Crop Responses to Elevated CO$_2$
and Interactions with H$_2$O, N, and Temperature

by

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Tomatoes Grown with CO$_2$-Enrichment ca. 1978
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

Starting in about 1980, funding of open-top and controlled-environment chamber experiments in Raleigh (Rogers), Gainsville (Allen), Starkville (Baker), Phoenix (Kimball), and others

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 °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 (C₃ woody perennial)
1989 FACE
1990 & 1991 FACE x H₂O

Wheat (C₃ grass)
1992-93 & 1993-94 FACE x H₂O
1995-96 & 1996-97 FACE x N

Sorghum (C₄ grass)
1998 & 1999 FACE x H₂O
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)
  - FACE x N; varieties
History of SoyFACE Project

• Soybean
  – 2001 CO₂
  – 2002 CO₂, O₃
  – 2003-2007 CO₂, O₃, CO₂+O₃
  – 2008 CO₂, O₃, CO₂+O₃, H₂O
  – 2009-2013 CO₂, O₃, CO₂+O₃, H₂O, Infrared Warming

• Corn
  – 2002 CO₂
  – 2004 CO₂
  – 2006 CO₂
  – 2008 CO₂
  – 2010 CO₂, Warming
  – 2012 CO₂, Warming
History of Chinese FACE Project

- Rice (C₃ grass)
  - 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$_2$O 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:

$\text{CO}_2$ and Water (Drought)
Difference in $\lambda$ET of Soybean at Elevated and Ambient Through a Drying Cycle in SoyFACE [(from Bernacchi et al. (2007))]

![Graph showing the difference in $\lambda$ET of Soybean at Elevated and Ambient through a drying cycle in SoyFACE. The x-axis represents the day of the year, and the y-axis shows $\lambda$ET elevated [CO$_2$] - Control (W m$^{-2}$). The data points are marked with error bars indicating variability.](image)

- $\lambda$ET elevated [CO$_2$] - Control (W m$^{-2}$)
- Day of Year

215 220 225 230 235 240

-80 -40 0 40 80

[Image of the graph showing the data points and error bars.]

(from Bernacchi et al. (2007))
Evapotranspiration (updated from Kimball, 2011)

Relative Changes Due to Elevated CO₂ (%)

-40 -20 0 20 40

when water limiting over seasonal time frame, little change in ET because plants use all water available

Cotton (woody)
Wheat (C₃ grass)
Sorghum (C₄ grass)
Maize (C₄ grass)
Poplar (woody)
Cotton (woody)
Sweetgum (woody)
Soybean (C₃ legume)
Potato (C₃ forb)

Ample N, Ample H₂O
Low N, Ample H₂O
Ample N, Low H₂O

All C₃ & C₄
Canopy Temperature (updated from Kimball, 2011)

- **Actual Changes Due to Elevated CO₂ (°C)**

- Ample N, Ample H₂O
- Low N, Ample H₂O
- Ample N, Low H₂O

- Wheat (C₃ grass)
- Rice (C₃ grass)
- Sorghum (C₄ grass)
- Maize (C₄ grass)
- Cotton (woody)
- Poplar (woody)
- Potato (C₃ forb)
- Soybean (C₃ legume)
Above-Ground Biomass Accumulation (updated from Kimball, 2011)

-20 0 20 40 60 80 100 120

Relative Changes Due to Elevated CO₂ (%)

- Ample N, Ample H₂O
- Low N, Ample H₂O
- Ample N, Low H₂O

Wheat, ryegrass, rice, & barley (C₃ grasses)
Sorghum & maize (C₄ grass)
Potato sugarbeet casava (C₃ forbs w root tuber storage)
Clover (C₃ legume)
Soybean (C₃ legume)
Cotton, grape (woody)
Forest
Grassland
Desert
Agricultural Yields (updated from Kimball, 2011)

Relative Changes Due to Elevated CO₂ (%)

-20 0 20 40 60 80 100 120

Grape berries (woody)
Cotton bolls (seed + lint) (woody)
Clover forage (C₃ legume)
Potato tubers (C₃ forb)
Sorghum grain (C₄ grass)
Wheat, rice, barley grain (C₃ grasses)
Hybrid rice grain China (C₃ grass)
Rice variety range Japan (C₃ grass)
Soybean pea peanut bean (C₃ grain leg.)
Sorghum grain (C₄ grass)
Maize (C₄ grass)
Potato tubers (C₃ forb)
Sugar Beet (C₃ forb)
Casava (C₃ forb)
Clover forage (C₃ legume)
Mustard (C₃ oilseed)
Cotton bolls (seed + lint) (woody)
Grape berries (woody)
Effects of:

Temperature Alone
Typical Temperature Response Curve

relative rate of growth or other process

T_\text{base}

T_\text{limit}

T_\text{optimum lower}

T_\text{optimum upper}
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

<table>
<thead>
<tr>
<th>Daily Temperatures (°C)</th>
<th>Max Air</th>
<th>Min Air</th>
<th>Historic Highs</th>
<th>Historic Lows</th>
<th>Crop Max</th>
<th>Crop Min</th>
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<th>Daily Temperatures (°C)</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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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

\[ Y = 985.2 - 4.919X - 0.8353X^2 \]
Effects of:

$\text{CO}_2$ & 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 CO₂ versus Mean Air Temperature [from Baker et al. (1989; 1993)]

From Baker et al. (1989)

From Baker et al. (1993)
Effects of Elevated CO₂ and Warming in Tunnels on Two Varieties of Wheat (from Dias de Oliveira *et al.*, 2013)

- **Degrees of Warming (°C)**
  - 0
  - 2
  - 4
  - 6
  - 8

- **Yield (g m⁻²)**
  - 0
  - 200
  - 400
  - 600
  - 800

- **Well-watered, Ambient (385 ppm) CO₂ + Ambient T**
- **Well-watered, 700 ppm CO₂ + Warming**
- **Drought, Ambient (385 ppm) CO₂ + Ambient Temp**
- **Drought, 700 ppm CO₂ + Warming**

Diagram showing the effects of degrees of warming on yield for two varieties of wheat: Janz and 38-19. The LSD bars indicate the least significant difference in yield.
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 CO₂, and +T+CO₂ (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
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.
Elevated-CO$_2$-caused increases in canopy resistance and increased temperature act in opposite directions on evapotranspiration.
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$_2$O 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.
• 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