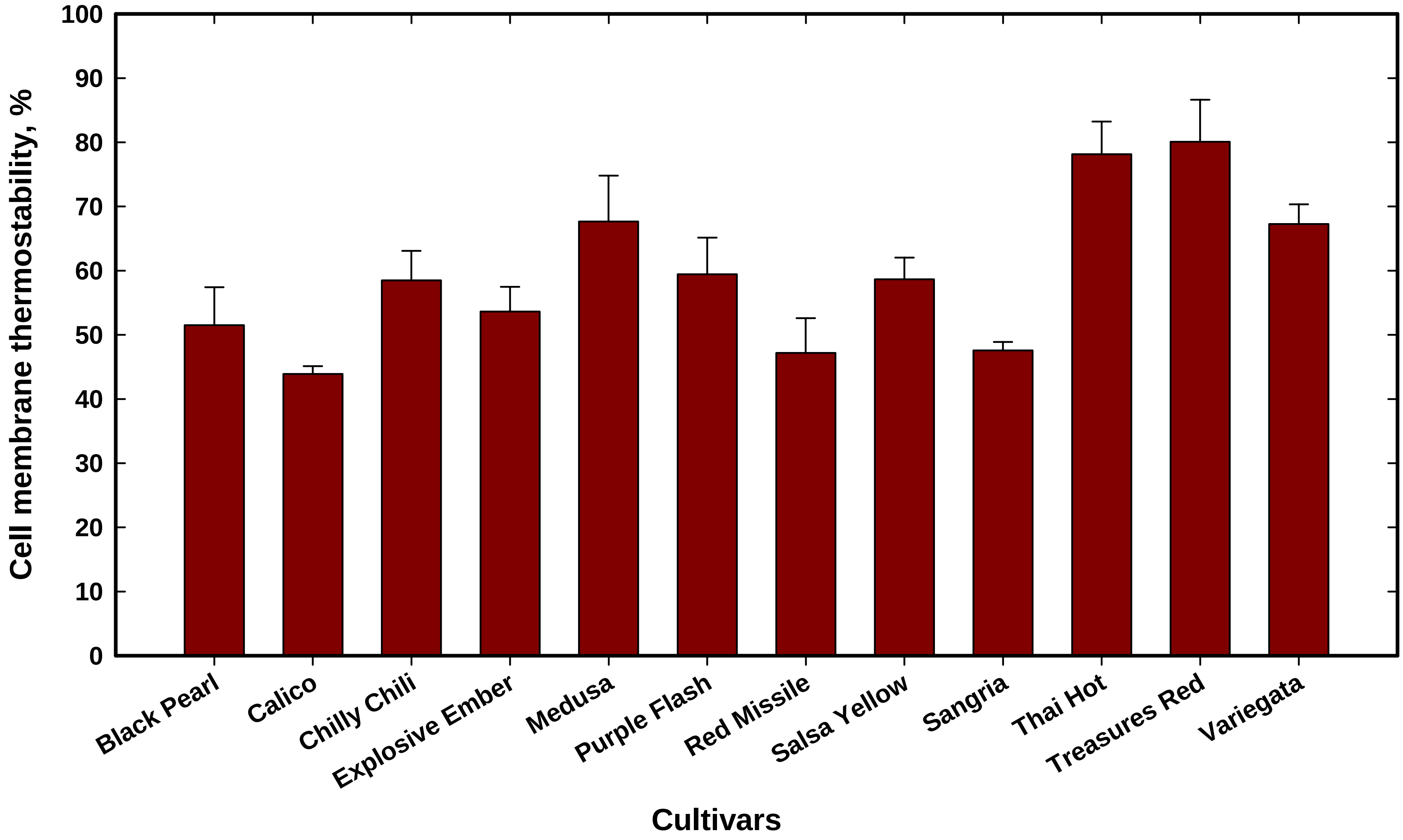
Physiological Parameters - Stomata Conductance and Yield



Traits and Abiotic Stress Tolerance

Physiological Parameters – Cell Membrane Thermostability

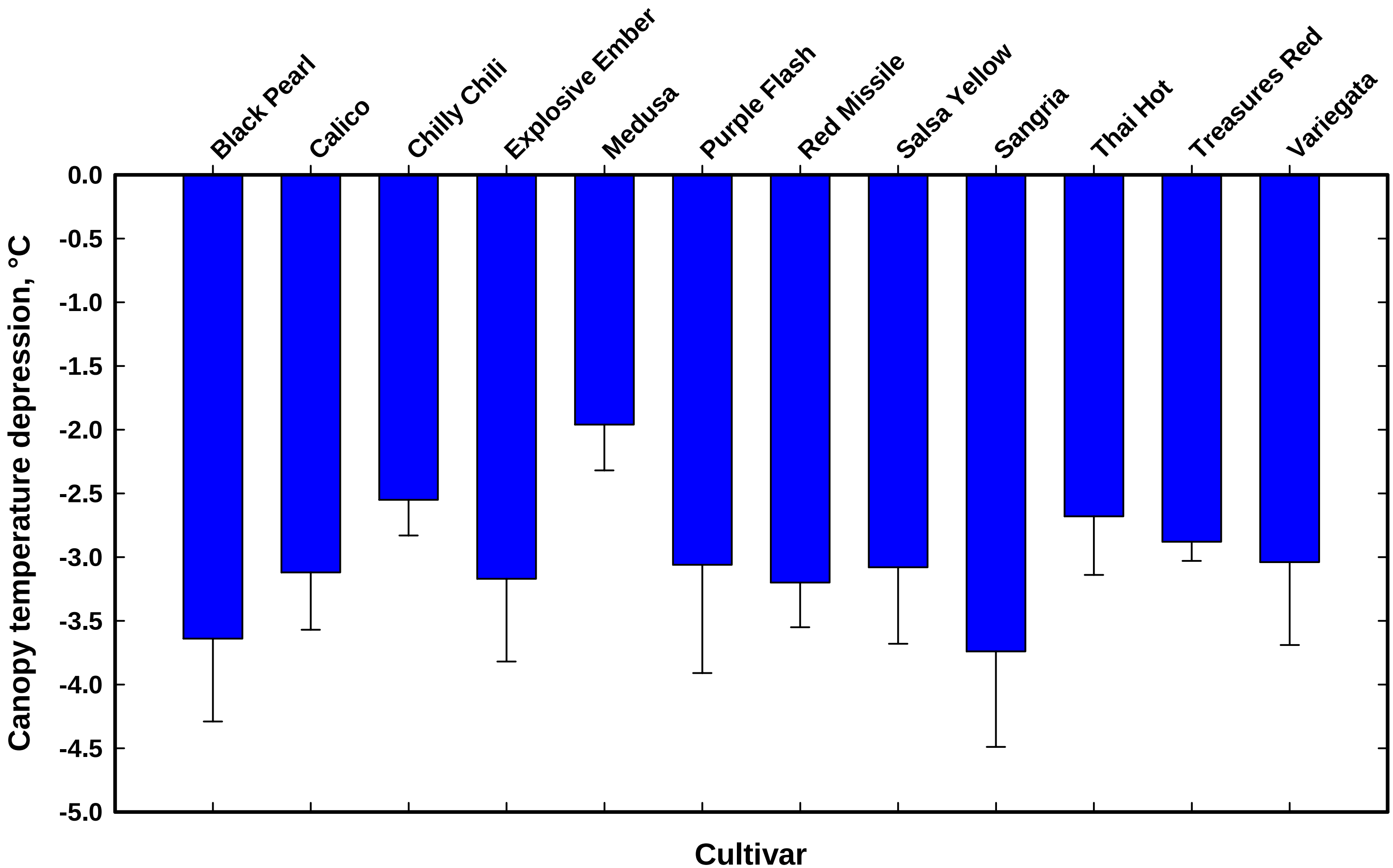
Genotypic Variability - Ornamental Pepper Cultivars



Traits and Abiotic Stress Tolerance

Physiological Parameters – Canopy Temperature Depression

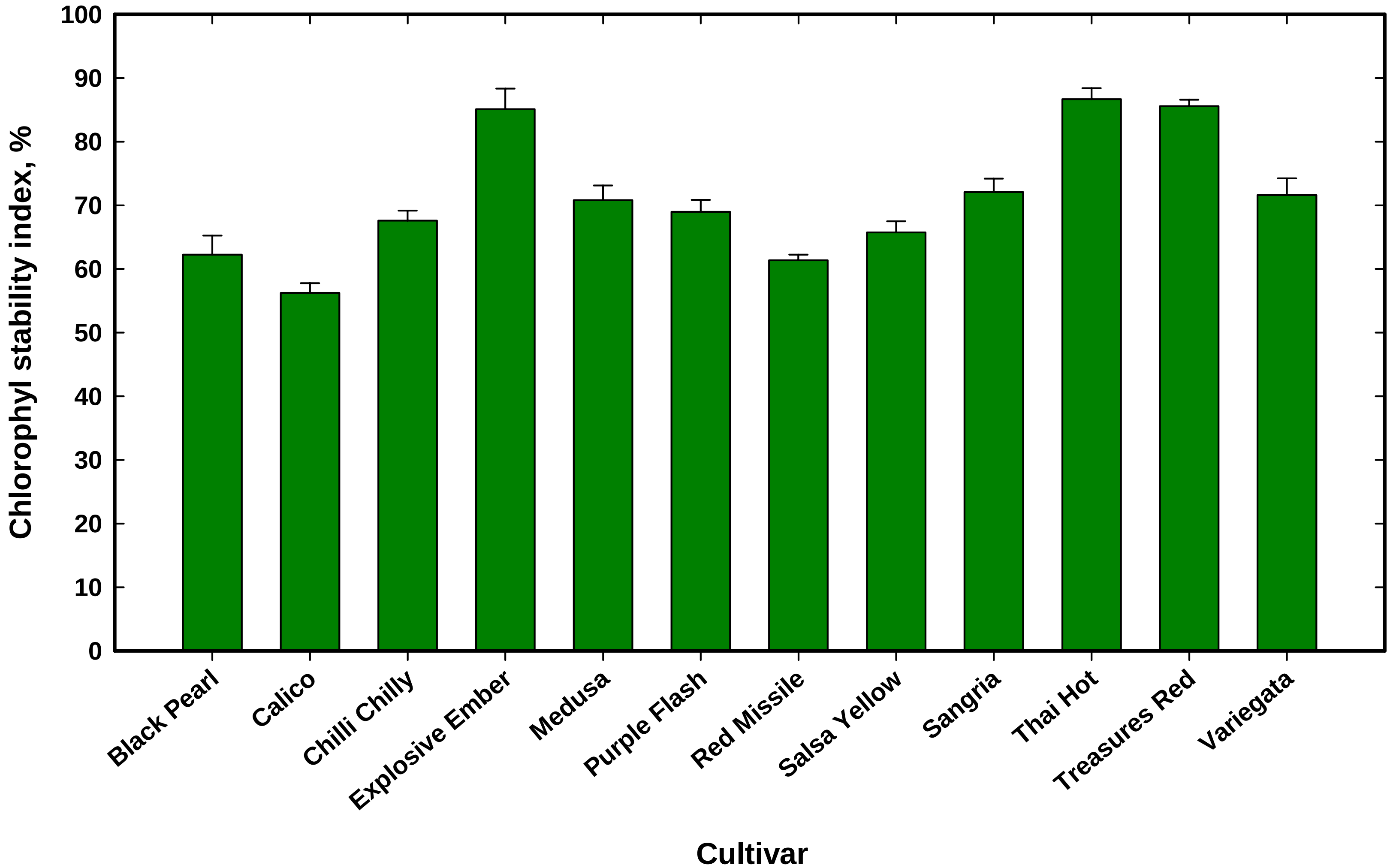
Genotypic Variability - Ornamental Pepper Cultivars



Traits and Abiotic Stress Tolerance

Physiological Parameters – Chlorophyll Stability Index

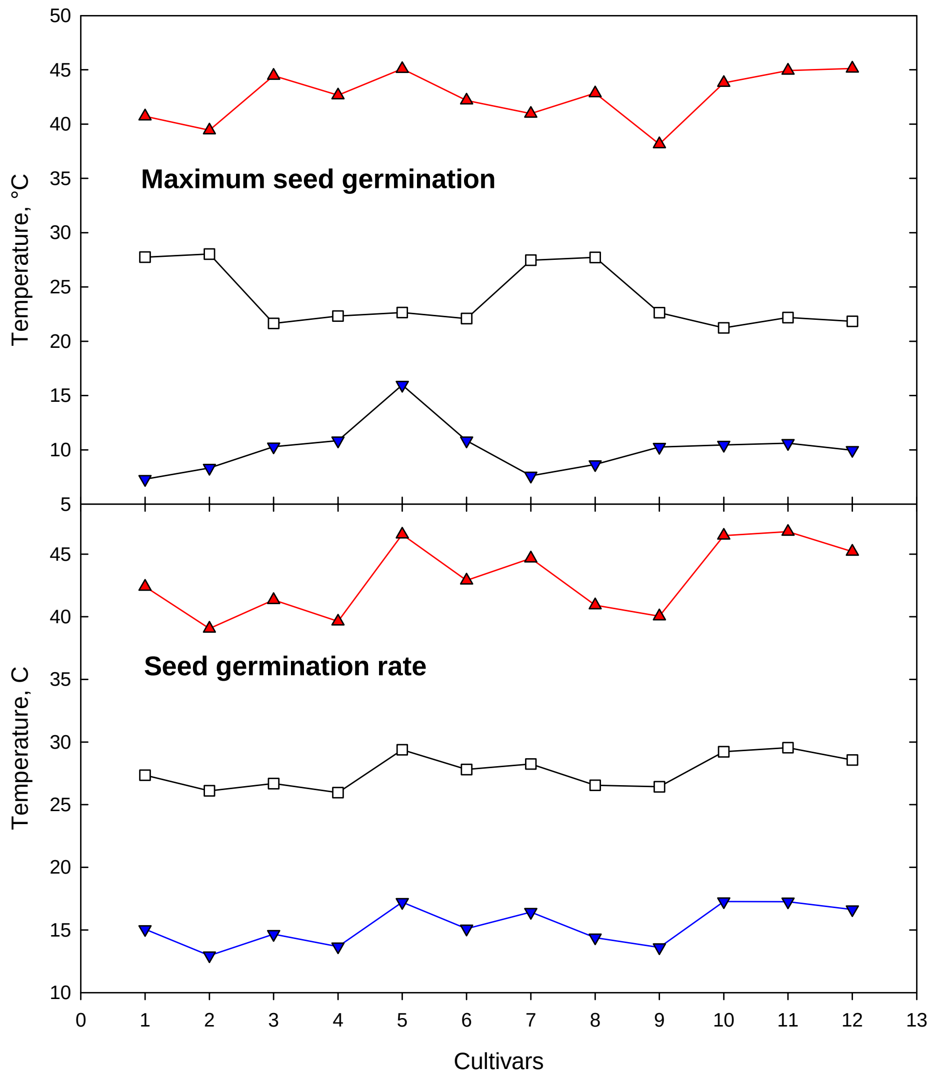
Genotypic Variability - Ornamental Pepper Cultivars



Traits and Abiotic Stress Tolerance

Seed-based Parameters – Genotypic Variability

Ornamental Peppers



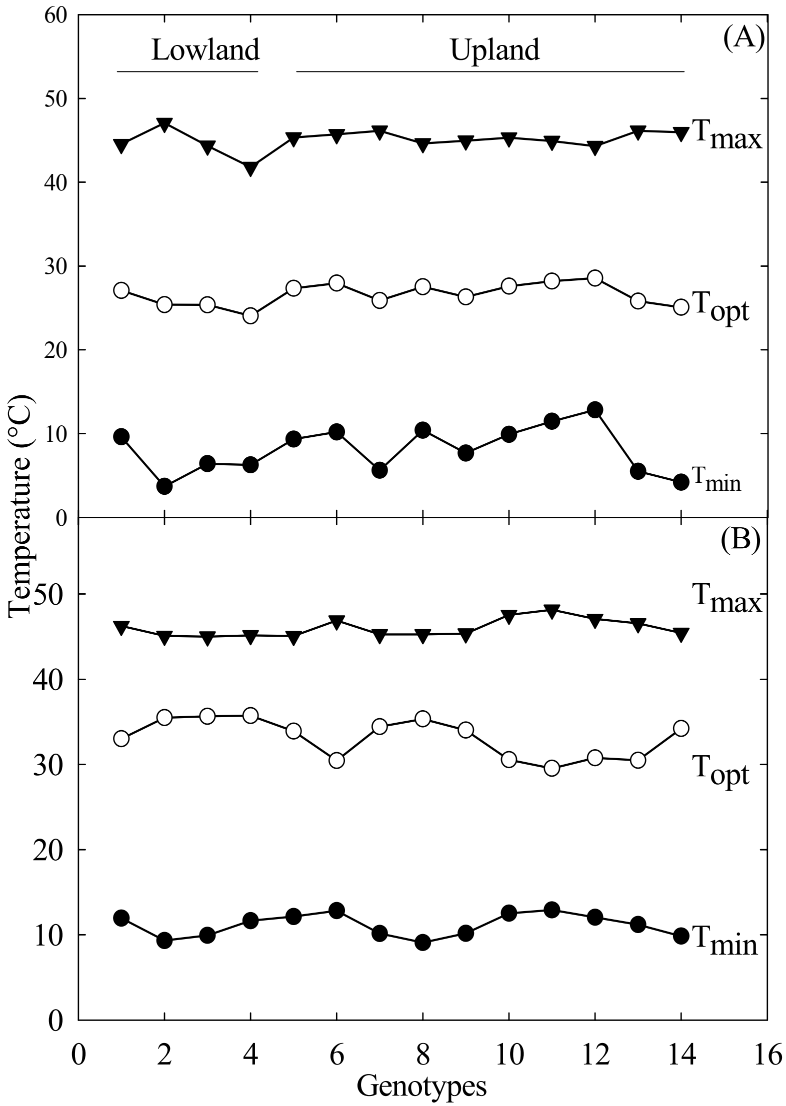
- Greater variability for cardinal temperatures among ornamental pepper cultivars.

Cardinal Temperature	MSG (mean)	SGR (mean)
T_{min}	10.1	15.3
T_{opt}	24.0	27.7
T_{max}	42.5	43.0

Traits and Abiotic Stress Tolerance

Seed-based Parameters – Genotypic Variability

Switchgrass Genotypes



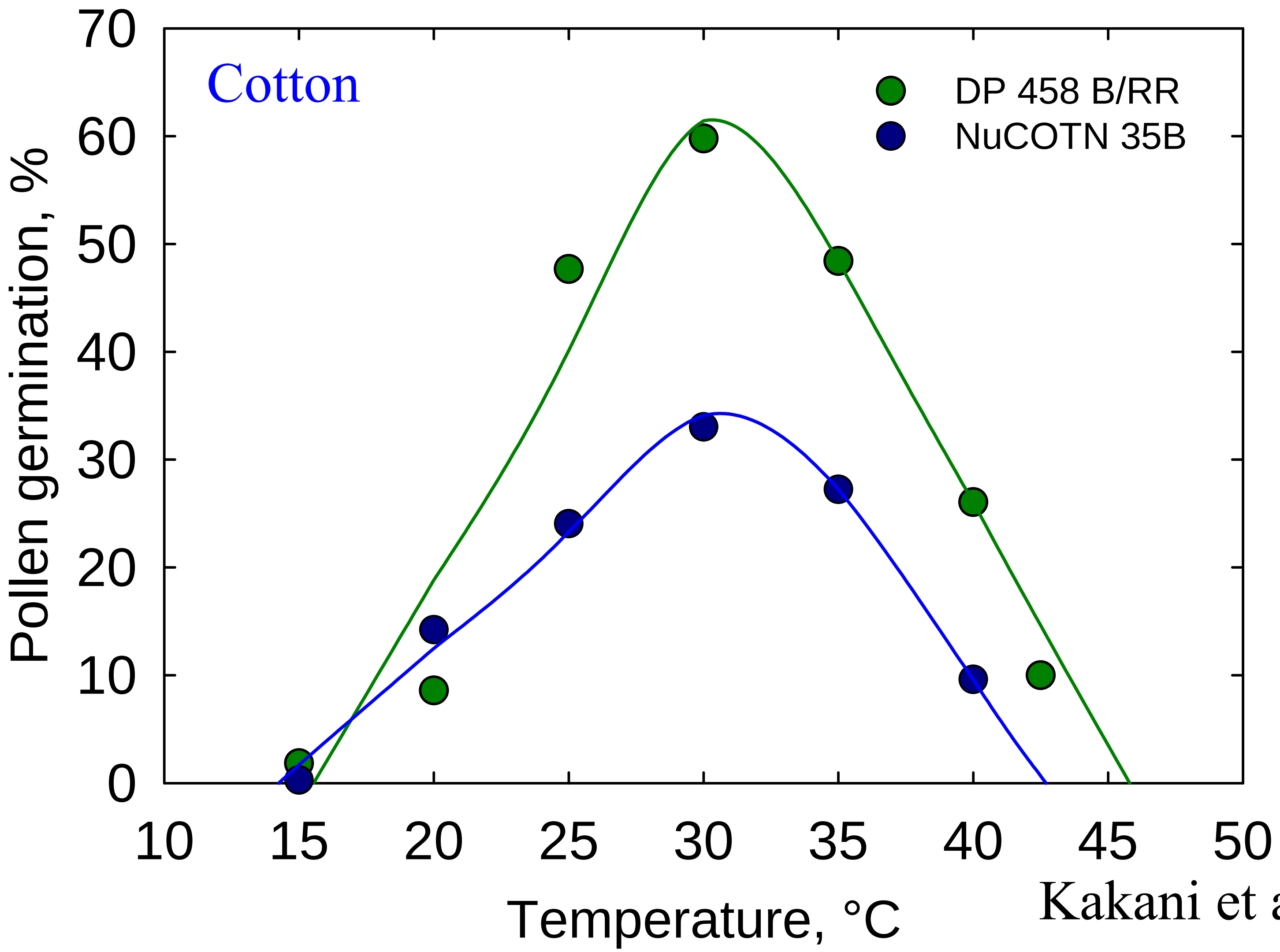
- Greater variability for cardinal temperatures among switch grass genotypes.

Cardinal Temperature	MSG (mean)	SGR (mean)
T_{min}	8.08	11.3
T_{opt}	26.58	33.12
T_{max}	45.09	46.01

Traits and Abiotic Stress Tolerance

Reproductive Parameters – Pollen Germination

Genotypic Variability - Cotton

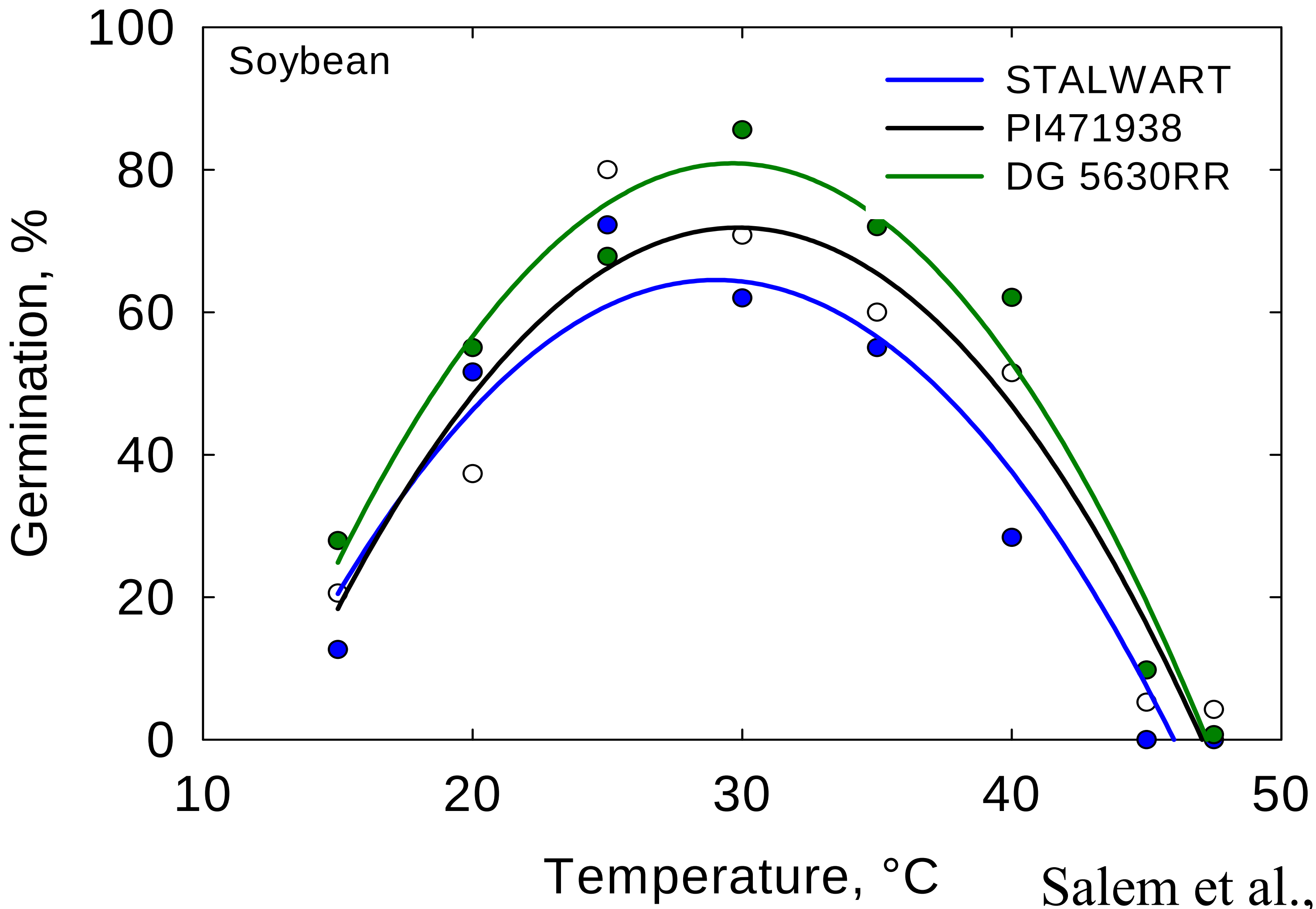


Kakani et al., 2005

Traits and Abiotic Stress Tolerance

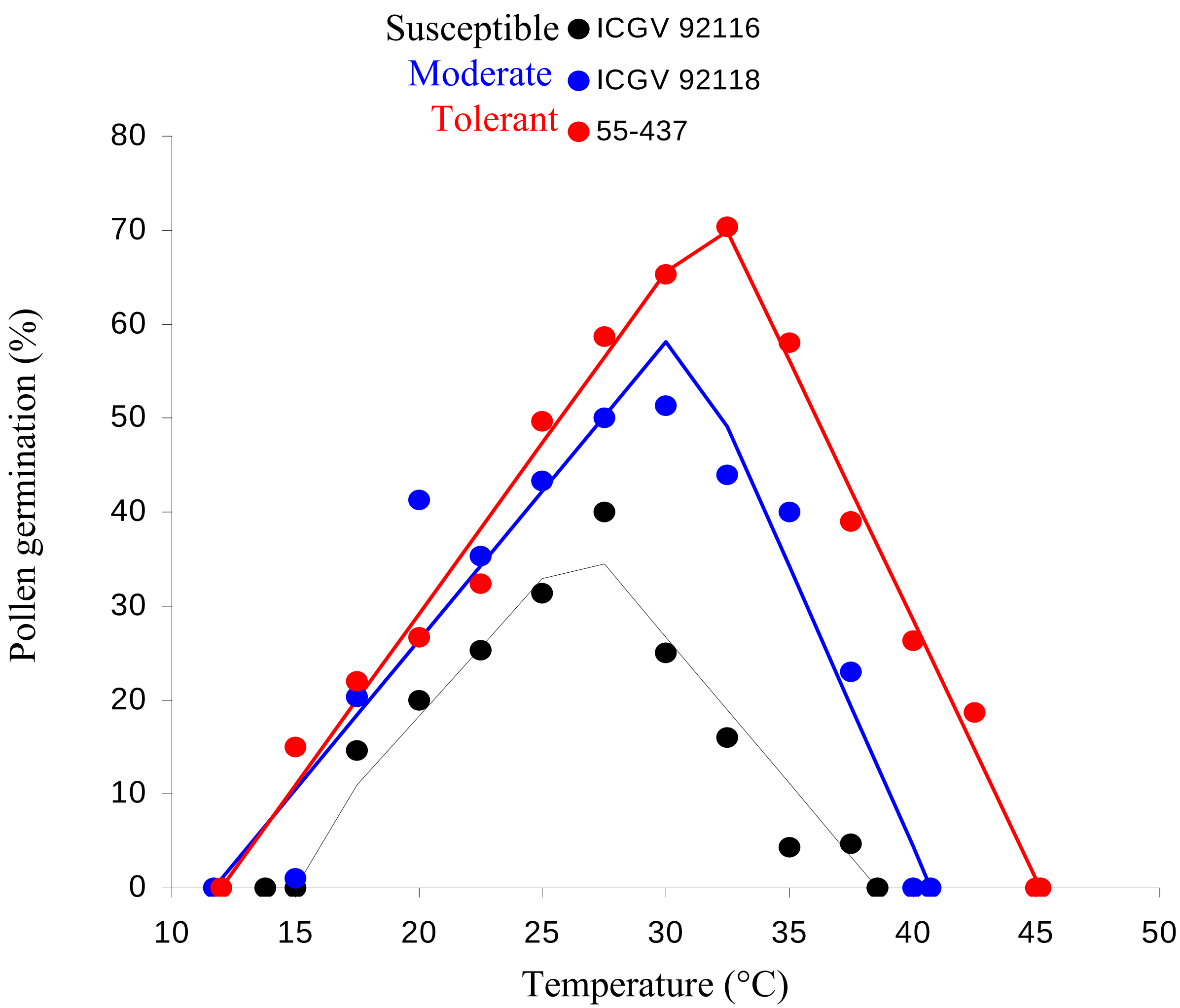
Reproductive parameters – Pollen Germination

Genotypic Variability - Soybean



Salem et al., 2006

Temperature – Pollen Germination - Groundnut

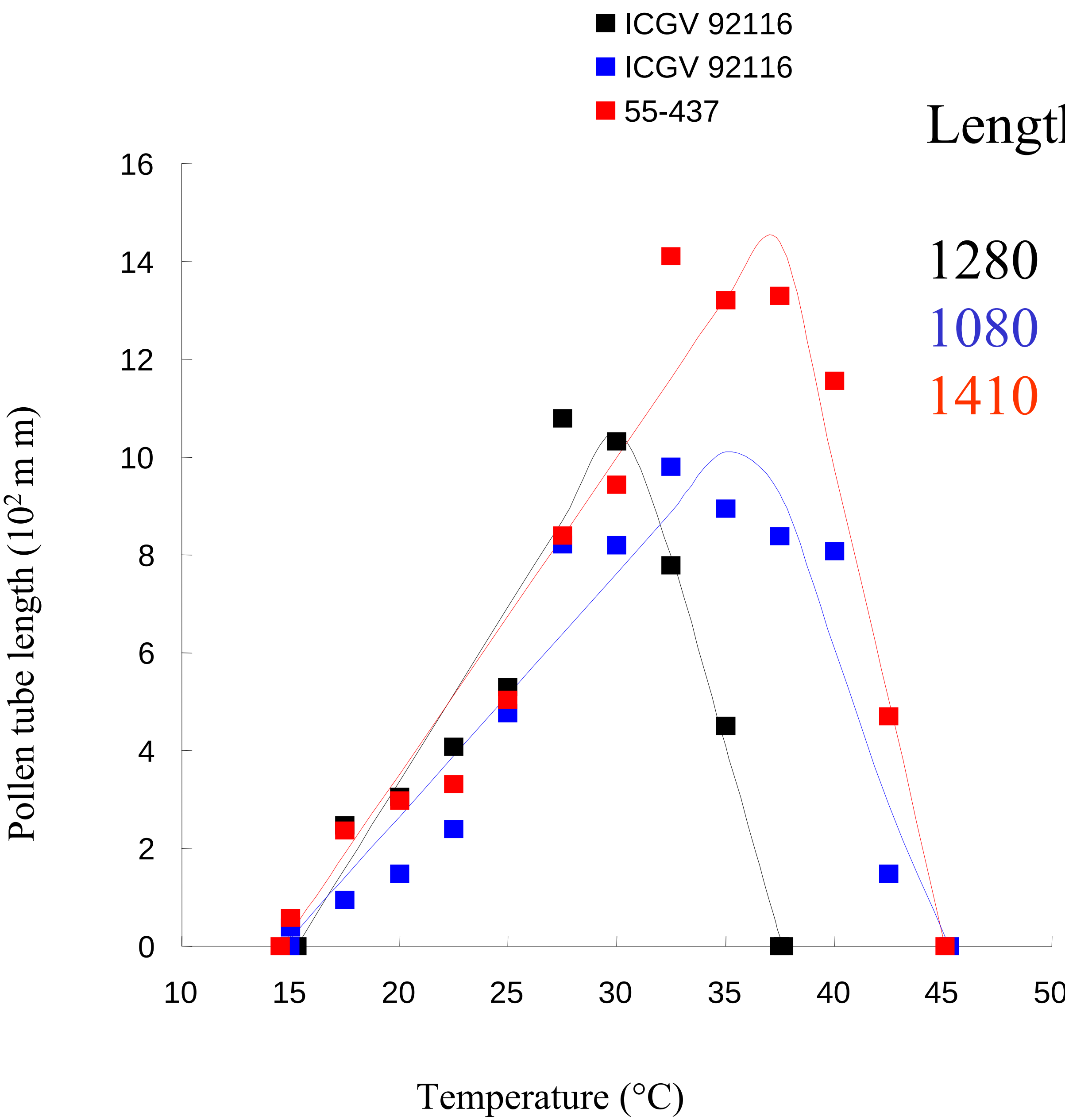


%	T_b	T_{opt}	T_{max}
40	13.8	26.5	38.5
51.5	11.7	30.6	40.7
70.3	11.9	31.9	45.2

Effect of temperature on percentage pollen germination of susceptible (T_{opt} < mean-LSD), moderately tolerant (T_{opt} = 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

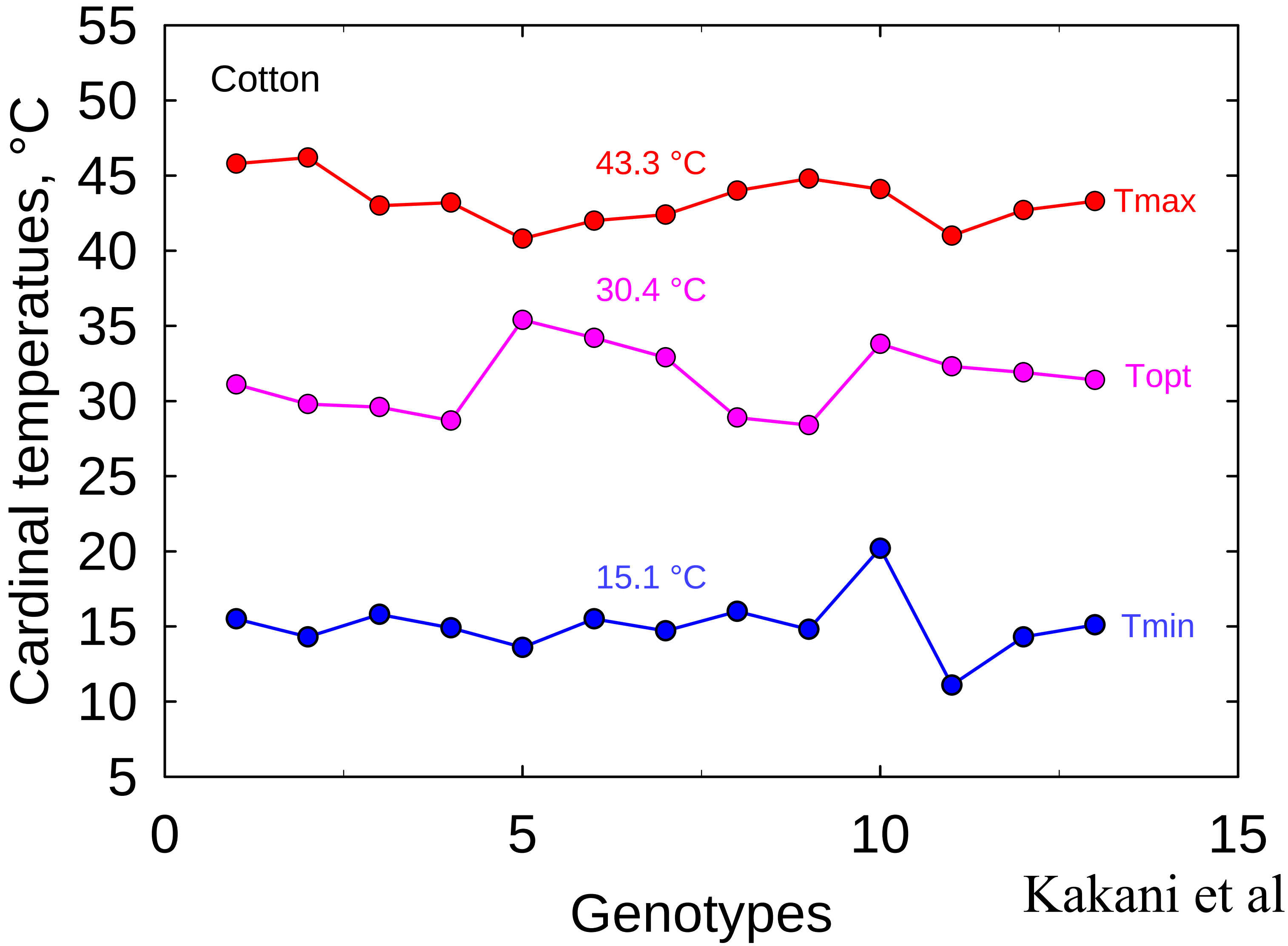


Length	T_b	T_{opt}	T_{max}
1280	16.0	36.4	45.5
1080	15.3	30.5	37.7
1410	14.5	37.6	45.1

Kakani et al., 2002

Traits and Abiotic Stress Tolerance

Reproductive parameters – Pollen Germination - Genotypic Variability

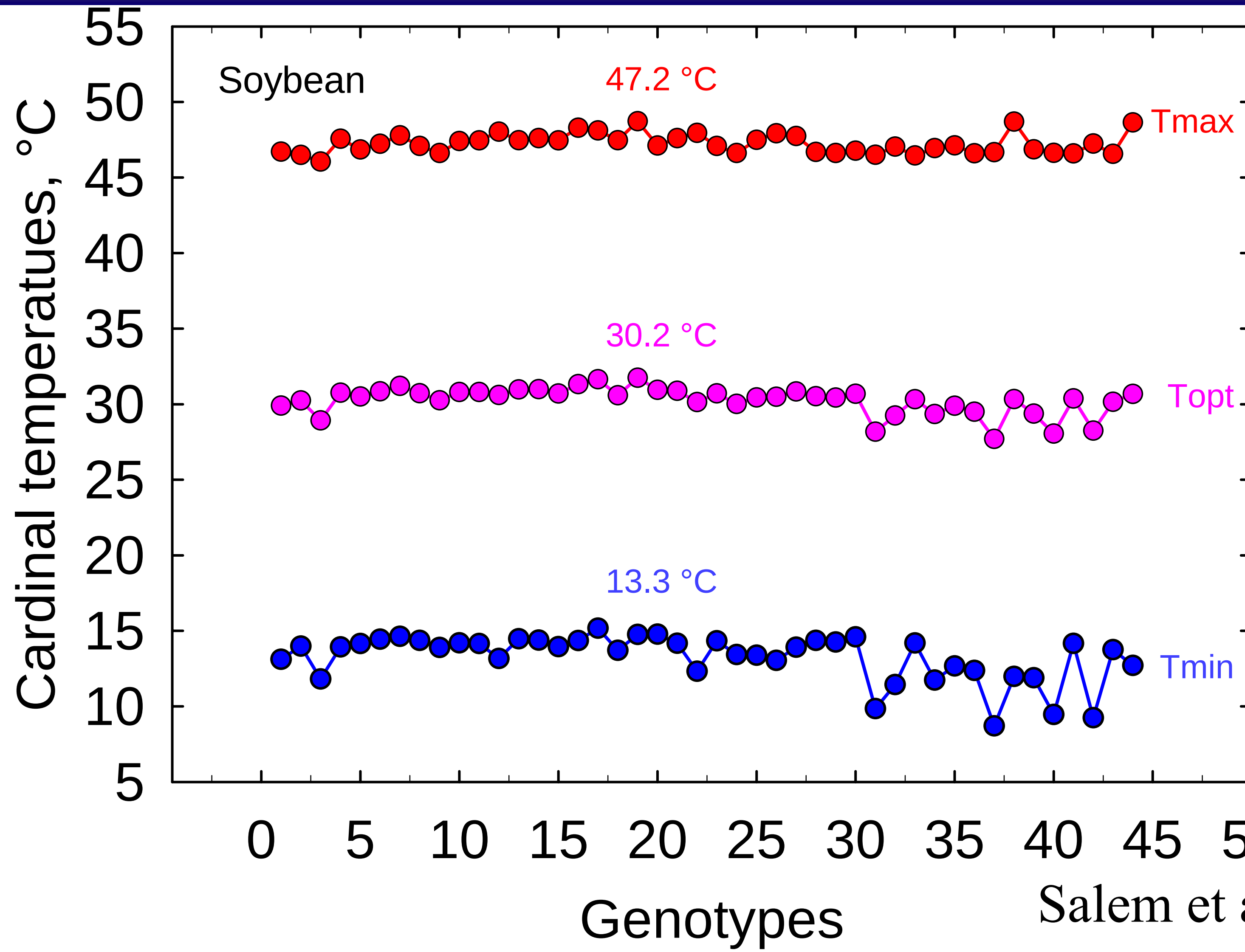


Kakani et al., 2005

Traits and Abiotic Stress Tolerance

Reproductive parameters – Pollen Germination

Genotypic Variability

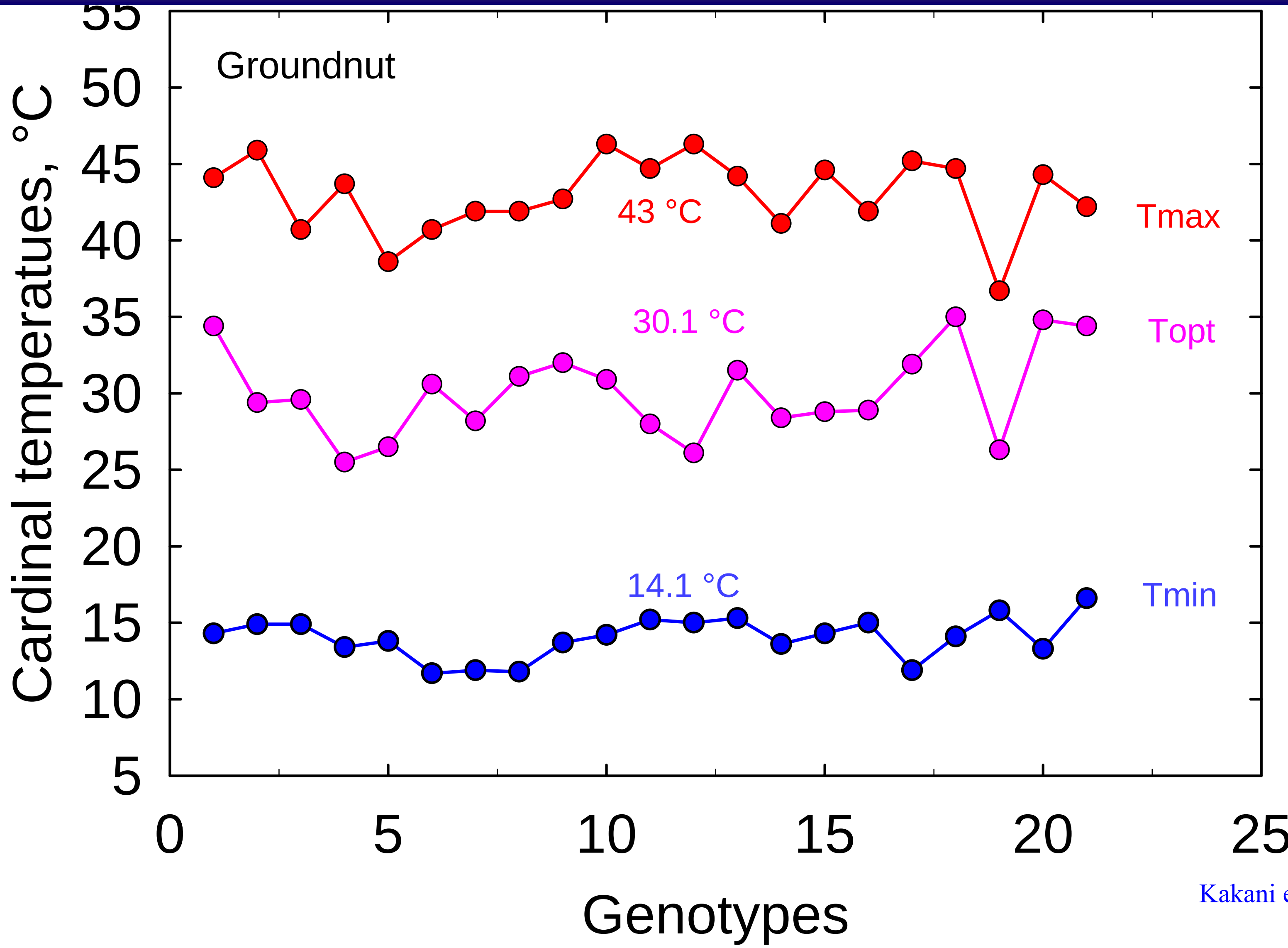


Salem et al., 2006

Traits and Abiotic Stress Tolerance

Reproductive parameters – Pollen Germination

Genotypic Variability



Kakani et al. 2002

Traits and Abiotic Stress Tolerance
Concluding Remarks

- 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.

Traits and Abiotic Stress Tolerance
Concluding Remarks

- 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.