Crop Responses to Elevated CO_2 and Interactions with H_2O, N, and Temperature

by

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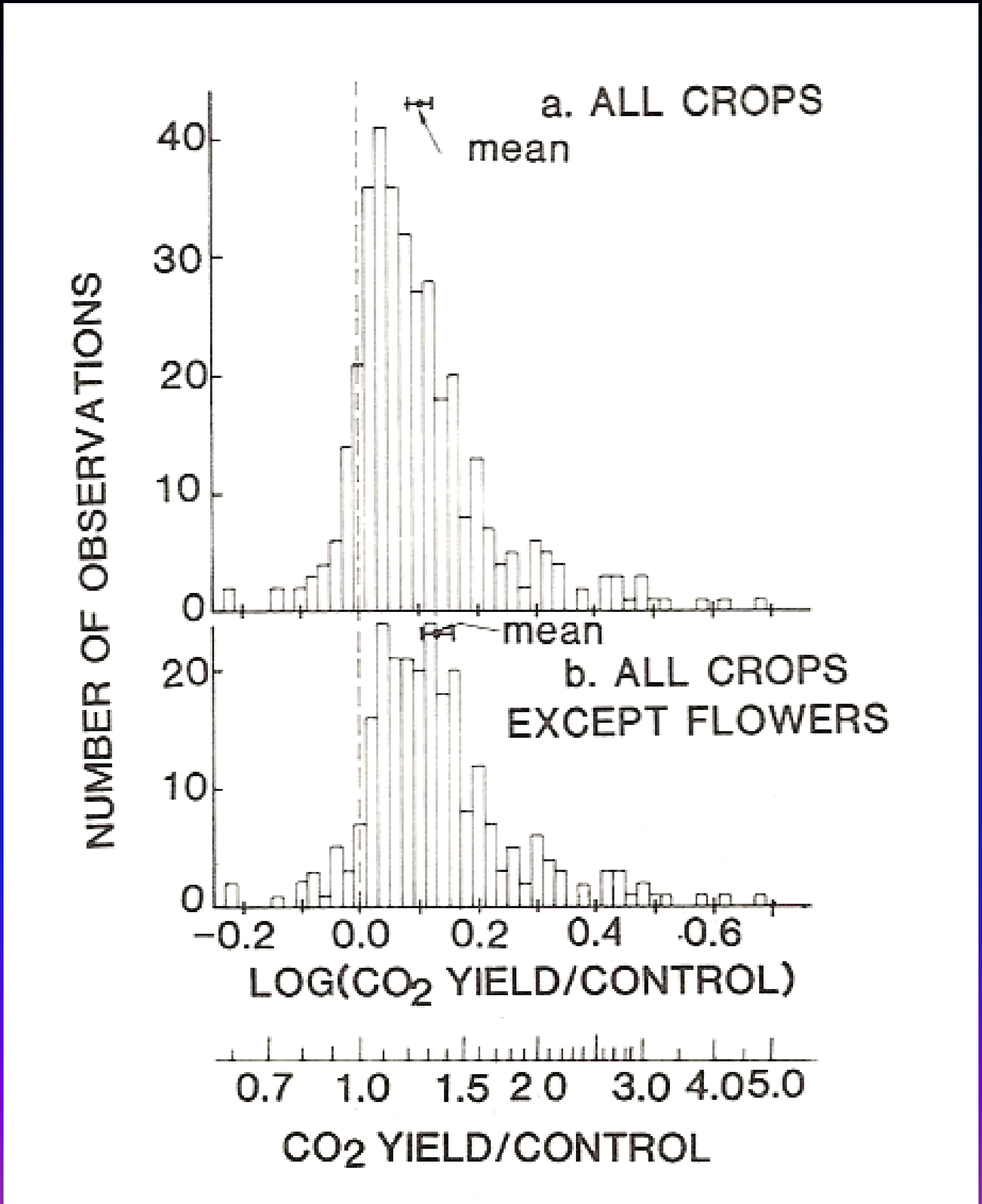
Tomatoes Grown with CO_2-Enrichment ca. 1978

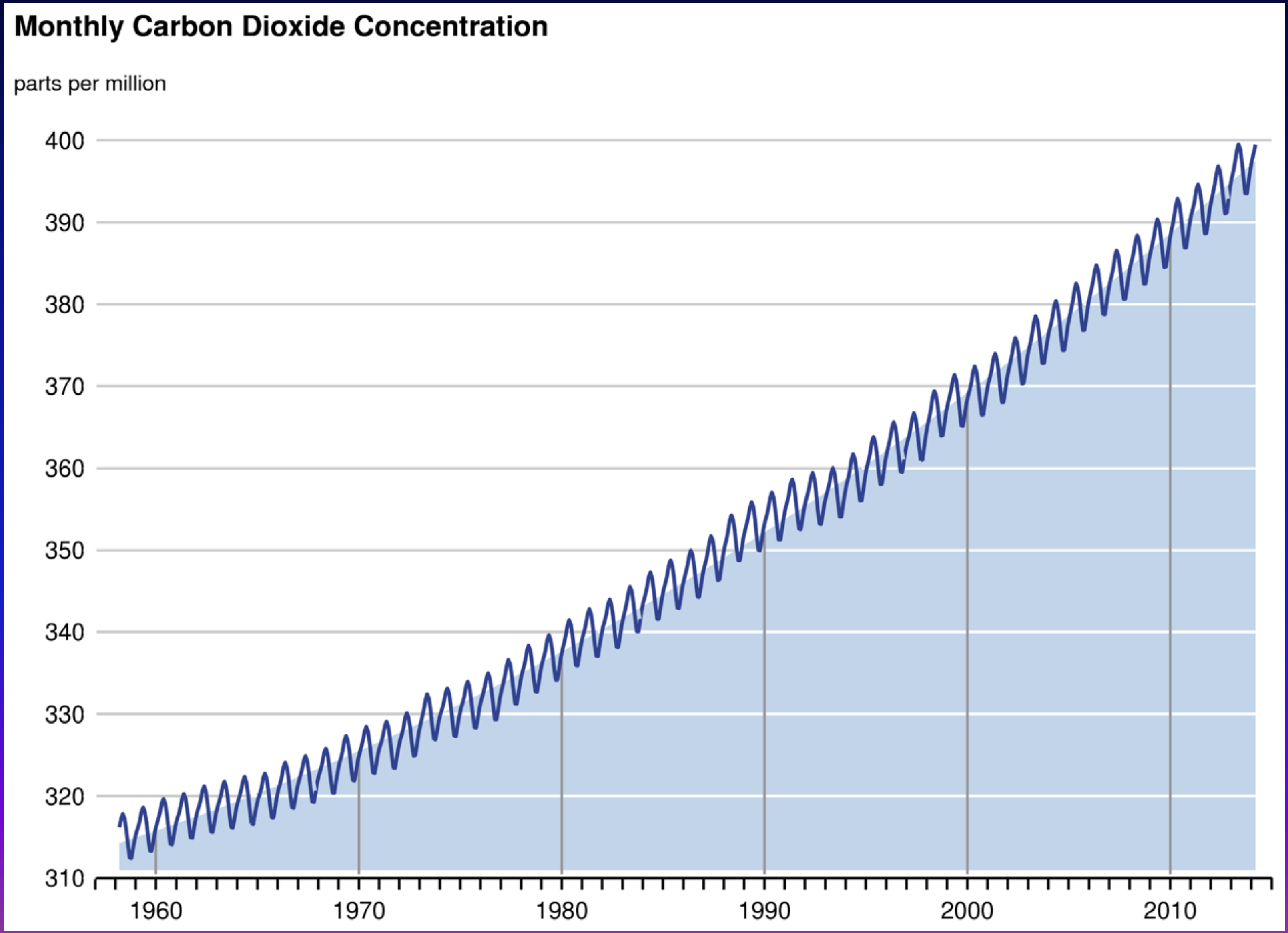
USDA Agricultural Research Service

U.S. Water Conservation Laboratory Phoenix, Arizona

Kimball (1983) was the first assemblage and analysis of prior observations of effects of CO_2-enrichment on yield. Mean yield increase was 33%.



Mauna Loa Data (Keeling) from Scripps CO_2 Program



Roger Gifford from CSIRO Started Studying Effects of Elevated CO_2 on Wheat in the 1970s Using Open-Top Chambers

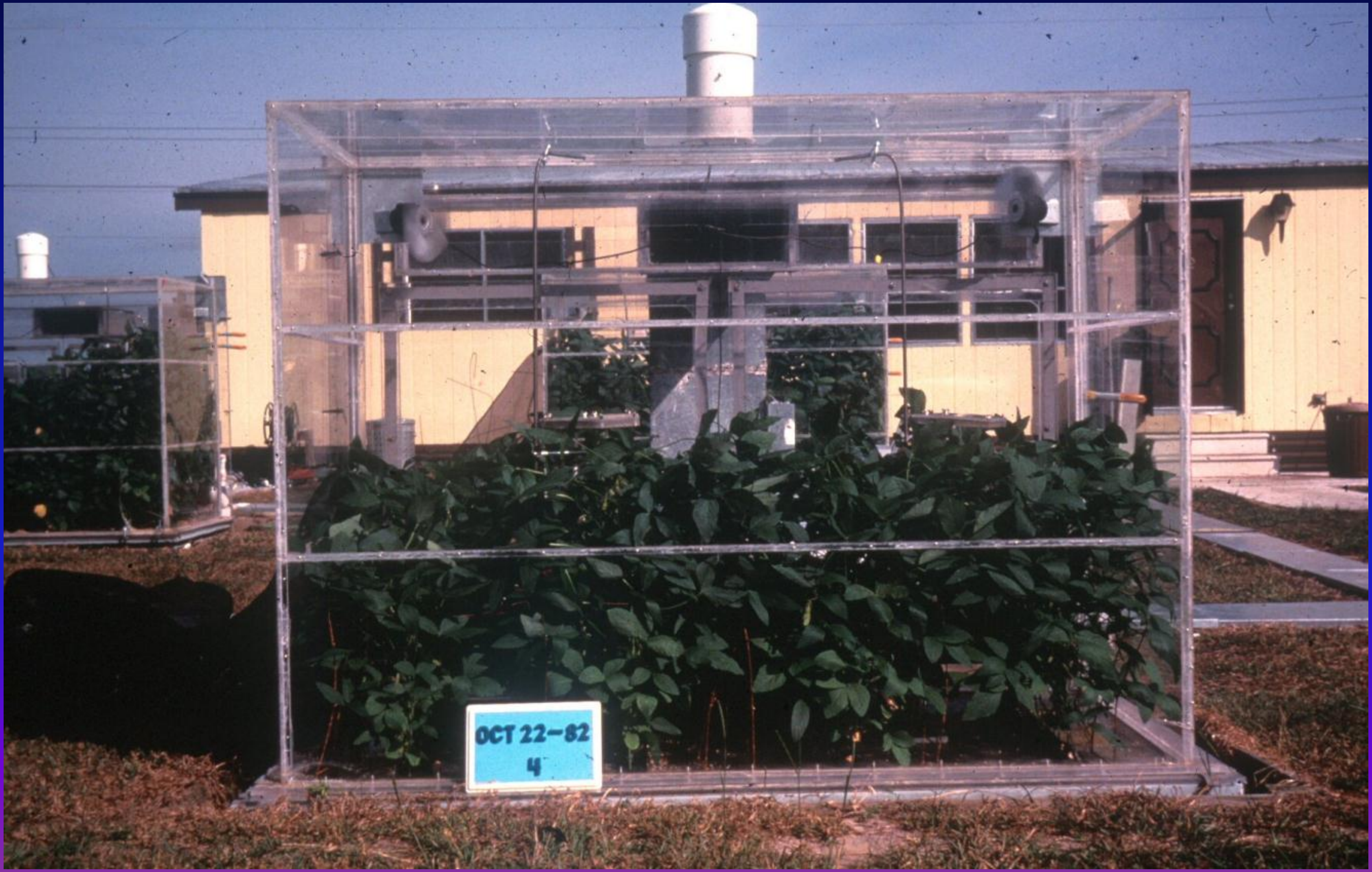
- Gifford, R.M. 1977. Growth pattern, carbon dioxide exchange and dry weight distribution in wheat growing under differing photosynthetic environments. Aust. J. Plant Physiol. 4:99-110.
- Gifford, R.M. 1979. Growth and yield of CO_2-enriched wheat under water-limited conditions. Aust. J. Plant Physiol. 6:367-378.

U.S. Dept. of Energy
"Responses of Vegetation to Carbon Dioxide"

- Starting in about 1980, Funding of open-top and controlled-environment chamber experiments in Raleigh (Rogers), Gainsville (Allen), Starkville (Baker), Phoenix (Kimball), and others
- Rising Atmospheric Carbon Dioxide and Plant Productivity: An International Conference," Athens, GA, 23-28 May 1982

Raleigh, NC; Rogers et al., 1982

Gainesville, FL; Allen et al., 1982



Starkville, MS;Baker et al., 1986

Open-Top CO_2-Enrichment Chambers (Cotton; Phoenix, Arizona; 1983-1987)

Differences Between the Environments inside Open-top Chambers and Outside

- Solar radiation reduced 0.7 to 1.0 of outside depending on sun angle and construction (especially presence of frustum or roof)
- Thermal radiation regime changed, higher especially at night
- Air movement drastically altered – typically much less in daytime and higher at night
- Inside air and foliage temperatures typically increased 0.5 to 2.5 ^{o}C
- Inside humidities increased and transpiration inside reduced 0.7-0.9 of that outside

Reasons to Prefer Free-Air CO_2 Enrichment (FACE) Approach

- Realism for both absolute and relative responses
- Large plot size enables:
  - Many cooperators to make many complimentary measurements on the same plant material
  - Highest quality seasonal data
    - Weekly or more often destructive harvests
    - Not continually touched by human hands
    - Ideal for plant growth model validation
  - An economy of scale, such that FACE is least expensive per unit of high-CO_2-grown plant material

History of Arizona FACE Project

Cotton (C_3 woody perennial)

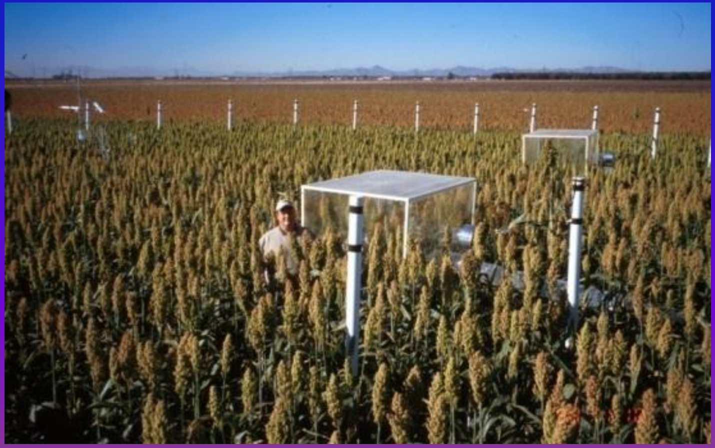
1989	FACE
1990 & 1991	FACE x H_2O

Wheat (C_3 grass)

1992-93 & 1993-94	FACE x H_2O
1995-96 & 1996-97	FACE x N

Sorghum (C_4 grass)

1998 & 1999	FACE x H_2O



History of Swiss FACE Project

- FACE x N x species x cutting frequency
- Species
  - ryegrass (C_3 grass)
  - white clover (C_3 legume)
  - (mixture)

- 1993-2002

History of Italian FACE Projects

- Grape (C_3 woody perennial)
  - 1994, 5, 6, 7

- Potato (C_3 forb with tuber storage)
  - 1995
  - CHIP
    - 1998
    - 1999

History of Japanese FACE Project

- Rice (C_3 grass)
  - 1998-2000; 2007-2008, 2010)
  - FACE x N; varieties

History of SoyFACE Project

- Soybean
  - 2001 CO_2
  - 2002 CO_2, O_3
  - 2003-2007 CO_2, O_3, CO_2+O_3
  - 2008 CO_2, O_3, CO_2+O_3, H_2O
  - 2009-2013 CO_2, O_3, CO_2+O_3, H_2O, Infrared Warming
- Corn
  - 2002 CO_2
  - 2004 CO_2
  - 2006 CO_2
  - 2008 CO_2
  - 2010 CO_2, Warming
  - 2012 CO_2, Warming

History of Braunschweig, Germany FACE Project

Oct 1999 – Jun 2000 Barley
Aug 2000 – Oct 2000 Grass
Apr 2000 – Sep 2000 Sugar Beet
Oct 2001 – Jul 2002 Wheat
Sep 2002 – Jun 2003 Barley
Aug 2003 – Oct 2003 Grass
Apr 2004 – Sep 2004 Sugar Beet
Oct 2004 – Jul 2005 Wheat
May 2007 – Oct 2007 Corn
May 2008 – Oct 2008 Corn

History of Chinese FACE Project

- Rice (C_3 grass)
  - 2001, 2002, 2003, 2004; FACE x N
  - 2004, 2005, 2006; FACE x hybrid varieties x N
- Wheat
    - 2001-92; FACE x N

History of AGFACE (Australian Grains) Project

2007-2009 Wheat, CO_2 x sowing date

2007-2008 Wheat, CO_2 x H_2O x N

2009 Wheat, 8 varieties

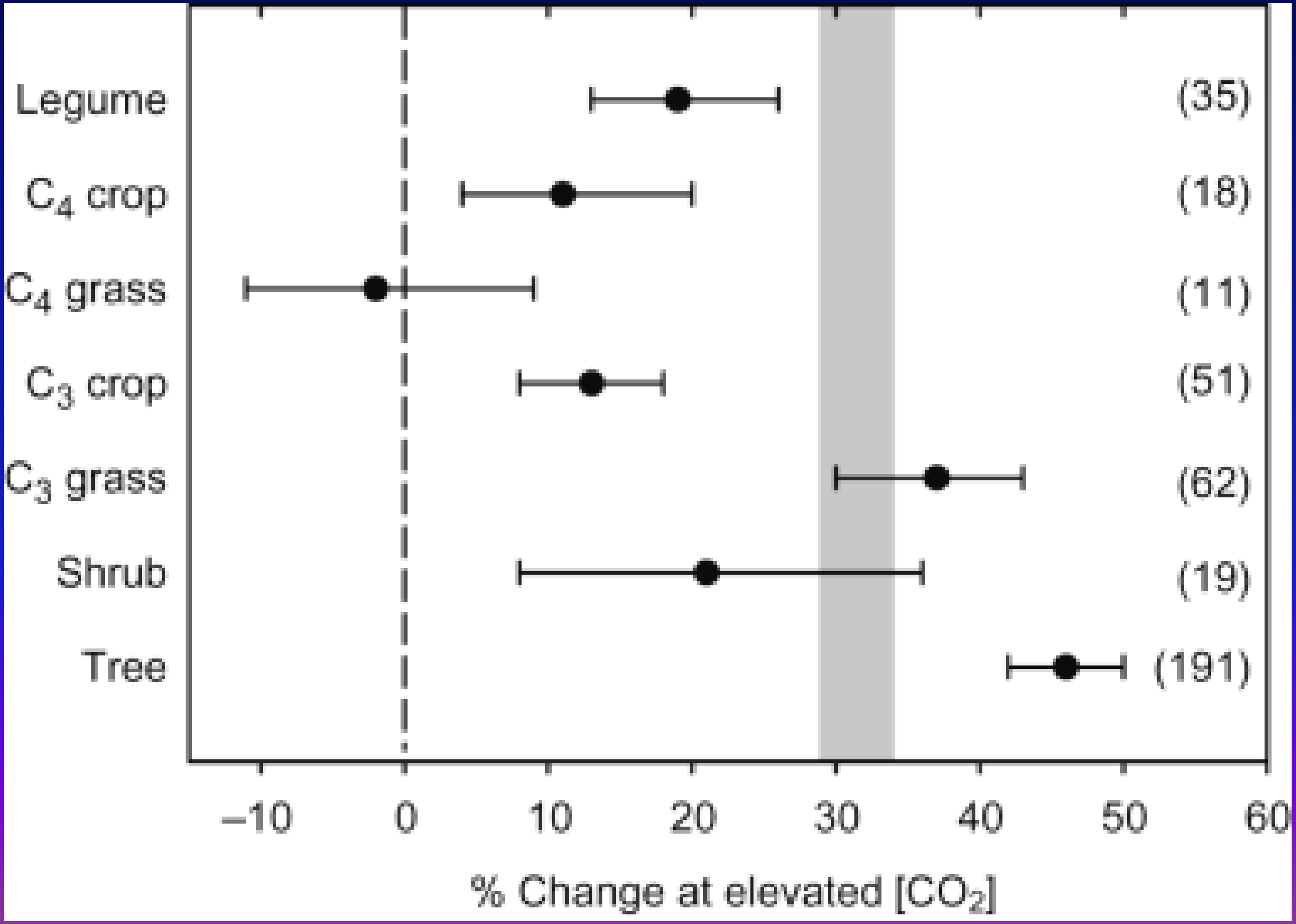
2010 Wheat & field pea rotation with 6 varieties of each

Effects of:

CO_2 Alone

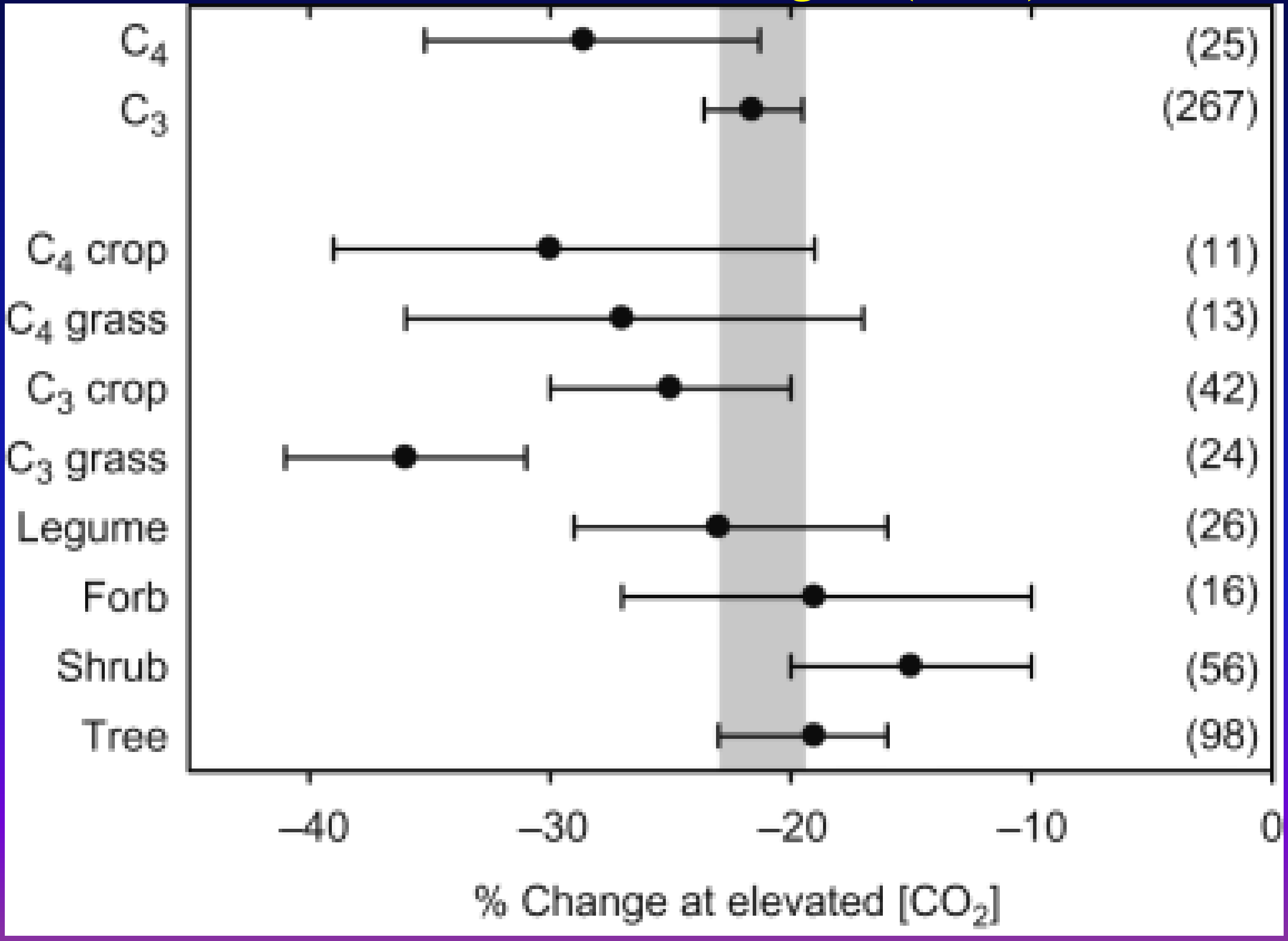
Light-Saturated Net Photosynthesis Response to Elevated CO_2 for Various Plant Classifications

[+200 ppm via FACE; from Ainsworth and Rogers (2007)]

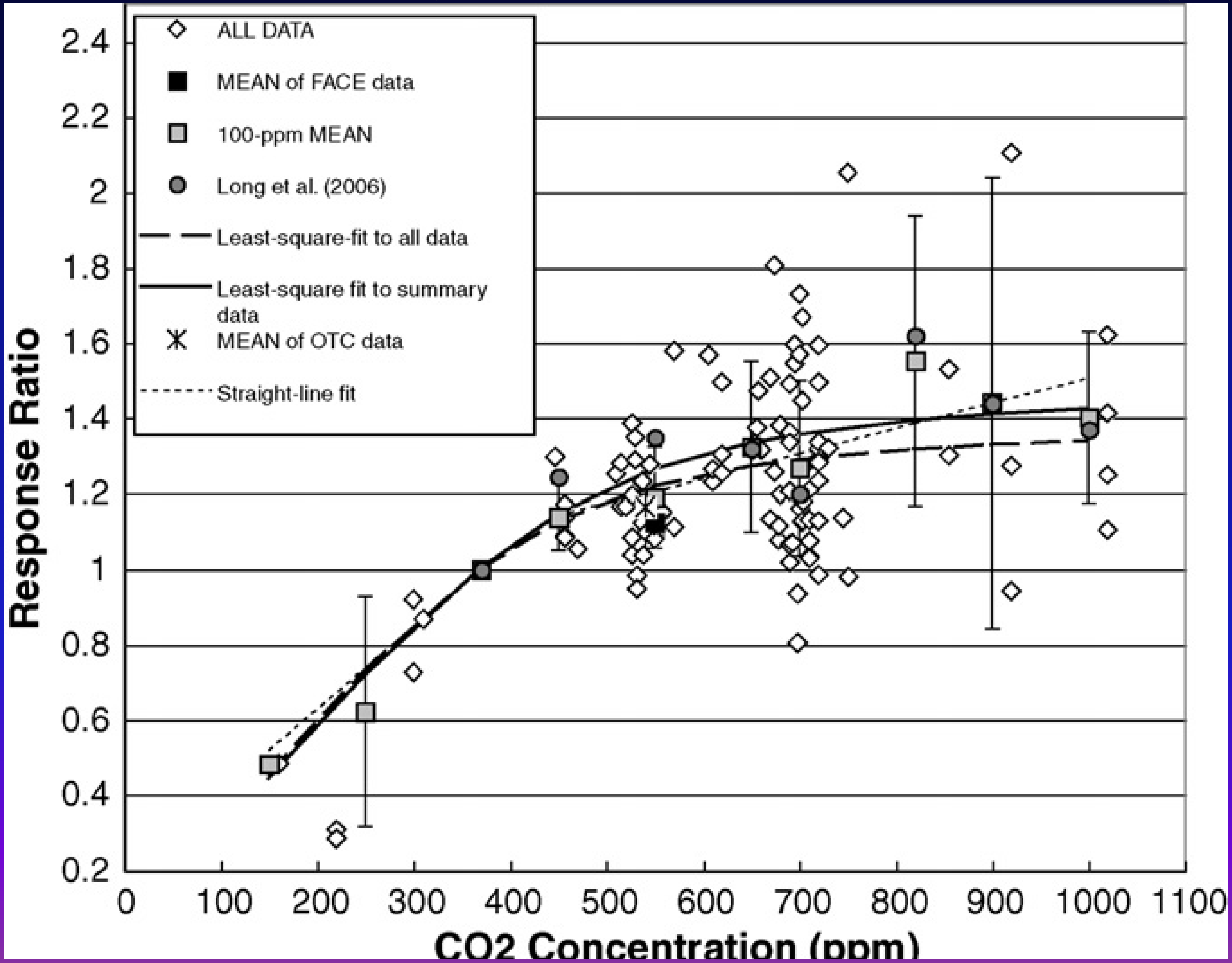


Stomatal Conductance Response to Elevated CO_2 for Various Plant Classifications (+200 ppm via FACE)

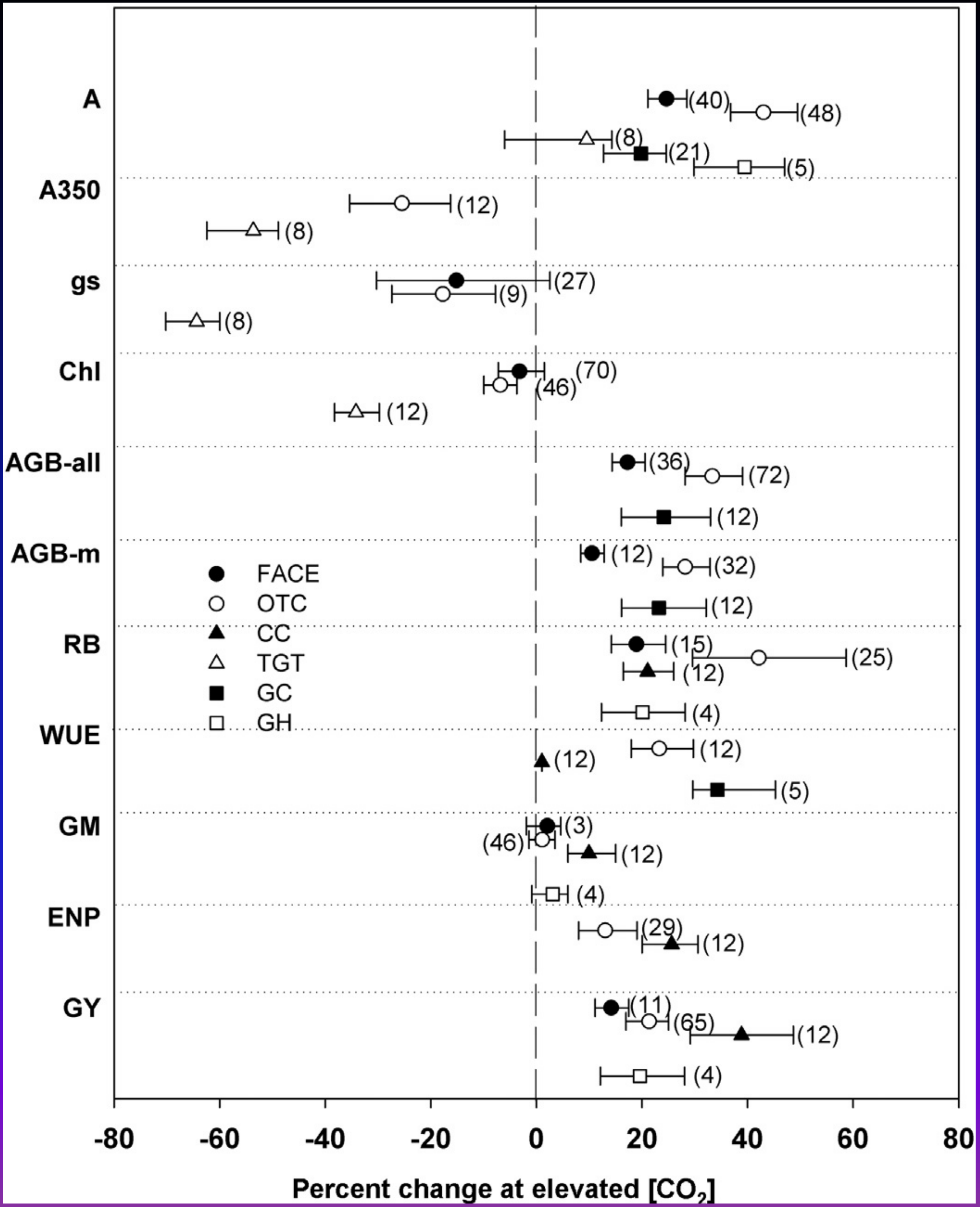
[from Ainsworth and Rogers (2007)]



Yield Response Ratios of Wheat vs. CO_2 Concentration (from Tubiello *et al.*, 2007)



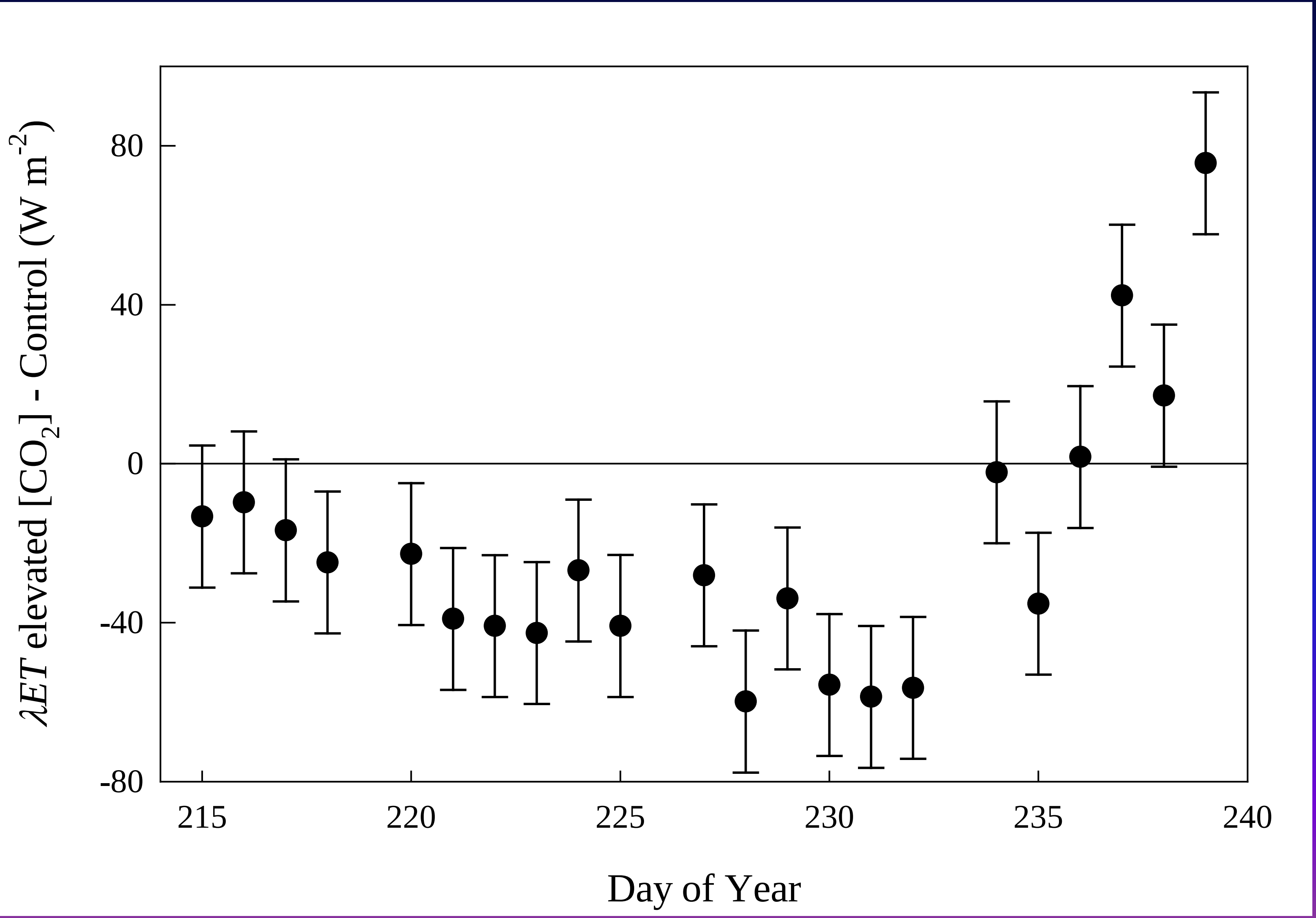
Wheat Responses to Elevated CO_2 Sorted by Exposure Method (from Wang et al., 2013)



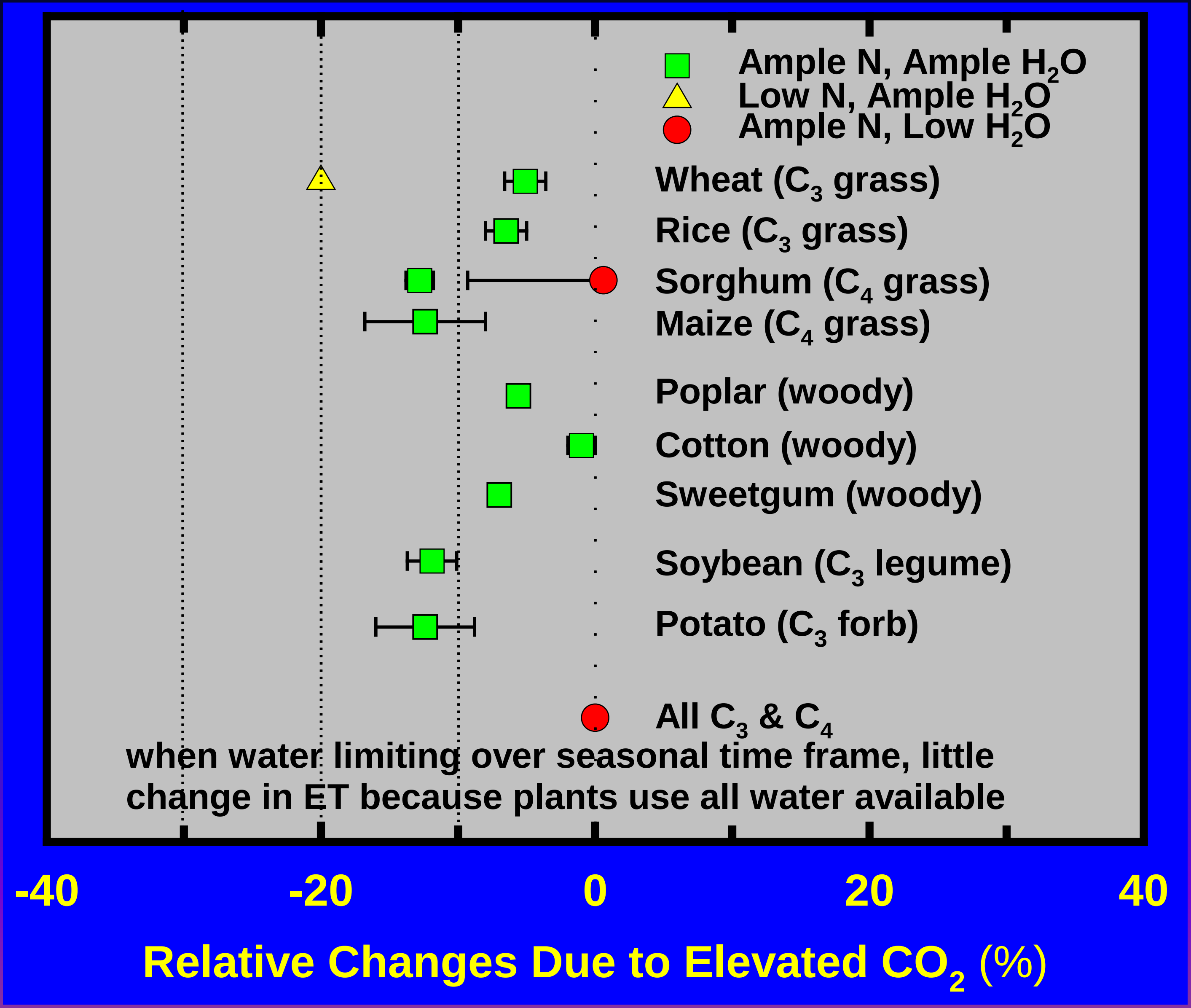
Effects of:

CO_2 and Water (Drought)

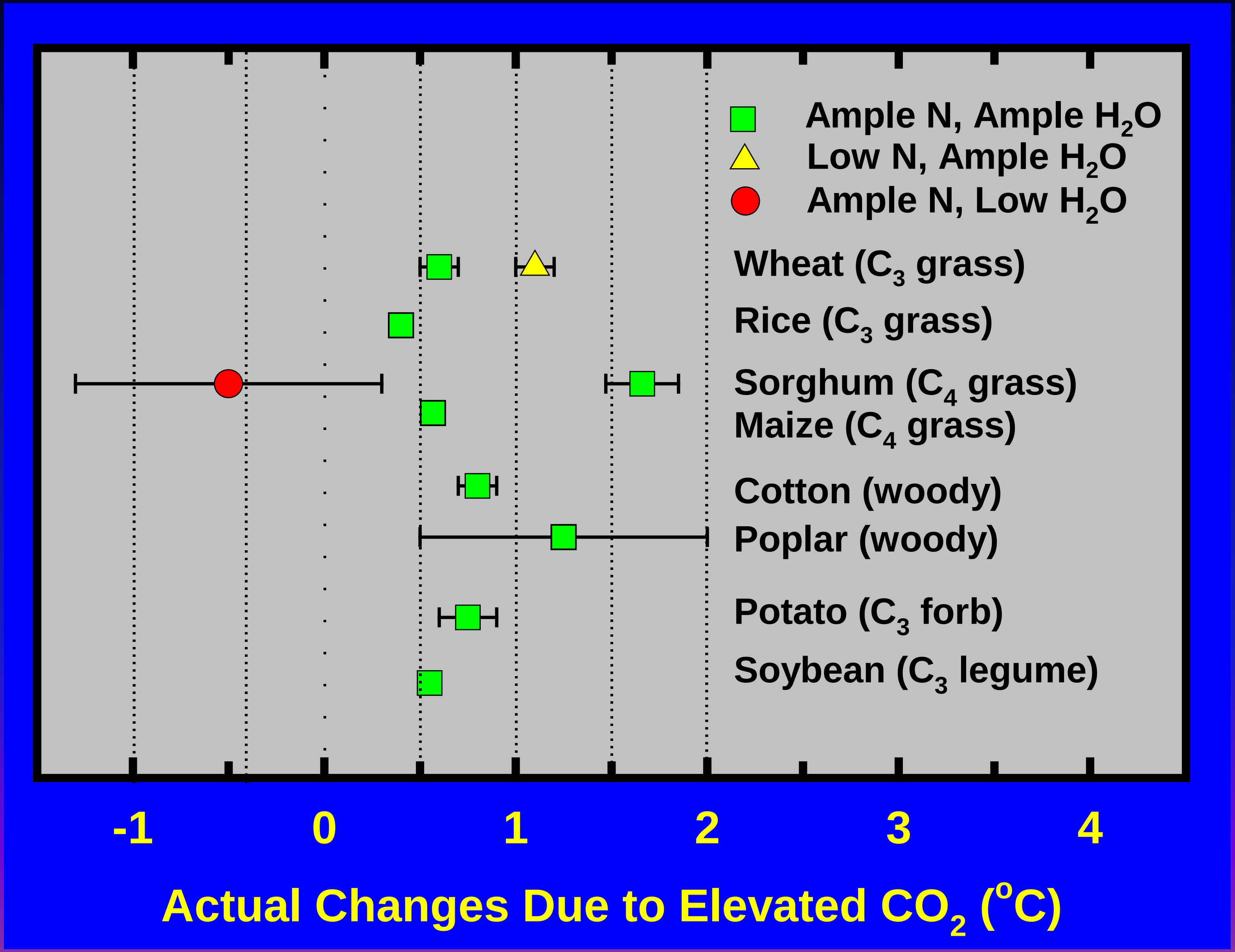
Difference in λET of Soybean at Elevated and Ambient Through a Drying Cycle in SoyFACE [(from Bernacchi *et al.* (2007)]



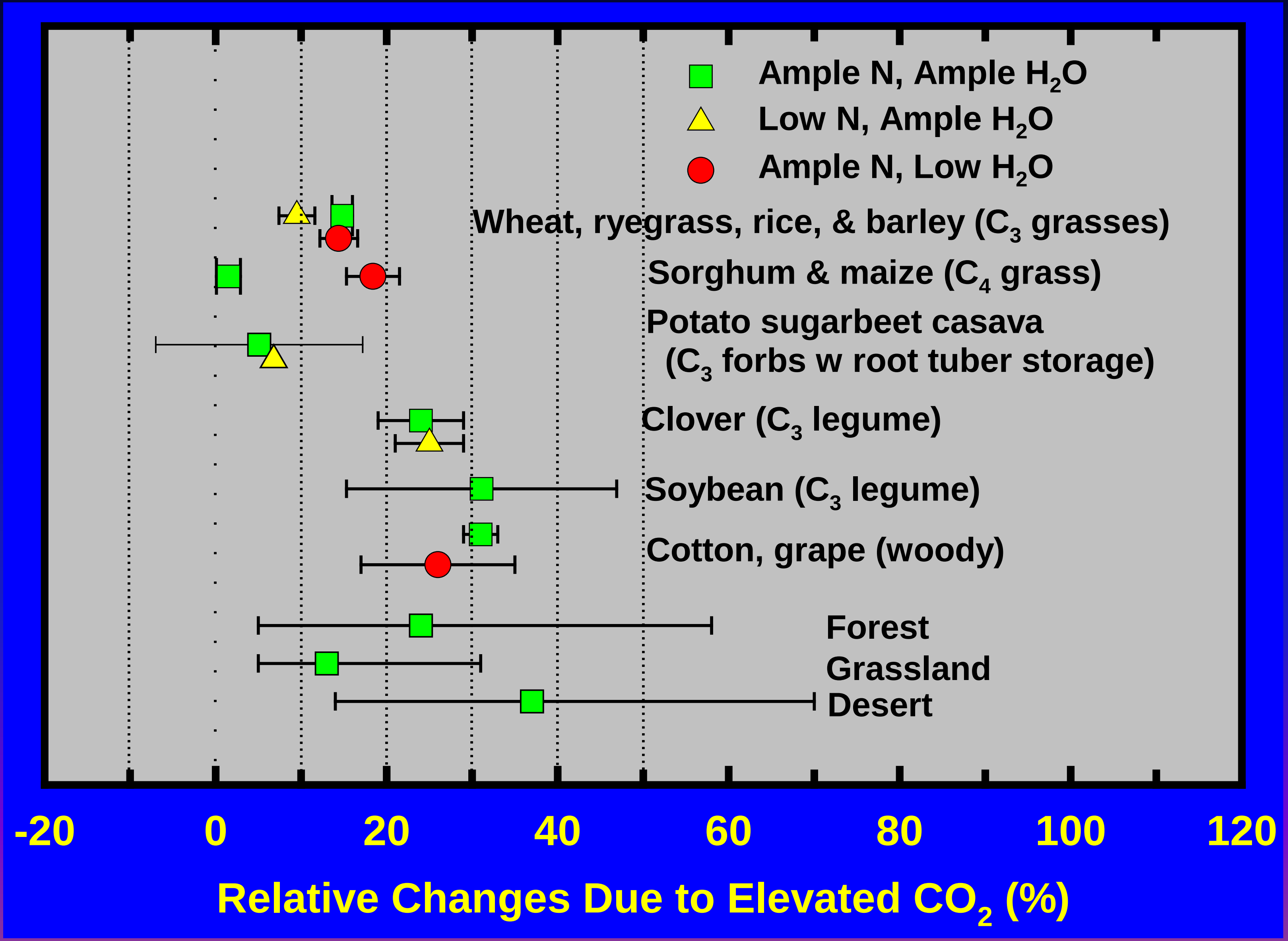
Evapotranspiration (updated from Kimball, 2011)



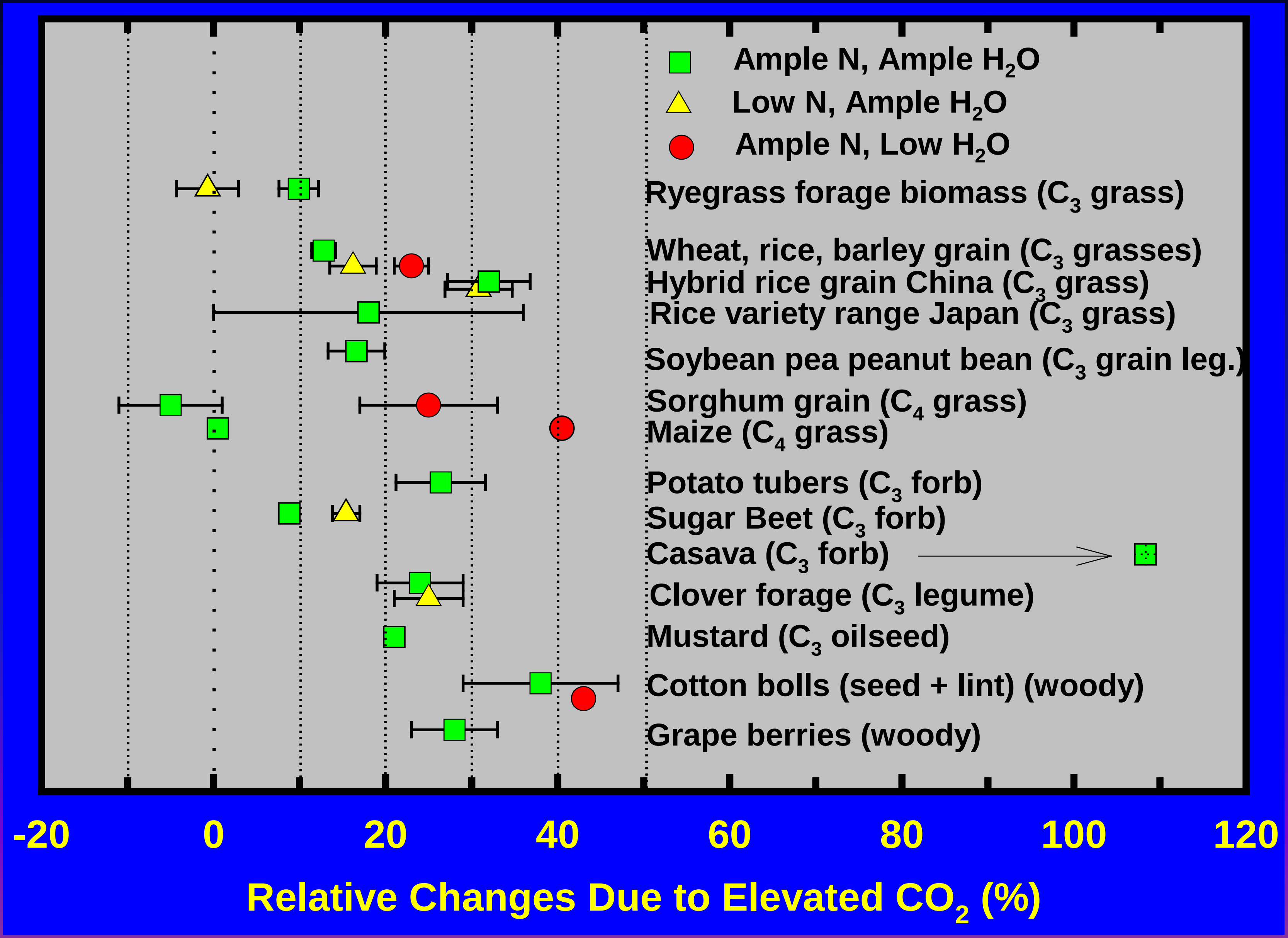
Canopy Temperature (updated from Kimball, 2011)



Above-Ground Biomass Accumulation (updated from Kimball, 2011)



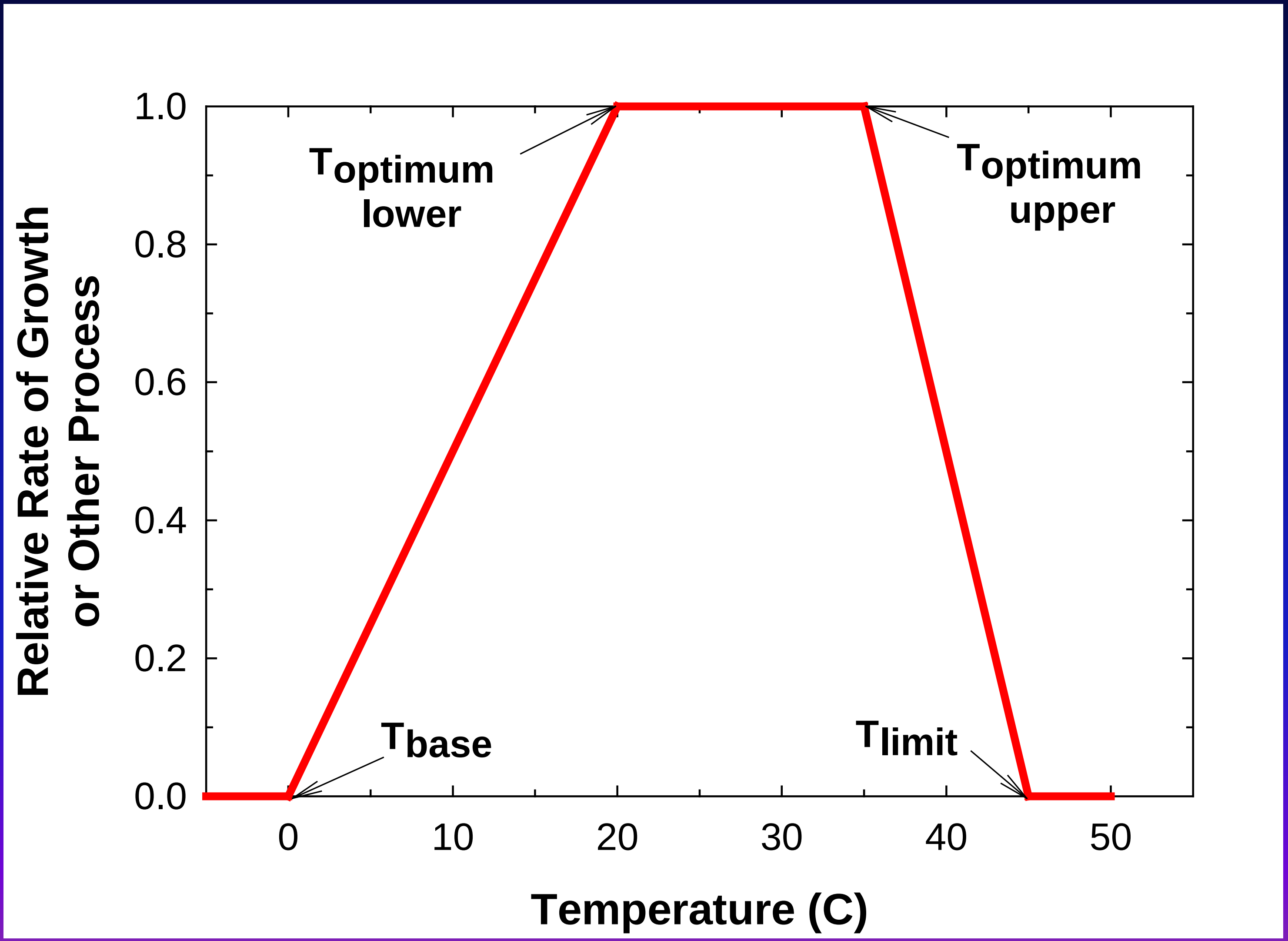
Agricultural Yields (updated from Kimball, 2011)



Effects of:

Temperature Alone

Typical Temperature Response Curve



Hexagonal 3-m-Diameter Array of Mor FTE 1000W Infrared Heaters Deployed Over Wheat at Maricopa, AZ on 24 November 2007.

Hot Serial Cereal Experiment, Maricopa, AZ; 10Mar2009

("Cereal" because it's on wheat, "Serial" because the wheat was planted serially every 6 weeks for 2 years (four of the planting dates are indicated on the photo), "Hot" because infrared heaters were deployed on some of the planting dates)

Daily Maximum & Minimum Air and Canopy Temperatures

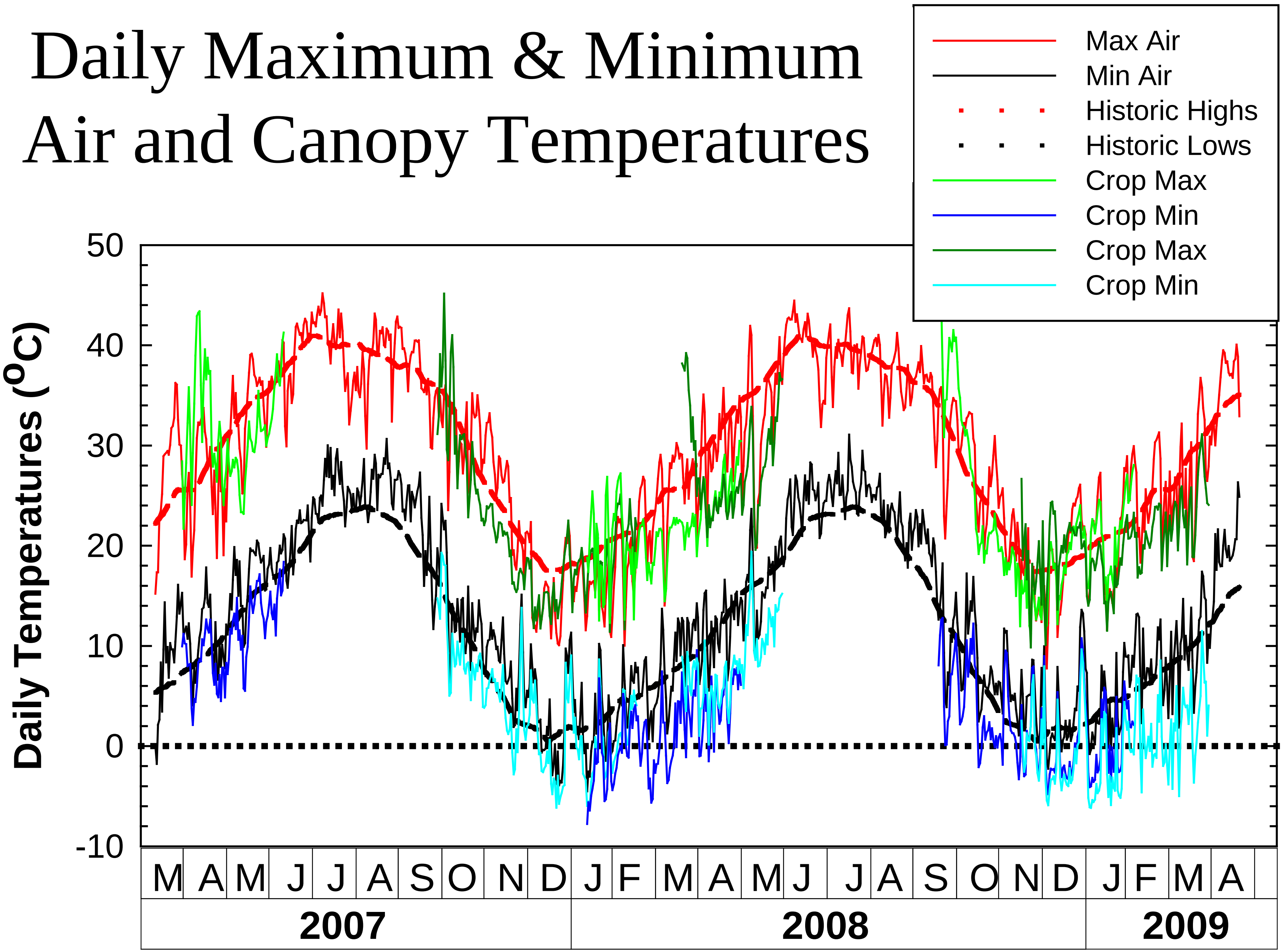
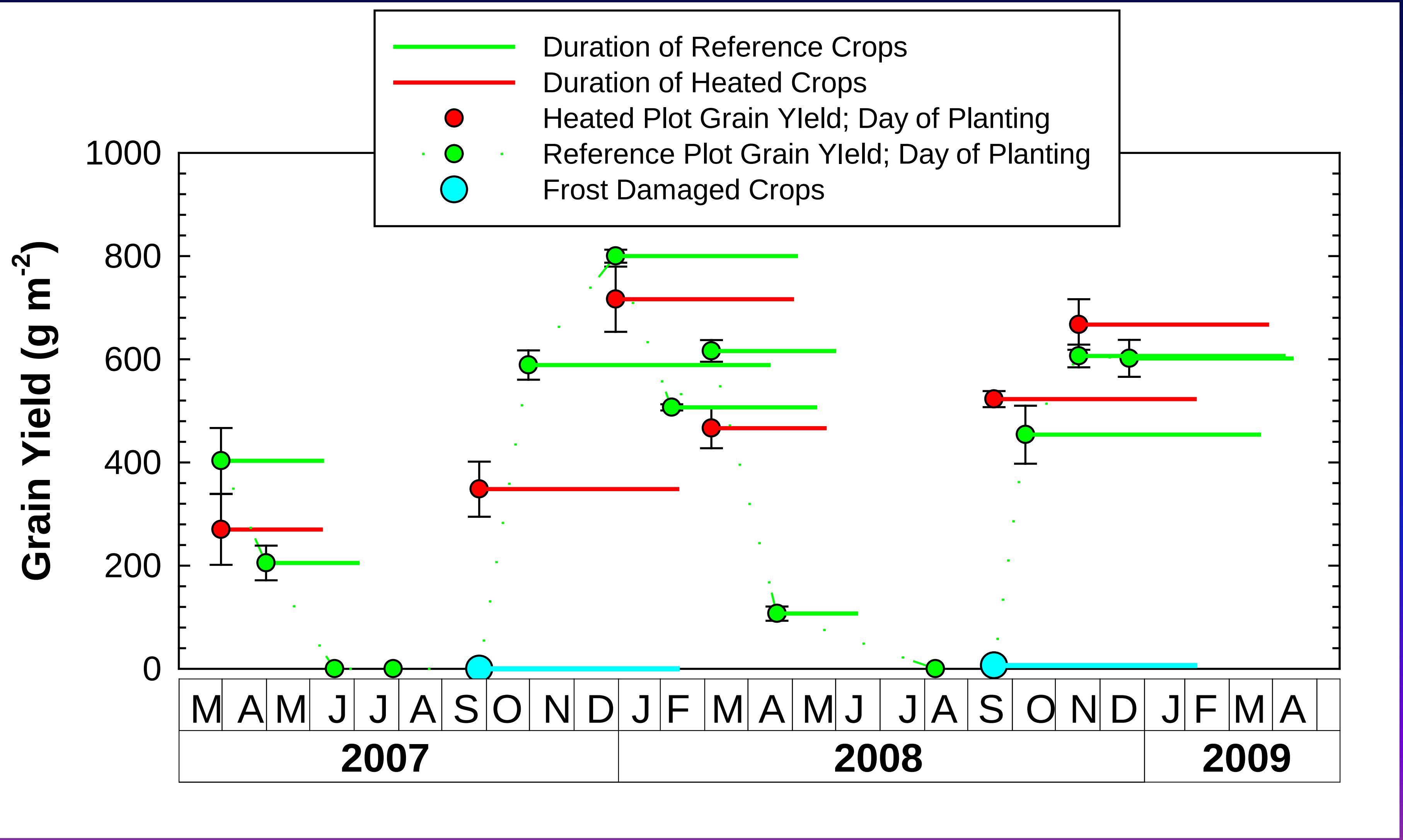
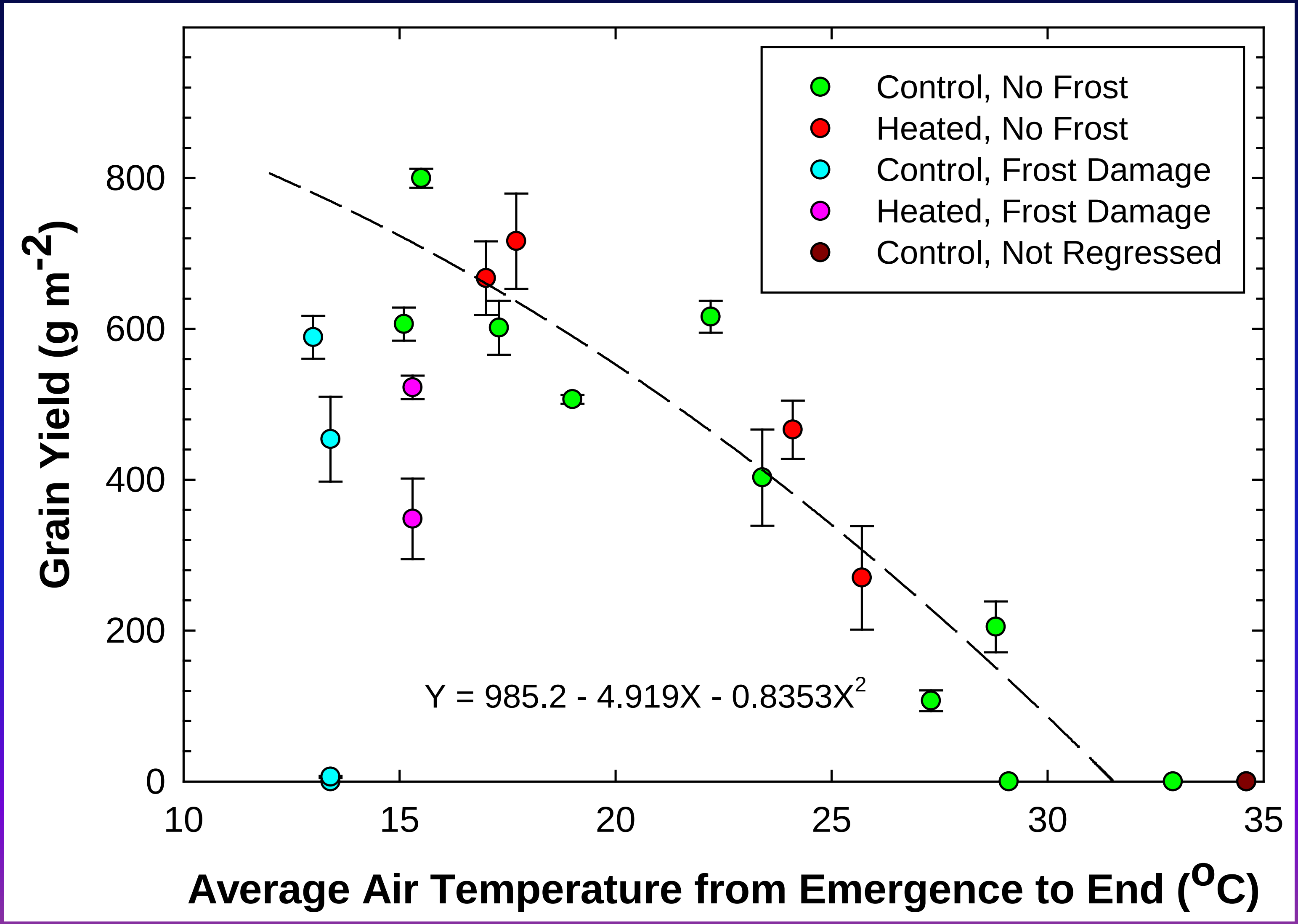


Photo taken 10 January 2008 shows heaters saved wheat plot from frost that occurred on 29 December 2007 in Hot Serial Cereal Experiment, Maricopa, Arizona

Winter-planted: highest yields – no effect of heaters
Spring-planted: yields reduced – heaters exacerbate problem
Fall-planted: frost damage! – heaters ameliorate problem
Summer-planted: crop failure



Grain Yield versus Average Air Temperature for Growing Season From Hot Serial Cereal Experiment

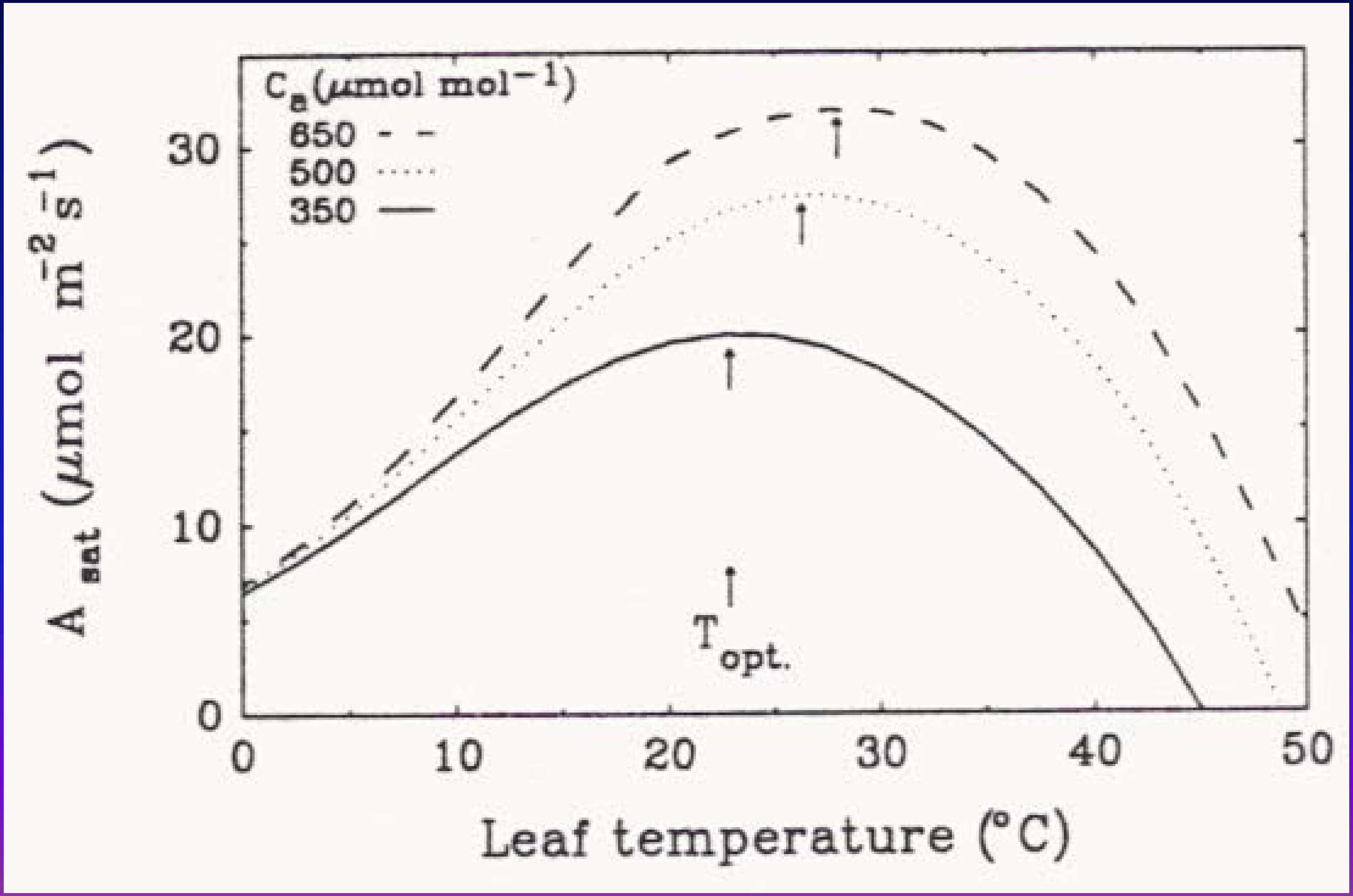


Effects of:

CO_2 & Temperature

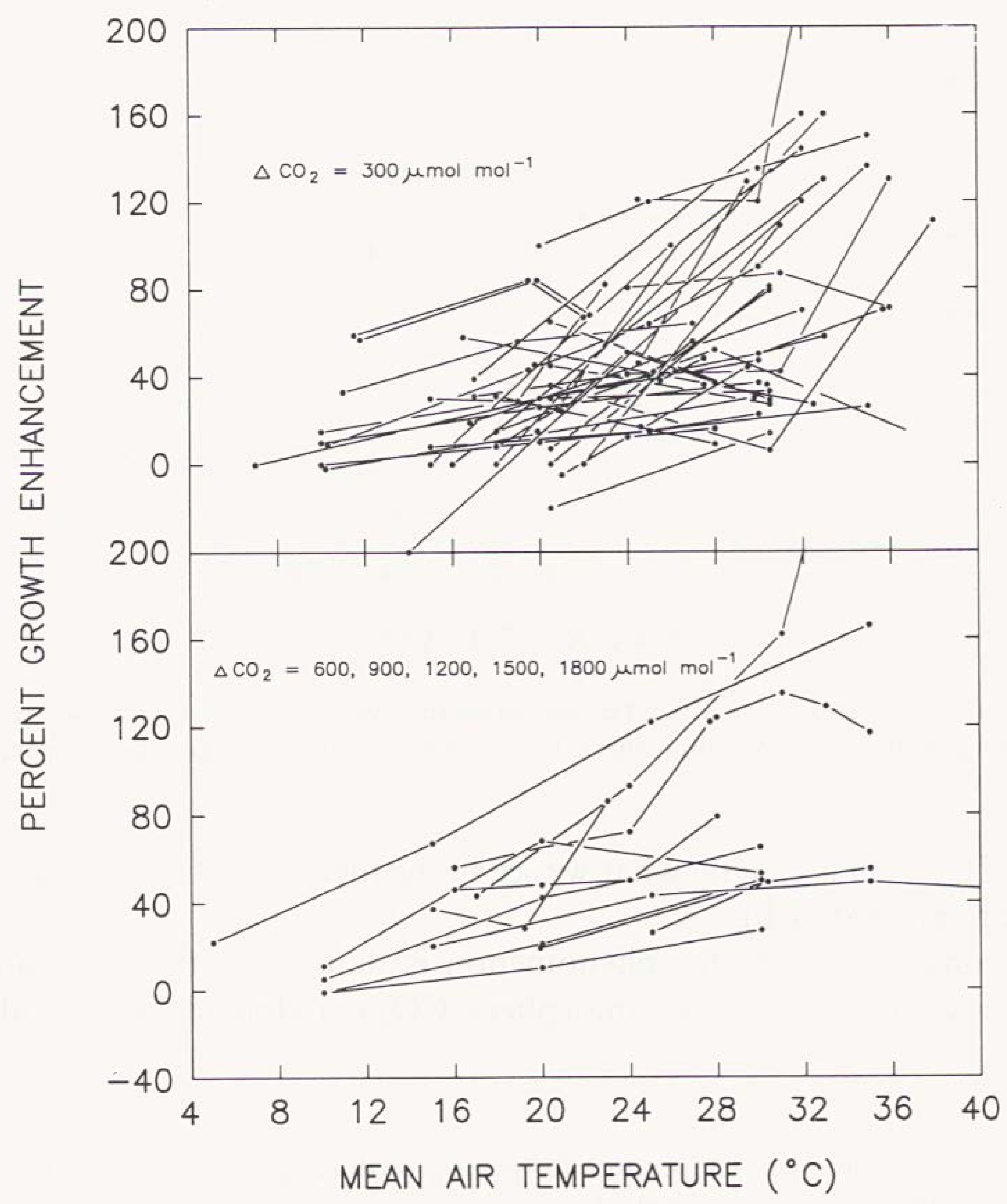
Predicted Response of Light-Saturated Net Photosynthesis to Temperature and CO_2

[from Long (1991)]



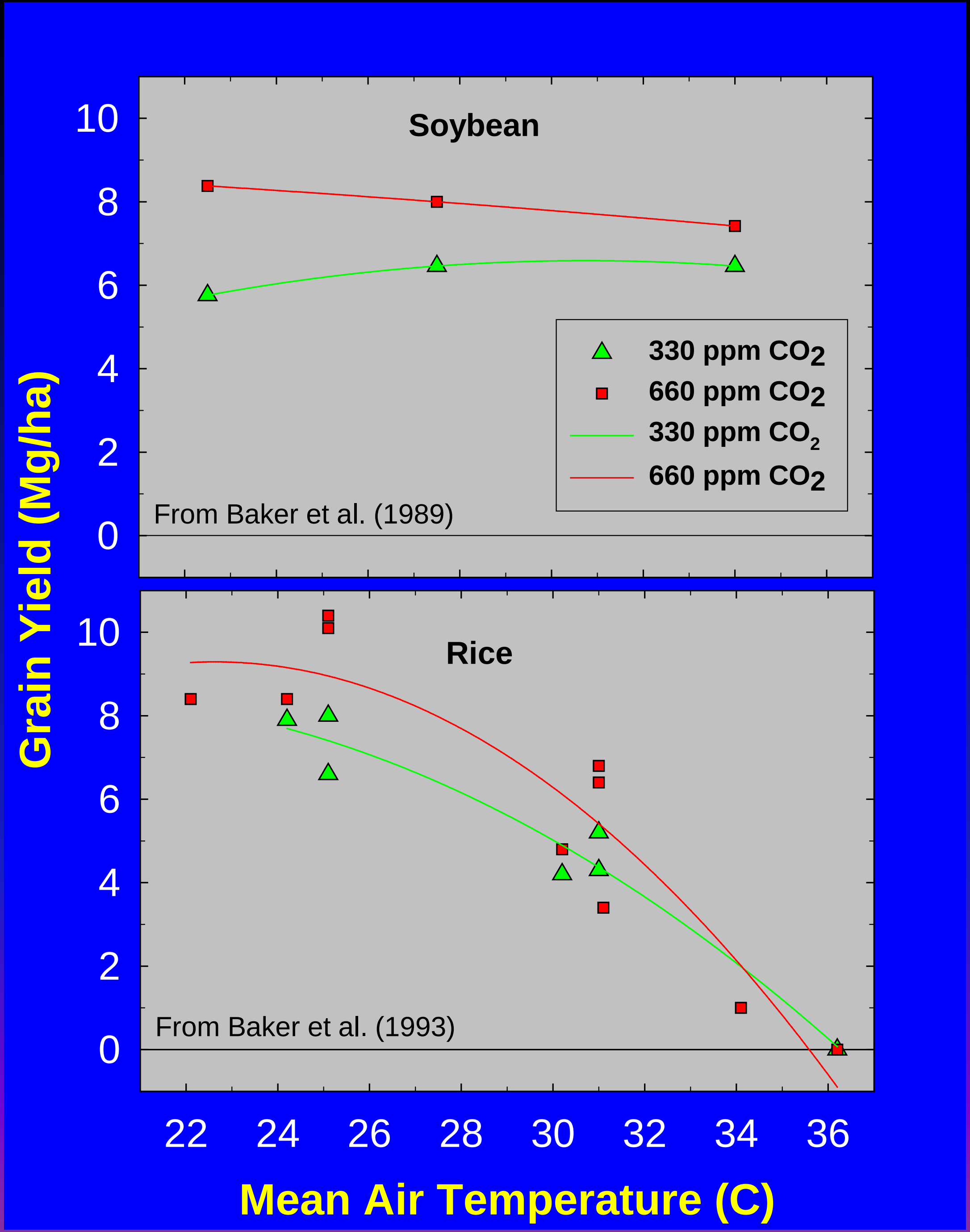
Increases in Growth and CER Due to Elevated CO_2 Versus Air Temperature

[From Idso and Idso (1994)]

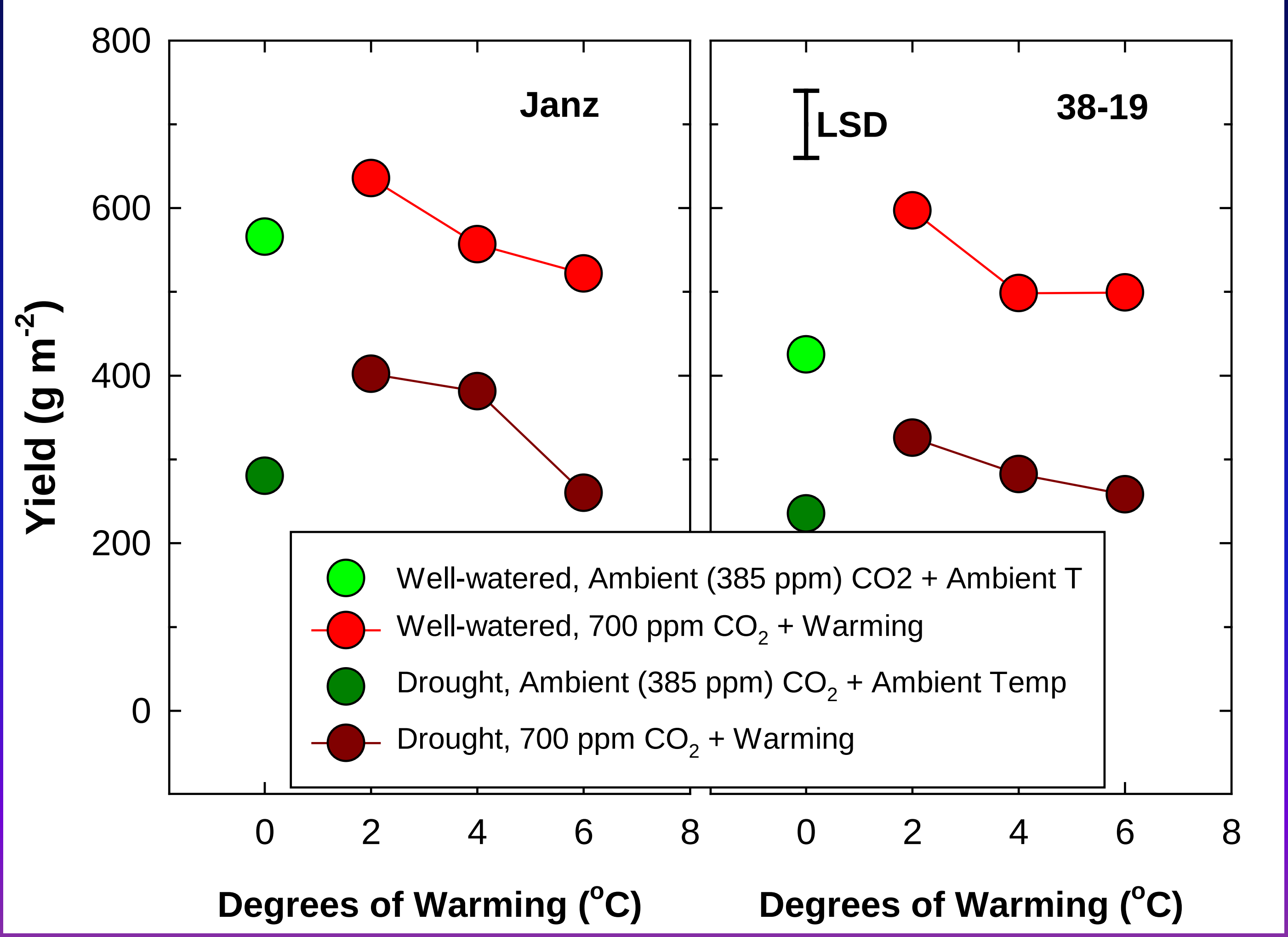


Grain Yields of Soybean and Rice at 330 and 660 ppm CO_2 versus Mean Air Temperature

[from Baker et al. (1989; 1993)]

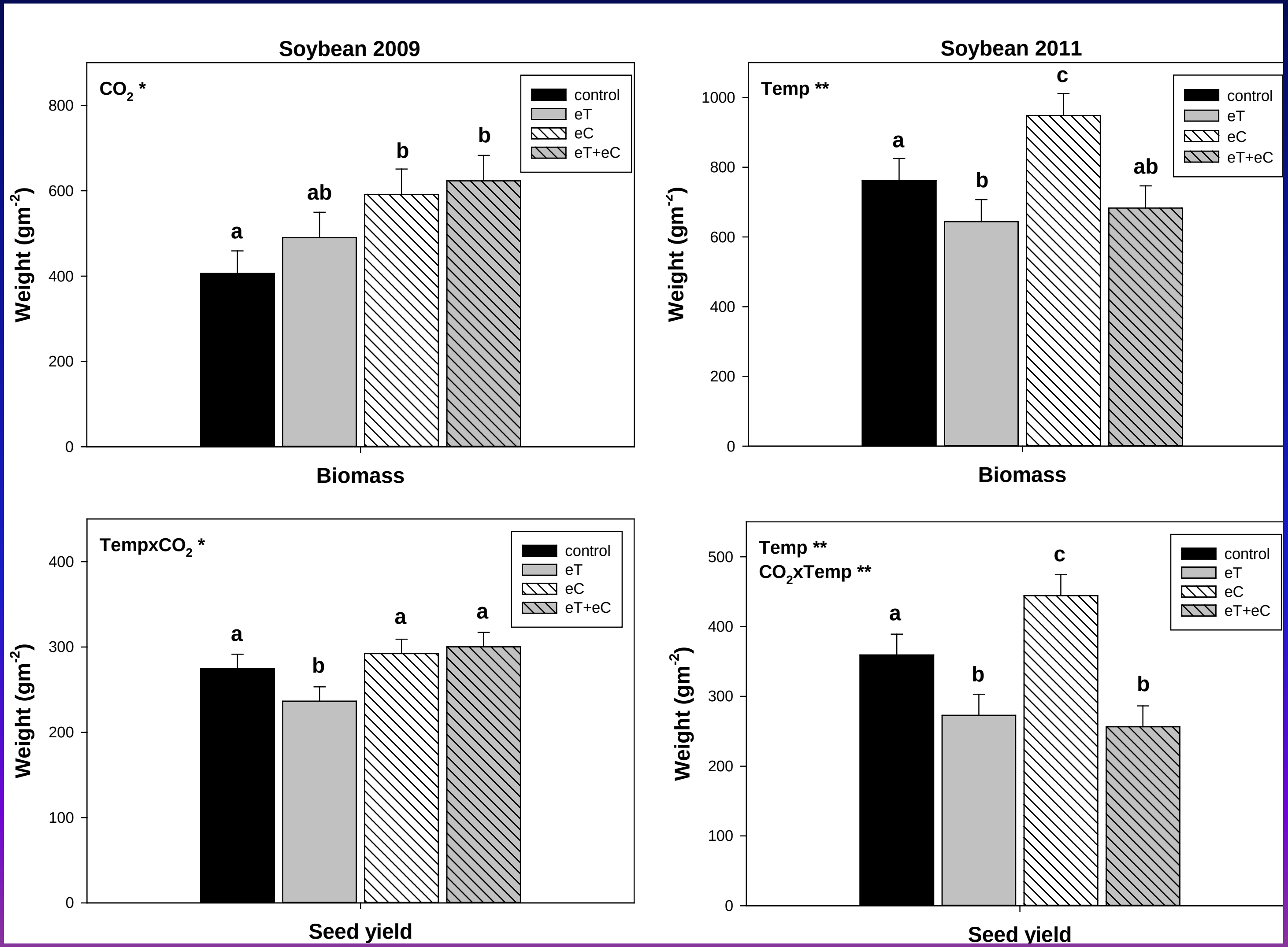


Effects of Elevated CO_2 and Warming in Tunnels on Two Varieties of Wheat (from Dias de Oliveira *et al.*, 2013)

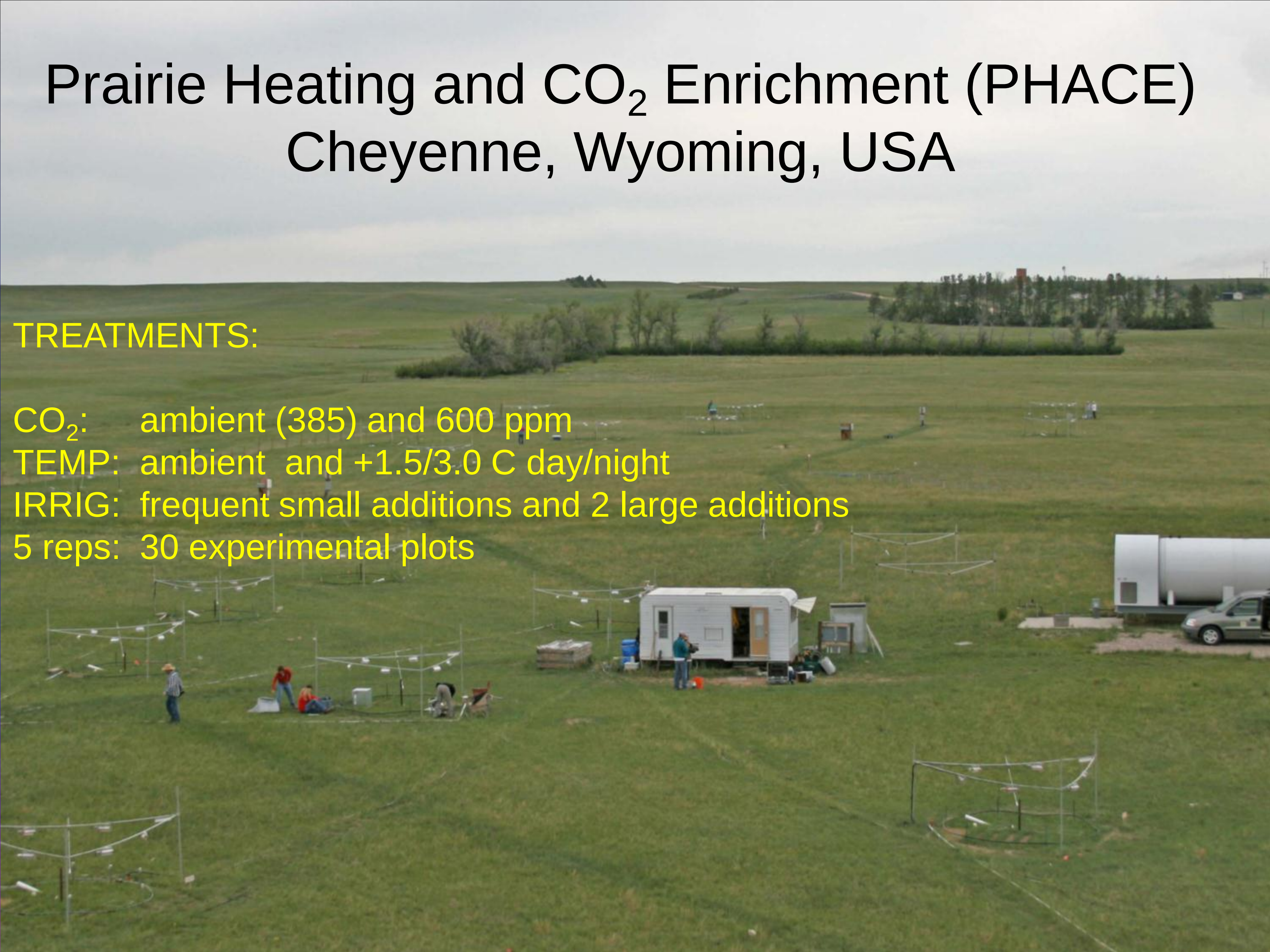


Carl Bernacchi in SoyFACE Project, Urbana, IL with 3-m Array of Four-Element Mor Heaters and Dummy Array in Back; 20 August 2009

Soybean Biomass, Grain Yield, and Harvest Index from SoyFACE in 2008 and 2011 for Control, +3.5°C, 550 ppm CO_2, and +T+CO_2 (from Ruiz-Vera et al., 2013)

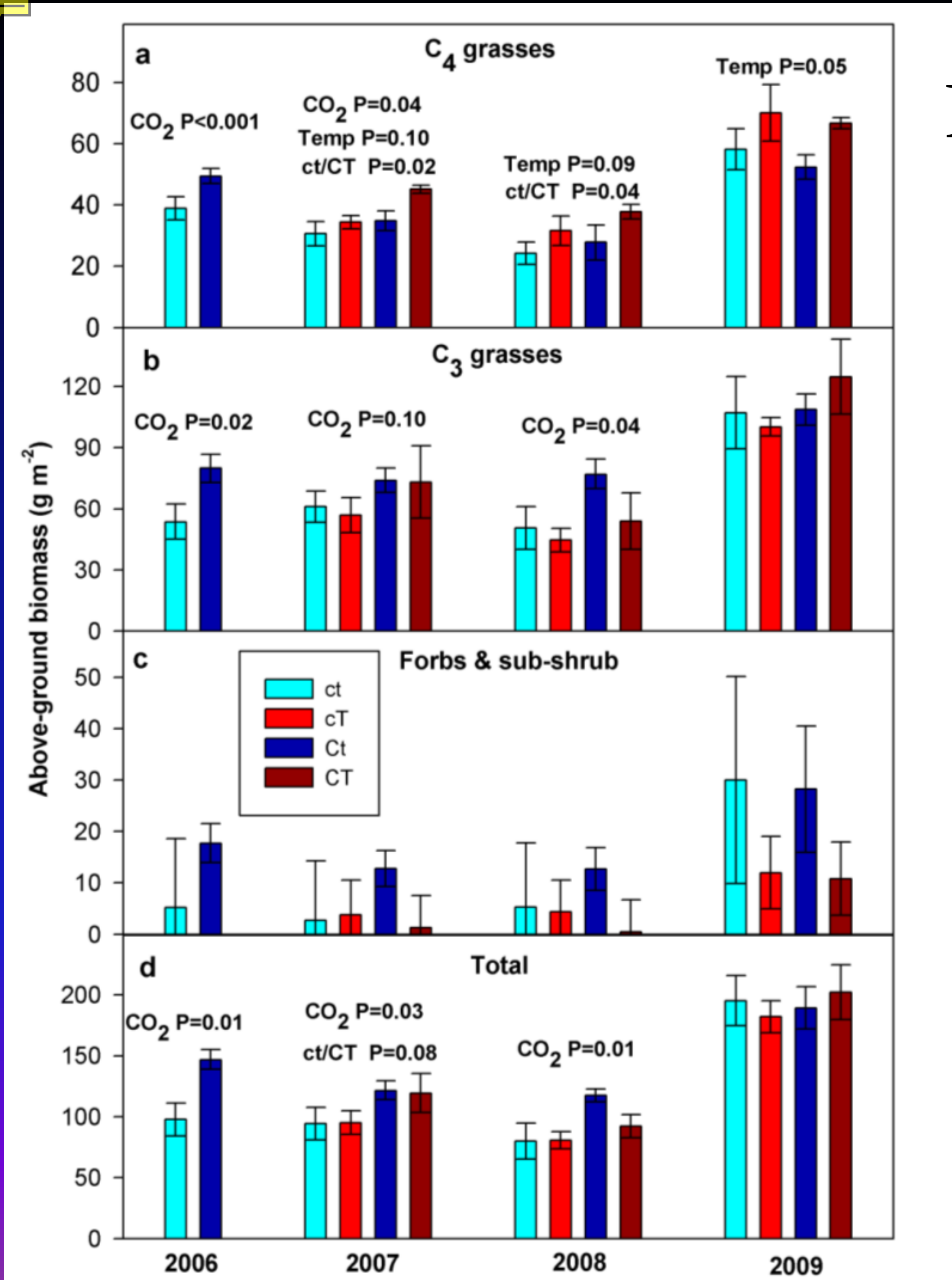


Prairie Heating and CO_2 Enrichment (PHACE)
Cheyenne, Wyoming, USA



TREATMENTS:

CO_2: ambient (385) and 600 ppm
TEMP: ambient and +1.5/3.0 C day/night
IRRIG: frequent small additions and 2 large additions
5 reps: 30 experimental plots



Plant Biomass Results

RESULTS:

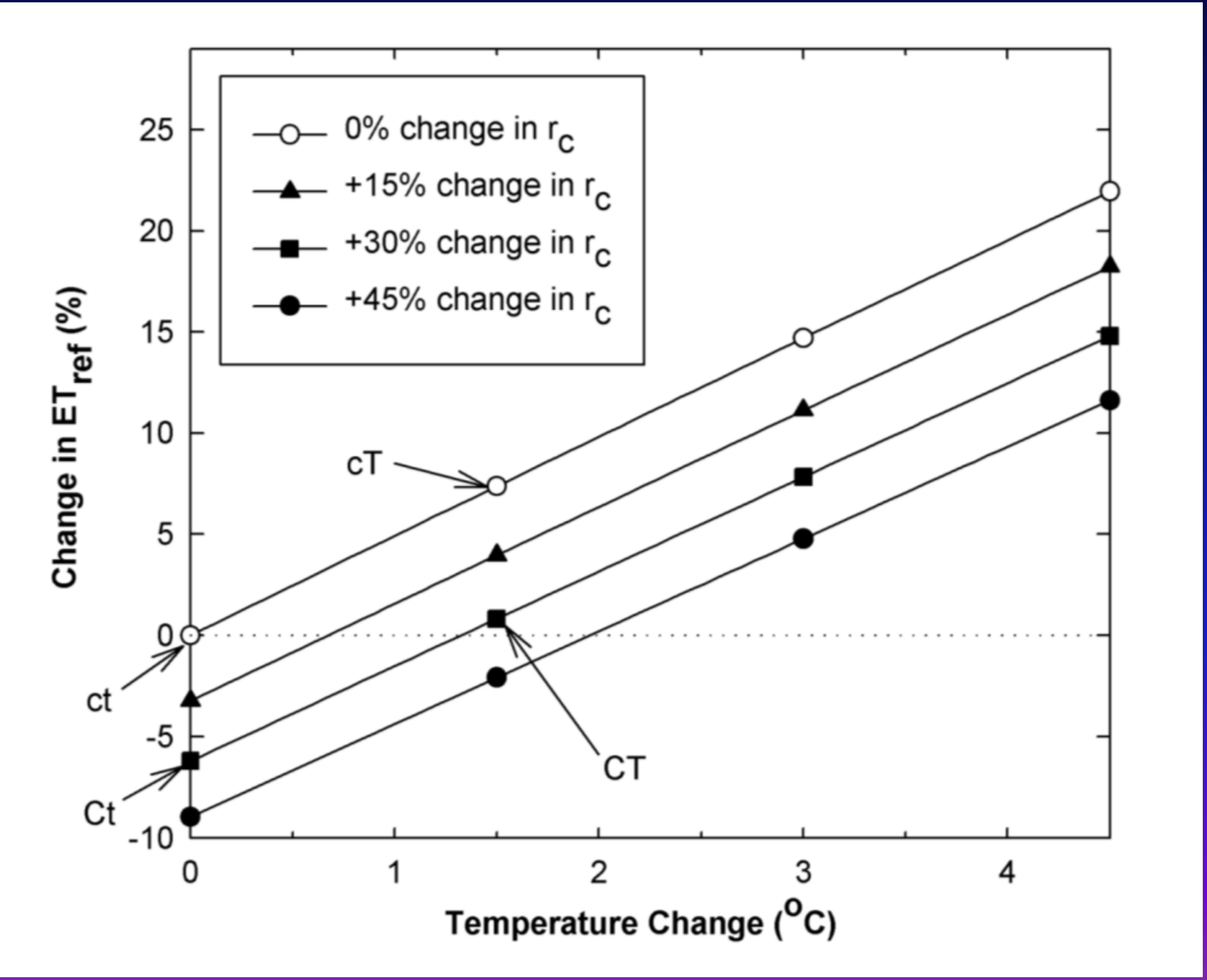
- Elevated CO_2 favored C_3 grasses
- Warming favored C_4 grasses
- Combination of elevated CO_2 & warming favored C_4 grasses

CONCLUSIONS:

- C_4 grasses may become more competitive
- Productivity may be higher in a warmer, CO_2- enriched world.

Morgan et al. (2011; Nature)

Elevated-CO_2-caused increases in canopy resistance and increased temperature act in opposite directions on evapotranspiration



Morgan et al. (2011; Nature)

Conclusions

- Elevated CO_2 alone:
  - Elevated CO_2 increased photosynthesis, biomass, and yield in all C_3 species, an average 21% for shoot biomass for enrichment to 550 µmol mol^{-1}, but less in C_4.
  - Elevated CO_2 generally also decreased stomatal conductance, and transpiration per leaf area while increasing soil water content, canopy temperatures, and water use efficiency in all plants.
  - Root biomass was generally stimulated more than shoot biomass
  - Woody perennials had large growth stimulations, while reductions in stomatal conductance were smaller
  - N concentrations went down while carbohydrate and other carbon-based compounds went up, with leaves affected more than other organ

Conclusions - continued

- Elevated CO_2 when H_2O is limited:
  - Growth stimulations are as large or larger under water-stressed compared to well-watered conditions.
  - Degree of CO_2 growth stimulation greatly dependent on dynamics of drought cycles. Reduction of ET following rain or irrigation event enables CO_2-enriched crop to sustain photosynthesis and growth more days into a growth cycle.
  - Once stomates close due to water stress, elevated CO_2 no longer effective.

Conclusions - continued

- Elevated temperature alone:
  - Increases growth and yield when normal temperature is below optimum for particular plant. If warmer temperature prevents frost damage, positive response can be dramatic.
  - Decreases growth and yield when normal temperature is above optimum for particular plant. If warmer temperature damages pollen and seed-set, negative response can be dramatic.
  - Accelerates plant development time. For determinant cereal crops like wheat, shortened grain-filling period can decrease yield.

Conclusions - continued

- Elevated CO_2 and elevated Temperature:
  - The temperature optimum for photosynthesis shifts to higher temperatures at elevated CO_2.
  - During the vegetative stage of plant growth and below the temperature optimum, the interaction appears mostly strong and positive.
  - Above the temperature optimum, partial stomatal closure and associated canopy temperature rise can exacerbate crop damage, especially with regard to seed-set issues.
  - At the same time, higher photosynthetic rates at elevated CO_2 enable plants to better withstand damaging high temperatures, sometimes at least, even enabling survival while ambient-CO_2 plants die.

The End
Thank You for Your Attention