Climate Change and Crop Productivity: Challenges and Opportunities

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Tennessee State University, Nashville, TN

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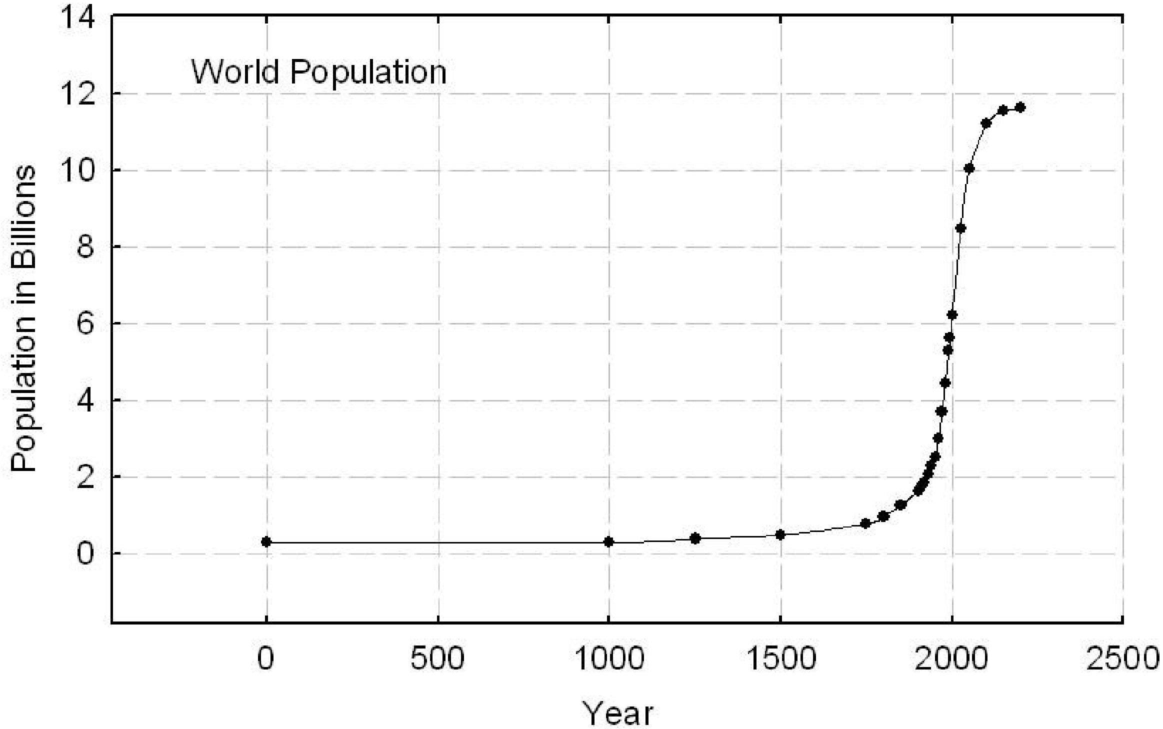
Trends, Signs and Signatures from the Earth

Past, Present and Future World Population



- Plant produce over 80% of the food we eat and protecting the health of the plants ensure a sustainable future.

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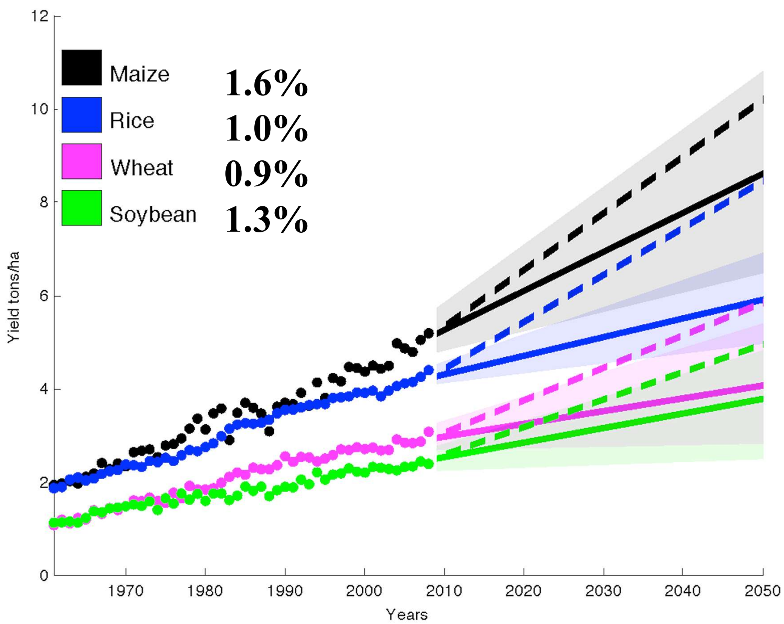
Trends, Signs and Signatures from the Earth

Yield Trends of Major Crops – Past and Future



- Yield must be doubled by 2050 to meet the demands of a rising population with higher earning capacity, diet shifts, and increasing biofuel consumption.
- Based on past trends, the projected rate of yield increase will be about **1.2%** per year, but we need about **2.4%** per year to double the current yields for major cereal crops, including rice.

Ray et al., 2013, PLOSOne

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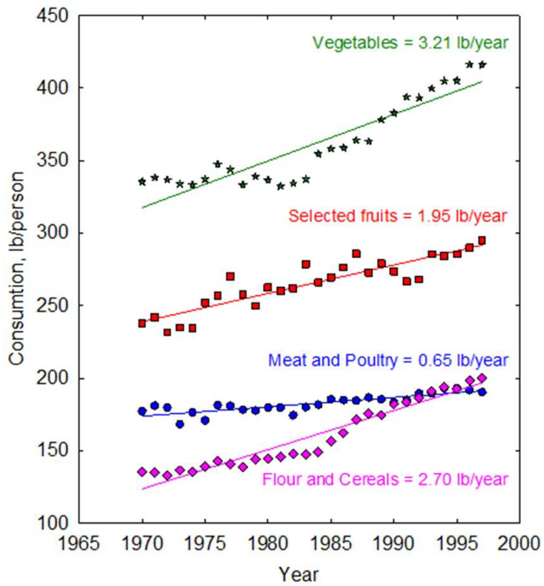
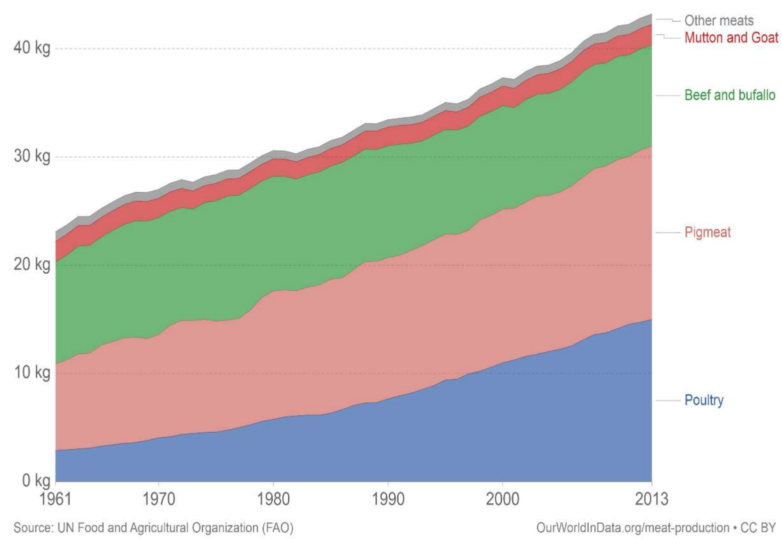
Trends, Signs and Signatures from the Earth
Major Foods – Consumption and Production

Per Capita Food Consumption



Food-use Dynamics



- Global food supply: Human consumption: 67%; animal feed = 24%, and industry: 9%

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Trends, Signs and Signatures from the Earth

Management Practices – Cropland area, Irrigation & Salinization

Whatever We do, It will Cost Us

Percentage change from Year 1985 to 2000

	Cropland area	Irrigated area	Salinized area
	---------------------------- Mha	-------------------------------	
China	124.0	54.4 (22%)	7-8 (14%)
India	161.8	54.8 (31%)	10-30 (50%)
USA	177.0	22.4 (13%)	4.5 -6 (15%)
USSR	204.1	19.9 (2%)	2.5-4.5 (21%)
World	1364.2	271.7 (21%)	62-82 (37%)

S.G. Pritchard and J. S. Amthor, 2005

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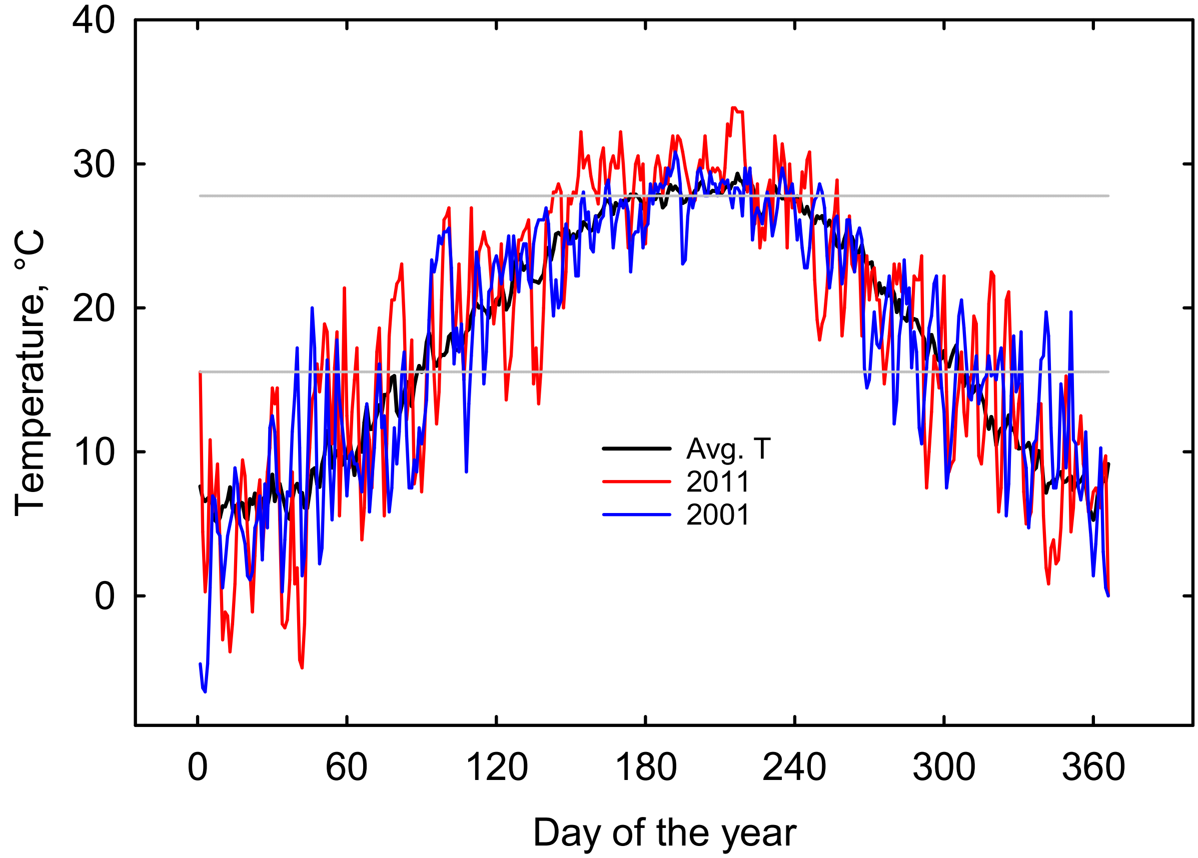
Trends, Signs and Signatures from the Earth

In a production environment, no two seasons are equal



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Here comes the greatest
challenge of our time,
The Global Climate Change

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Trends, Signs and Signatures from the Earth

What is Expected in the Future Climate?

- Greenhouse gases (CO_2, CH_4, N_2O etc.) ↑
- Temperatures ↑ and asymmetry in temperature ↑
- Glaciers ↓
- Oceans and sea-levels ↑
- Precipitation patterns ↓↑ and drought intensities ↑
- Stratospheric ozone ↓ and ground-level UV-B radiations ↑
- Frequency of extreme events ↑

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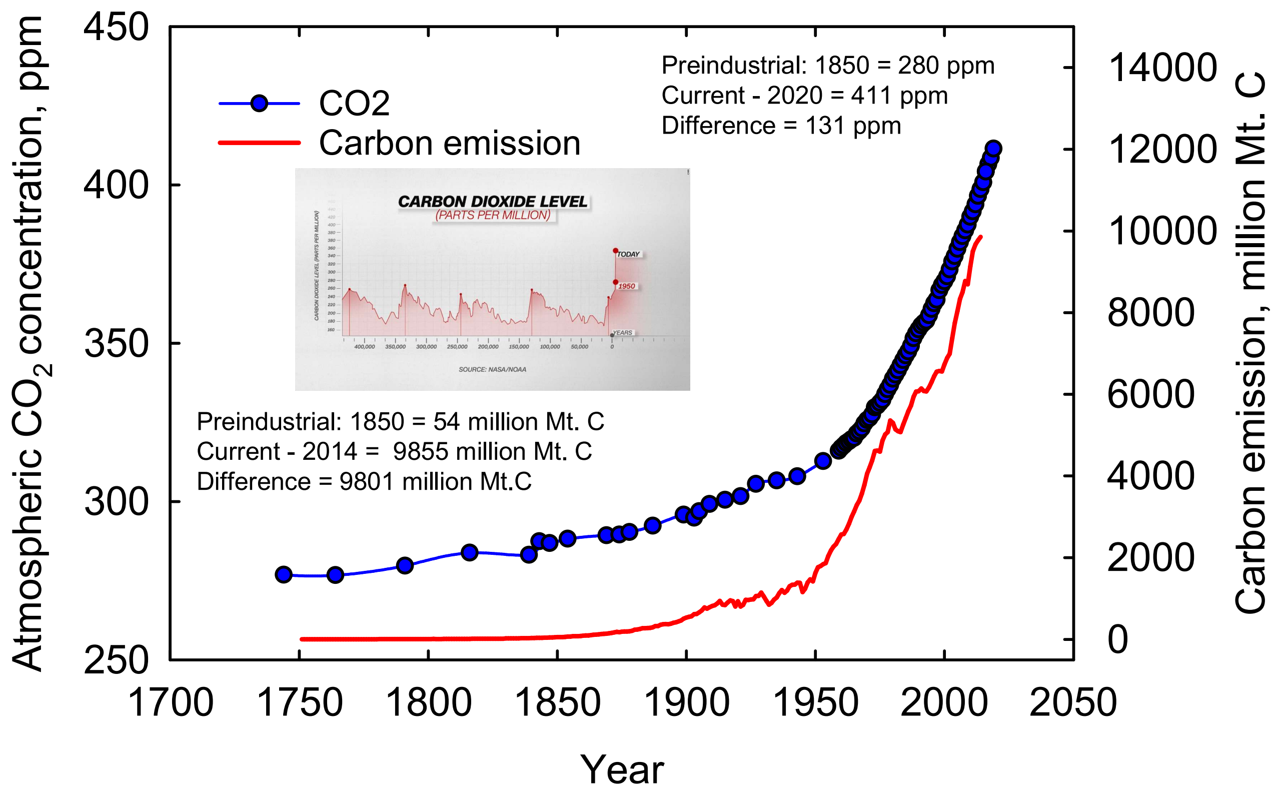
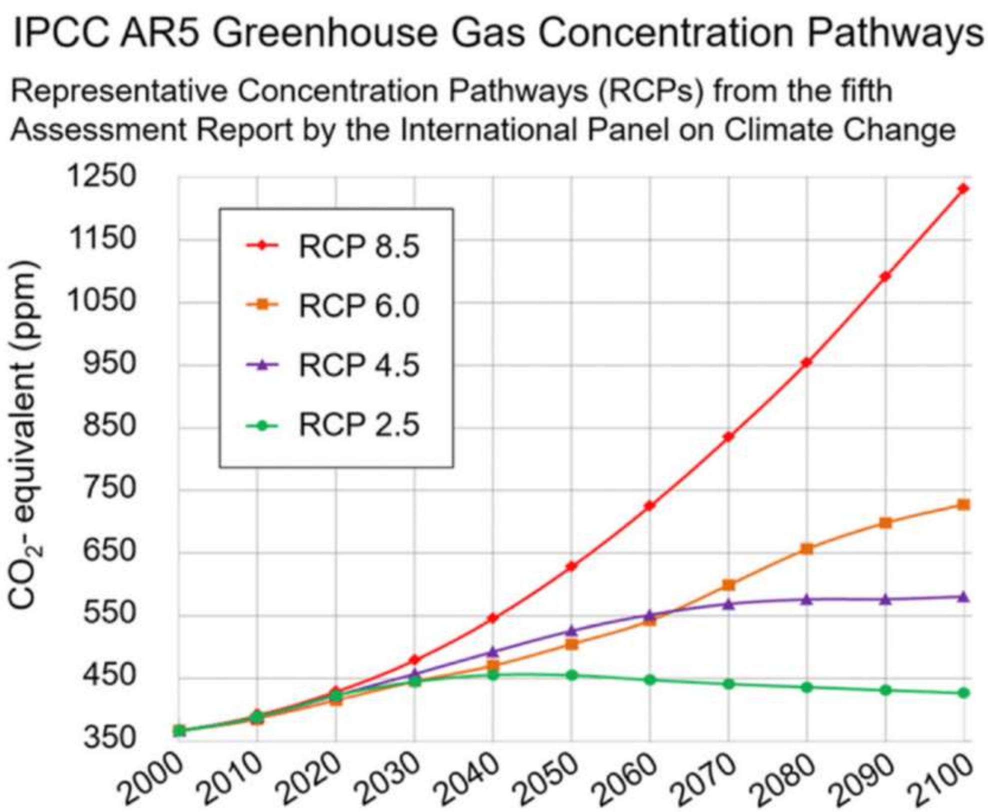
Trends, Signs and Signatures from the Earth

Atmospheric Carbon Dioxide Concentration



Global Carbon Dioxide Concentrations

Projected trends



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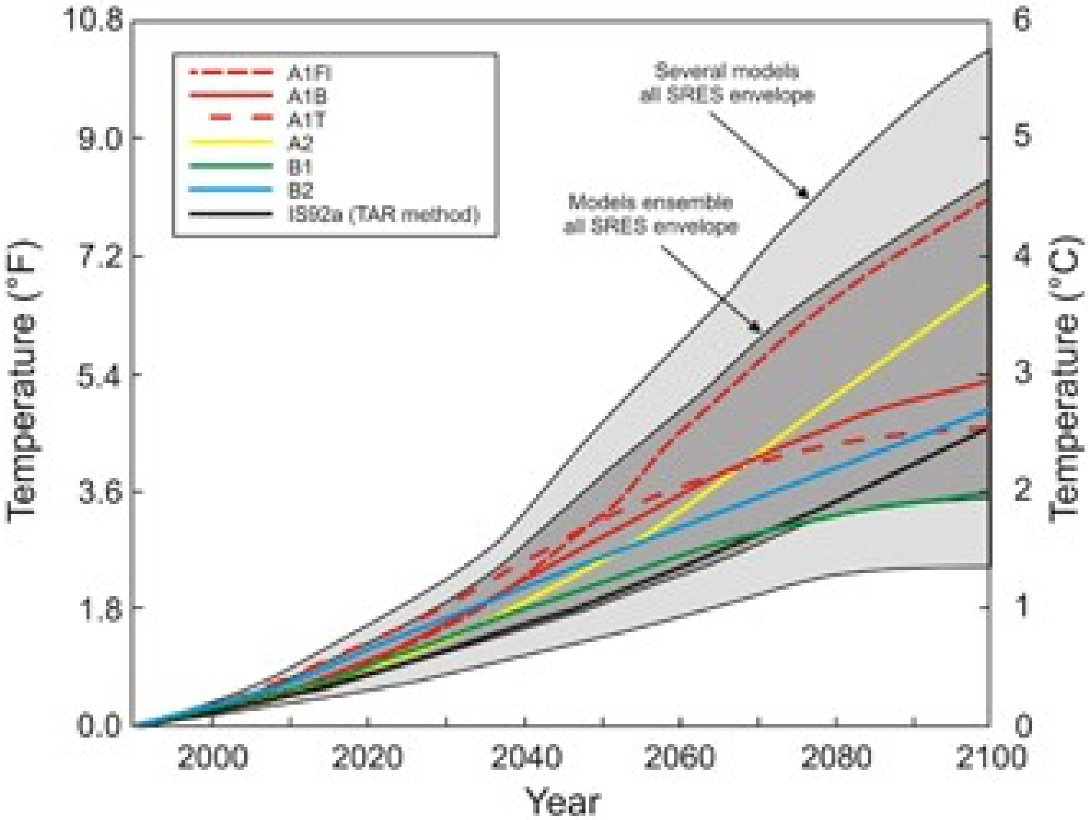
Future Trends in Global Surface Air Temperatures



This shows temperatures associated with seven different carbon dioxide (CO_2) emissions scenarios. The low end of the IPCC range suggests that in the year 2100 the concentration of CO_2 in the atmosphere would be approximately 550 parts per million (ppm), or approximately double the pre-industrial value, while an alternate scenario suggests that the concentration could be close to 1,000 ppm. The other five scenarios fall somewhere in between. http://ccir.ciesin.columbia.edu/nyc/ccir-ny_q1e.html

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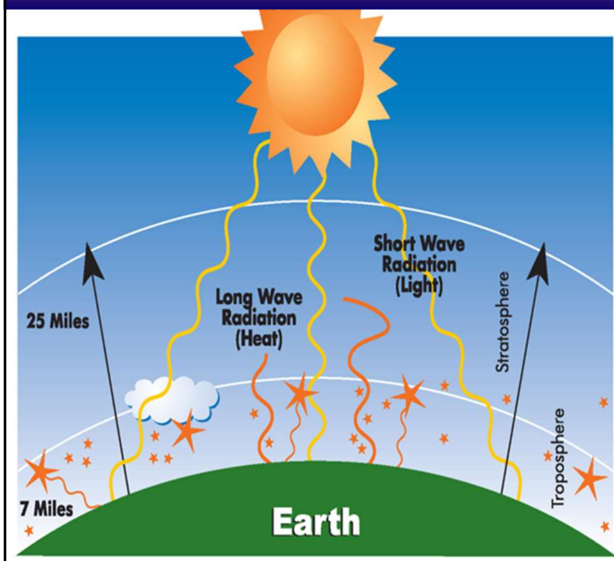
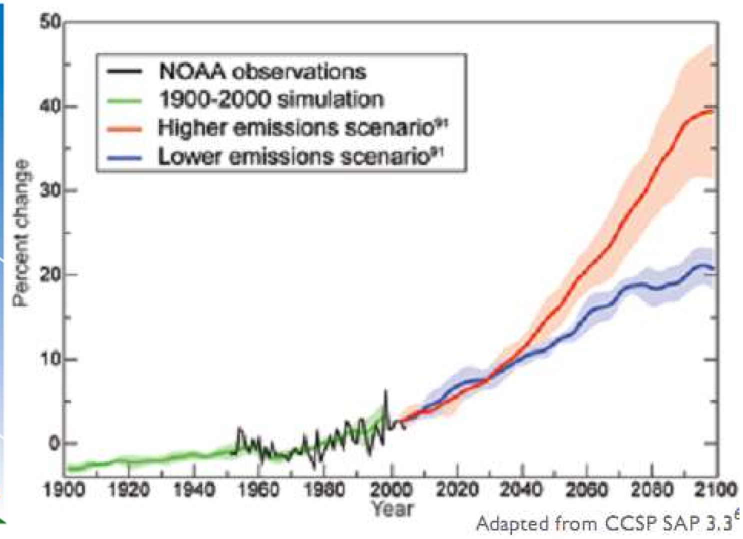
Trends, Signs and Signatures from the Earth

Changes in Night Time Temperature





The graph shows the observed and projected change in percentage of very warm nights from the 1950-1990 average in the United States. Under the lower emissions scenarios, the percentage of very warm nights is projected to increase about 20% by 2100. Under the higher emissions scenario it is projected to increase by about 40%. The shaded areas show the likely ranges, while the lines show the central projections from climate models. The projections appear smooth because they show the calculated average of many models.

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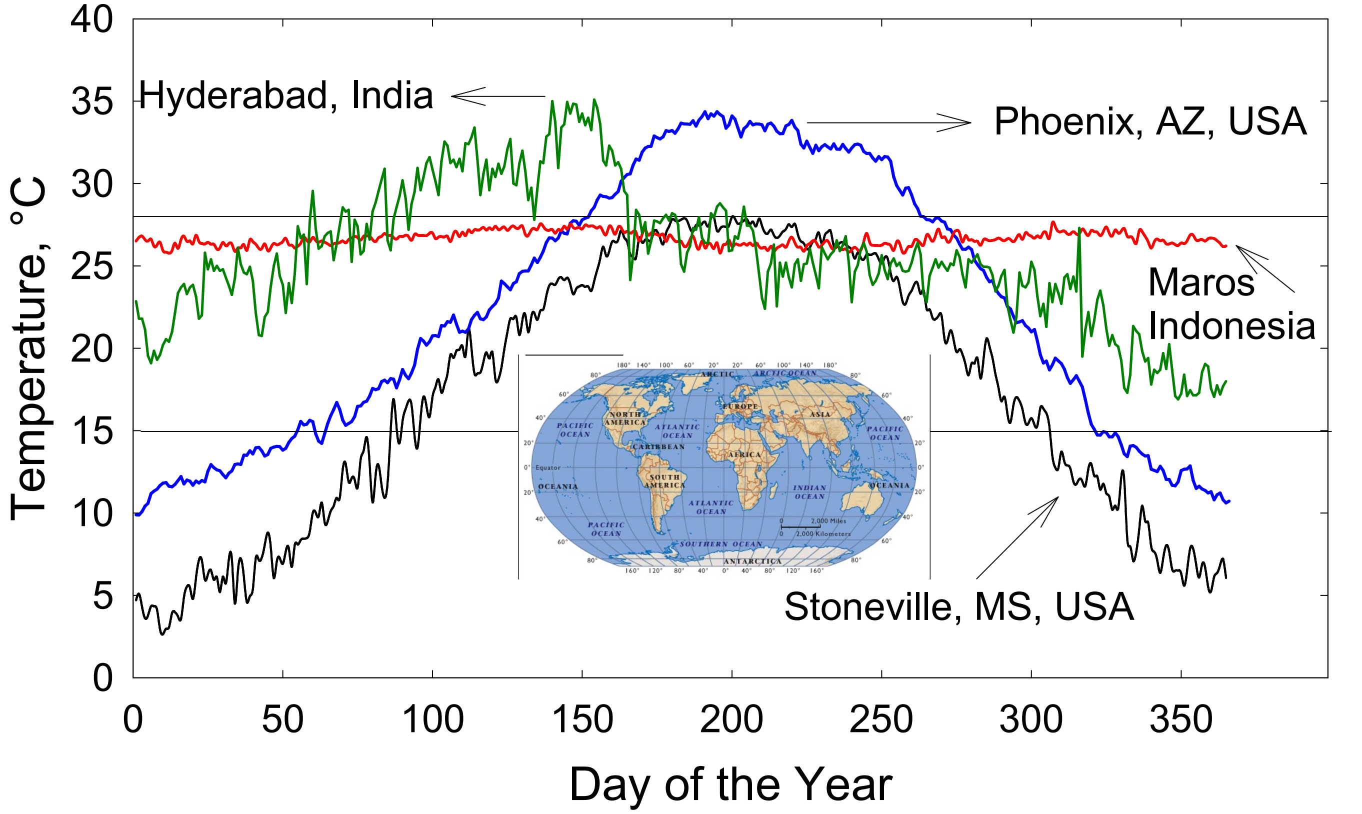
Trends, Signs and Signatures from the Earth

Spatial and Temporal Trends in Climate



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Environmental Stresses and Crop Production

Environmental stresses are threatening our bounty of food production

Trends, Signs and Signatures from the Earth

Factors that Affect Plants?

- Atmospheric CO_2
- Temperatures, including extremes
- Solar radiation, including UV-B radiation
- Precipitation patterns and drought intensities
- Flooding
- Soil minerals, including heavy metals
- Salinity

Environmental Stresses and Crop Productivity

Factors Affecting Yields of Major US Crops

Major US Crops – Record yield, average yield and losses due to various factors

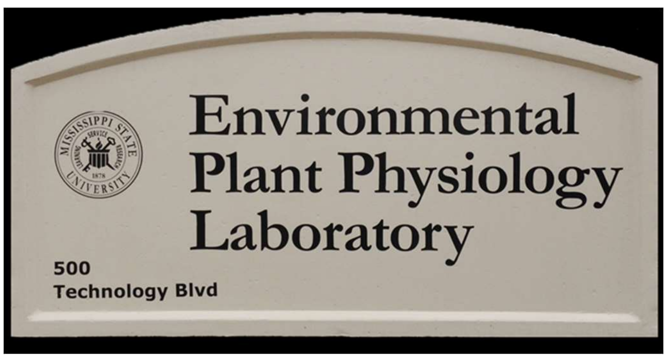
	Yield, kg ha^{-1}						Physiochemical
Crop	**Record**	**Average**	**Diseases**	**Insects**	**Weeds**	**Physiochemical**	**%**
Maize	19,300	4,600	836	836	697	12,300	64
Wheat	14,500	1,880	387	166	332	11,700	81
Soybean	7,390	1,610	342	73	415	4,950	67
Sorghum	20,100	2,830	369	369	533	16,000	80
Oat	10,600	1,720	623	119	504	7,630	72
Barley	11,400	2,050	416	149	356	8,430	74
Potato	94,100	28,200	8,370	6,170	1,322	50,000	53
Sugar beet	121,000	42,600	10,650	7,990	5,330	54,400	45
Mean	**100**	**21.5**	**5.1**	**3.0**	**3.5**	**66.9**	**67**

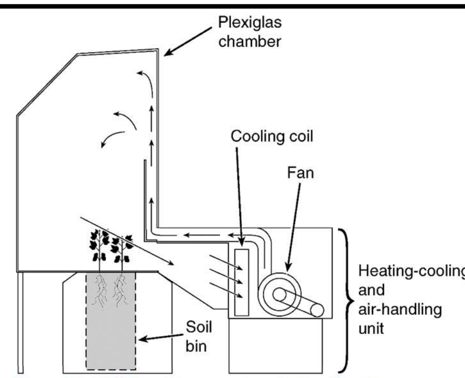
Physiochemical = Record yield – (average yield + disease loss + insect loss + weed loss)

Book: Water Relations of Plants and Soil by P.J. Kramer and J.S. Boyer, 1995
Chapter 12: Evolution and agricultural water use, pp.377-404.

Environmental Plant Physiology Research

Addressing Issues Related Crop Performance in the Current Environment and Beyond



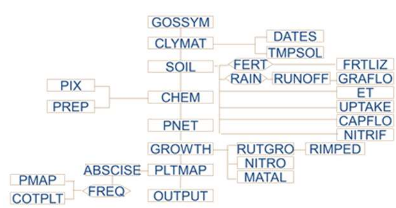


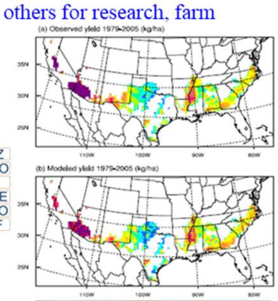
Crop Model Development and Application

Crop Modeling and Applications – Regional Scale

- Over 200 functions, generated from SPAR facility, have been used to develop/upgrade the cotton simulation model, GOSSYM and several other variants.
- The model has been used by USDA and others for research, farm management, and policy arenas.

Cotton simulation model, GOSSYM





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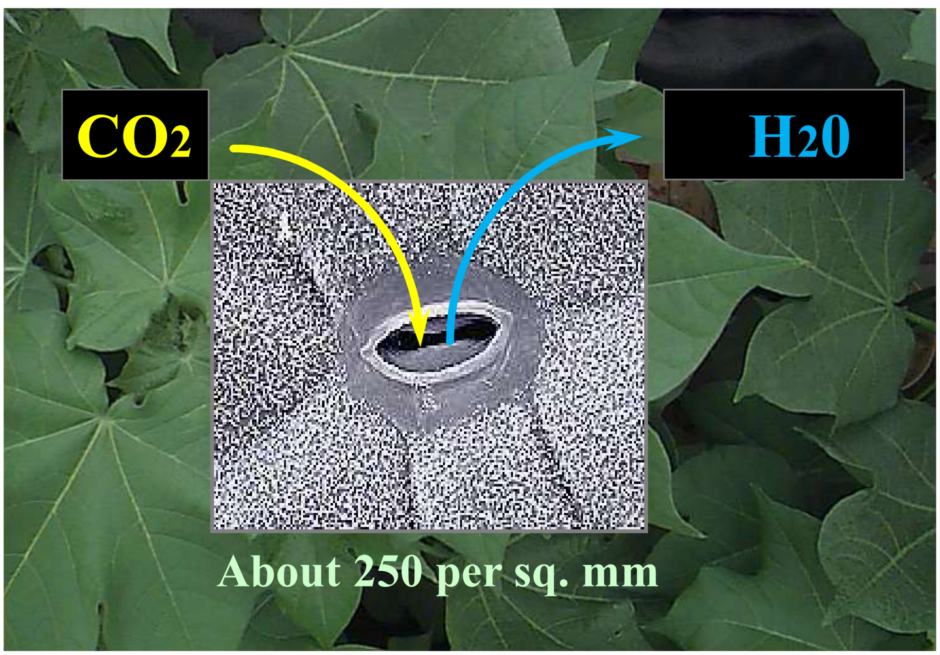
Environmental Stresses and Crop Productivity

Photosynthesis – the Mother of all Plant Process

$$6\ CO_2 + 6\ H_2O \xrightarrow[\text{Nutrients}]{\text{Light, plant}} 1\ C_6H_{12}O_6 + 6\ O_2$$



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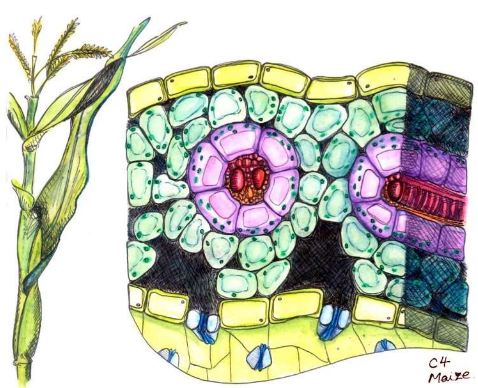
Crop Responses to Atmospheric Carbon Dioxide

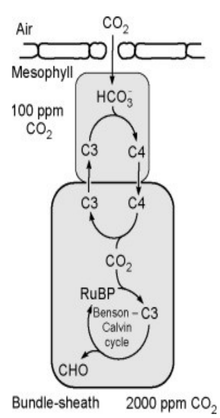
Photosynthesis Response to CO_2 - Species Variability

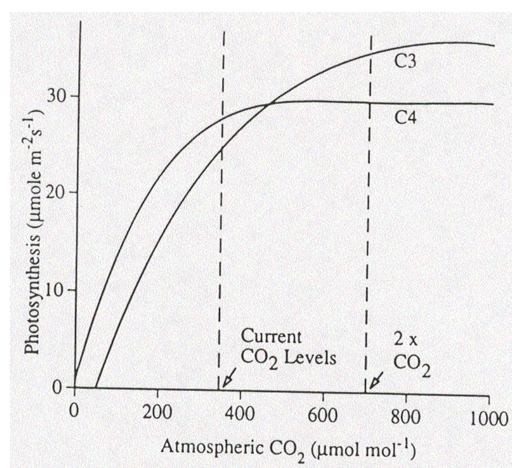
Of the 250,000 higher plant species:

- C3 photosynthetic model = 222,000 (89%)
- C4 photosynthetic model = 8,000 (3.2%)
- Crassulacean Acid Metabolic (CAM) photosynthetic model = 20,000 (8%)

- 25-32 million years ago – Convergent evolution.
- 6-7 million years ago – Became ecologically significant.
- Currently about 3.2% of higher plants contribute to about 30% of global carbon fixation & 25% of land plant biomass.







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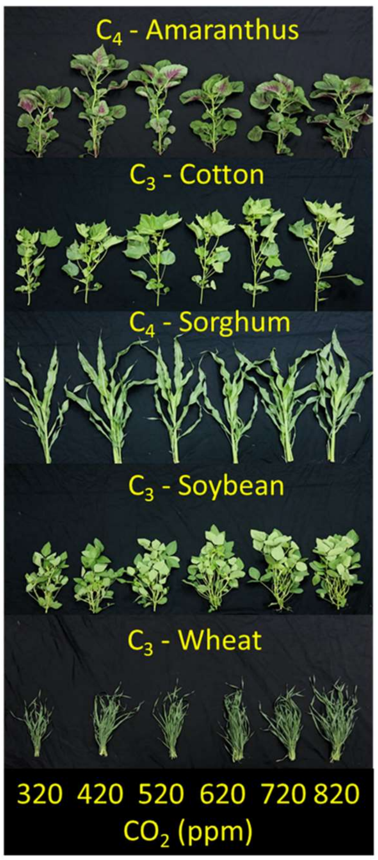
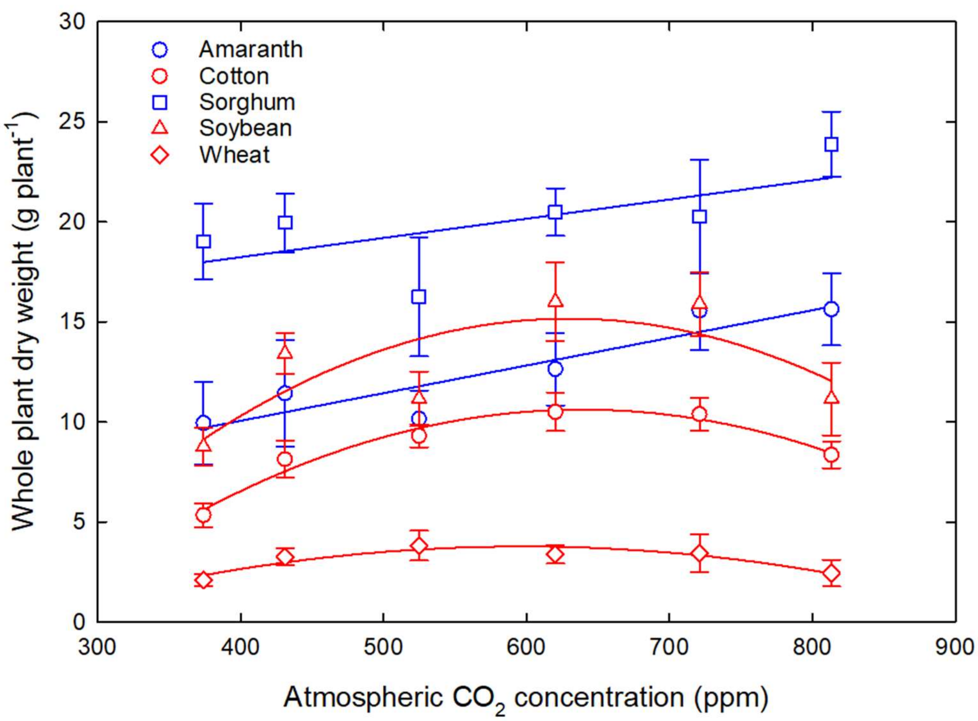
Climate Change and Crop Species Variation

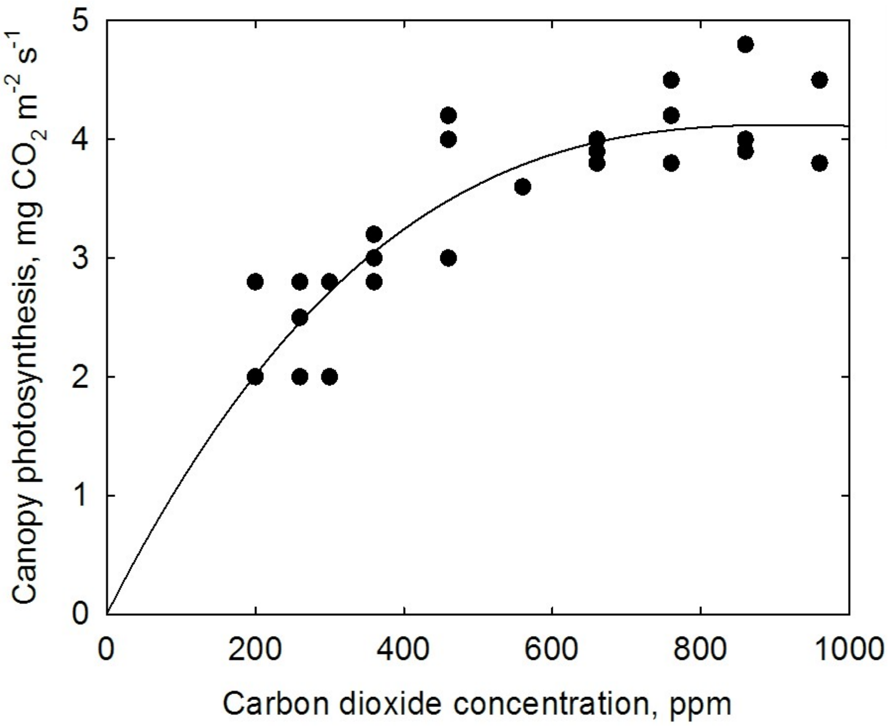
Photosynthesis – Carbon Dioxide Concentration





Environmental Stresses and Crop Productivity

Photosynthesis – CO_2 – C_3 plant - Cotton



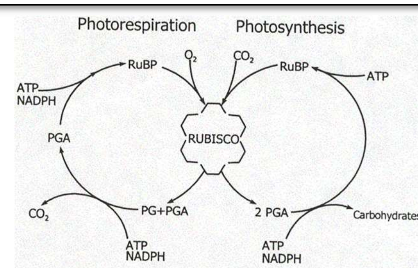
Low ⟷ High

Photosynthesis

Light, Plant

$6\ CO_2 + 6\ H_2O \Longrightarrow C_6H_{12}O_6 + 6\ O_2$

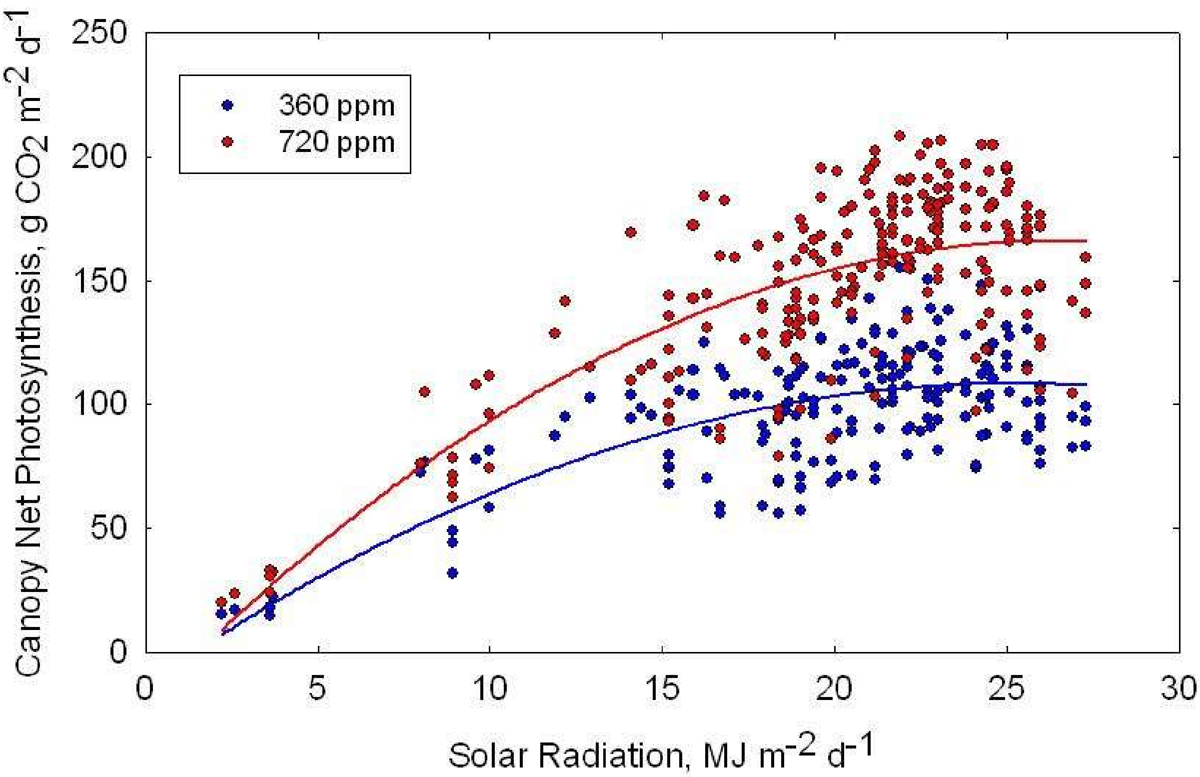
Water, Nutrients



Preindustrial – 286 ppm
1958 – 315 ppm + 29 ppm
2013 – 400 ppm + 114 ppm
2017 – 406 ppm + 120 ppm
2023 – 420 ppm + 134 ppm

20% increase in PHS
Between
1958 and 2023

Environmental Stresses and Crop Productivity
Photosynthesis – Solar Radiation



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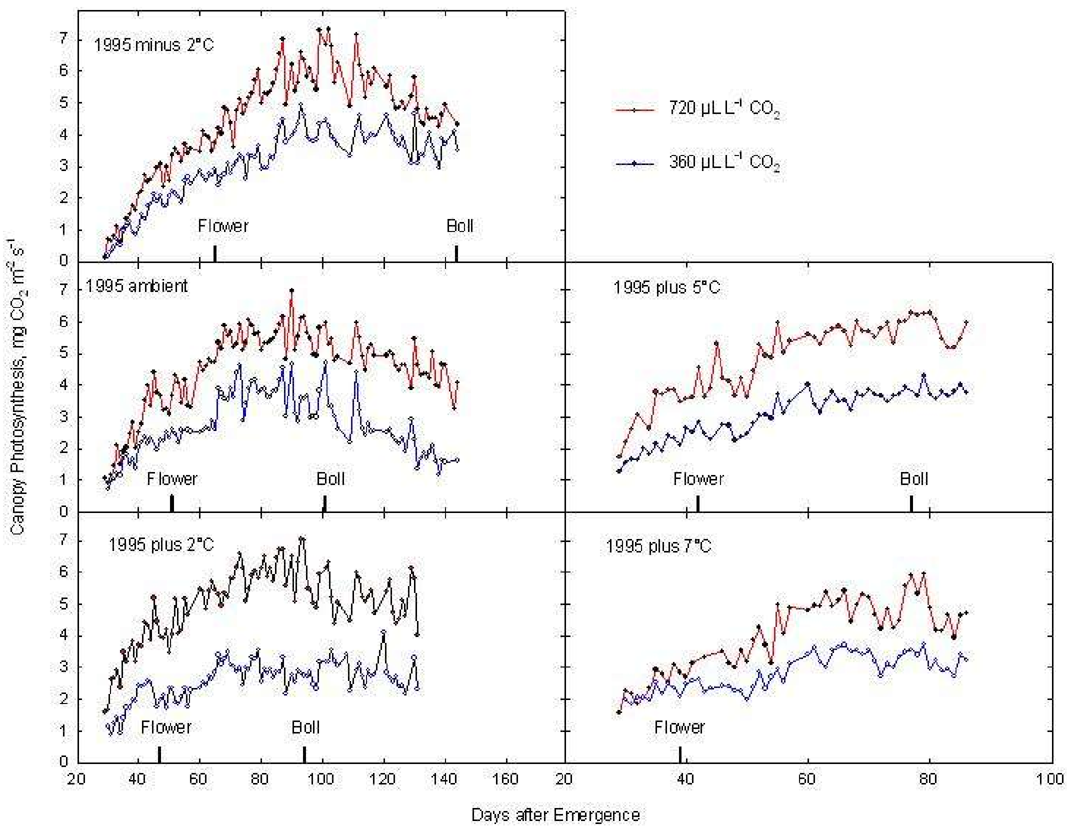
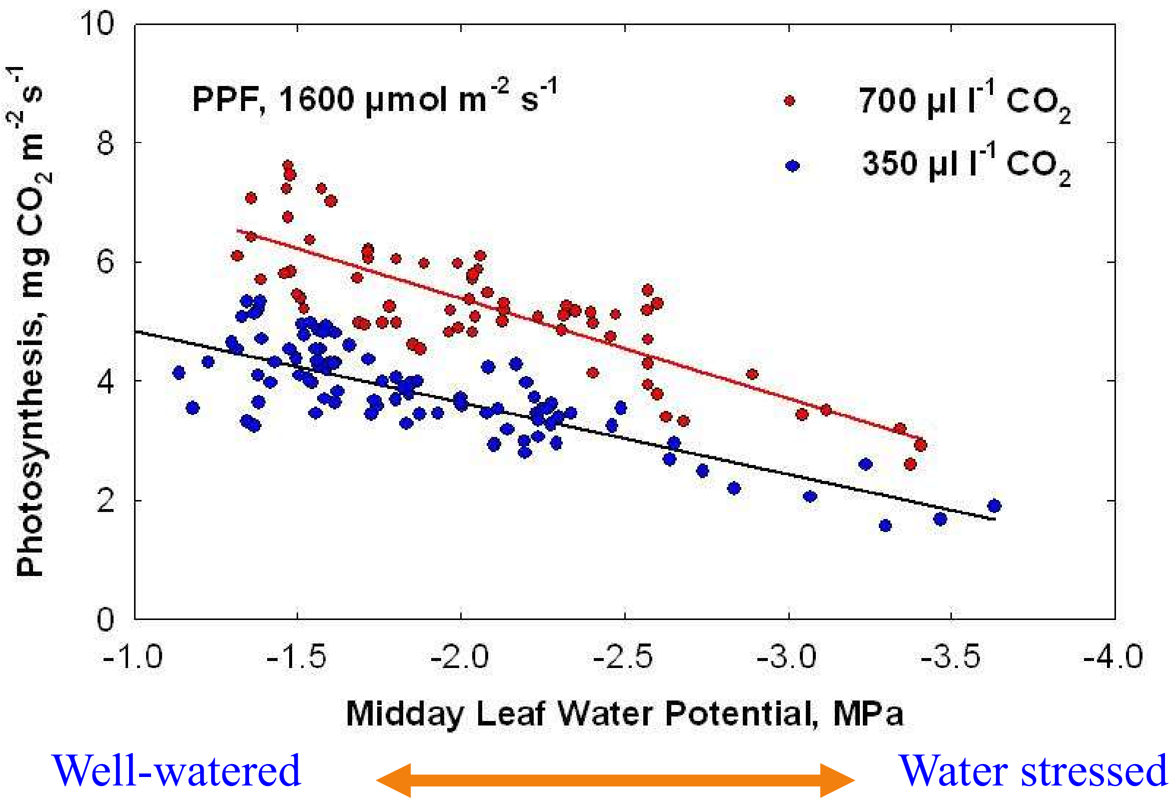
Environmental Stresses and Crop Productivity
Cotton Photosynthesis – Temperatures



Environmental Stresses and Crop Productivity
Photosynthesis – Leaf Water Potential



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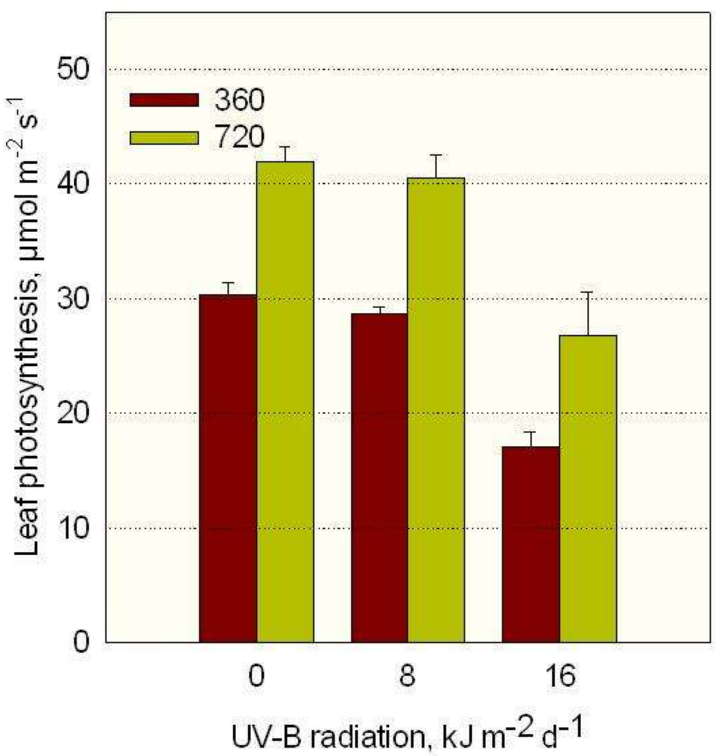
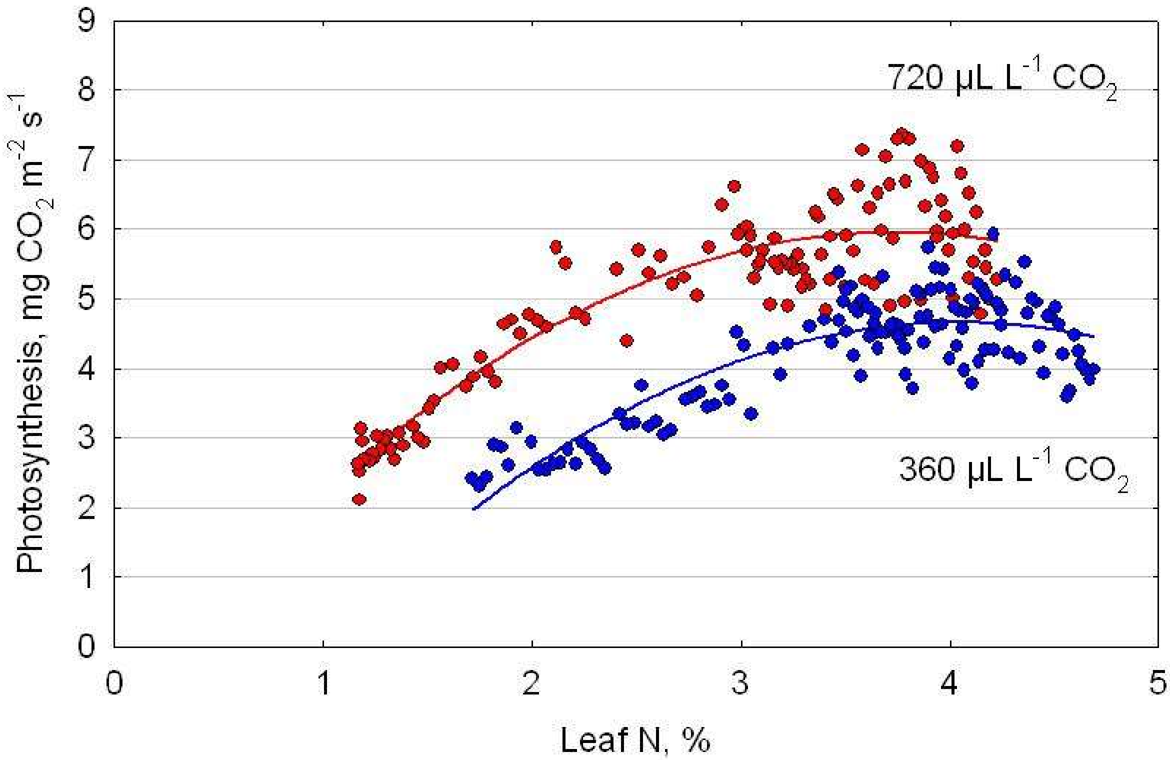
Environmental Stresses and Crop Productivity
Cotton Photosynthesis – UV-B Radiation



0 UV-B ⟷ Higher UV-B

Environmental Stresses and Crop Productivity
Cotton Photosynthesis – Nitrogen Nutrition



N-Starved ⟷ N-well-fertilized

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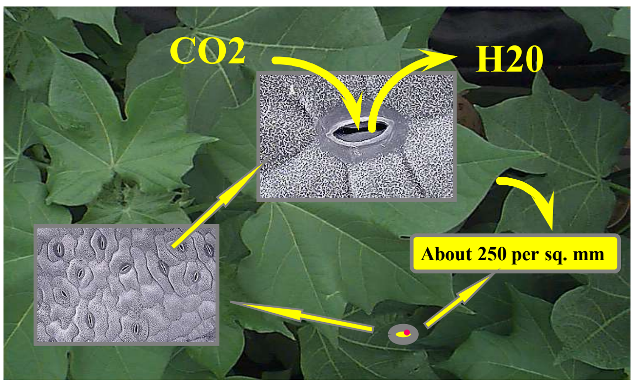
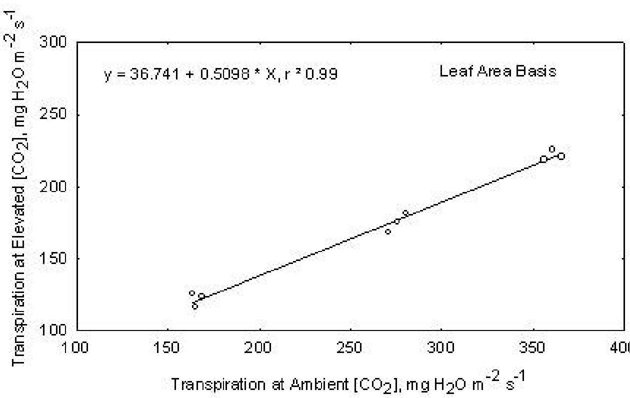
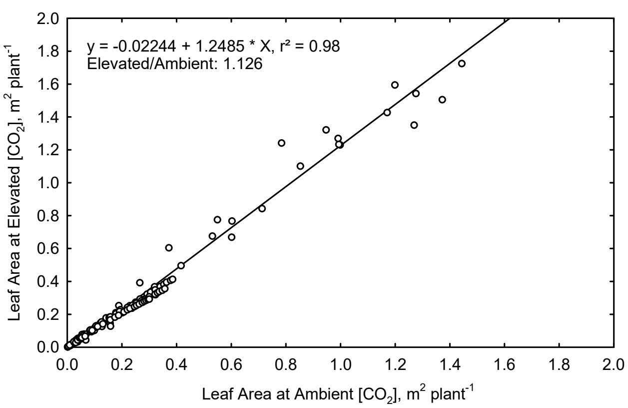
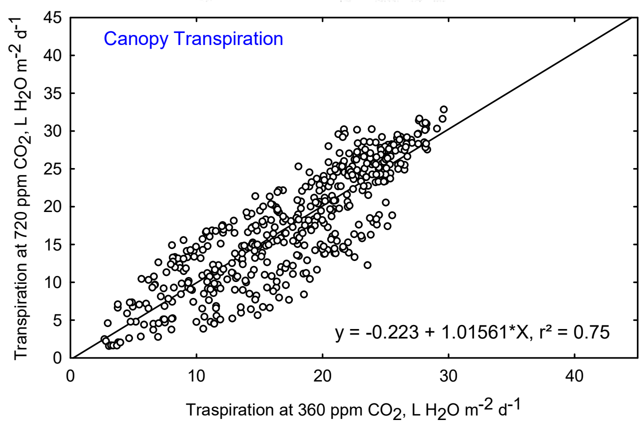
Environmental Stresses and Crop Productivity

Cotton - Leaf and Canopy Transpiration and Leaf Area









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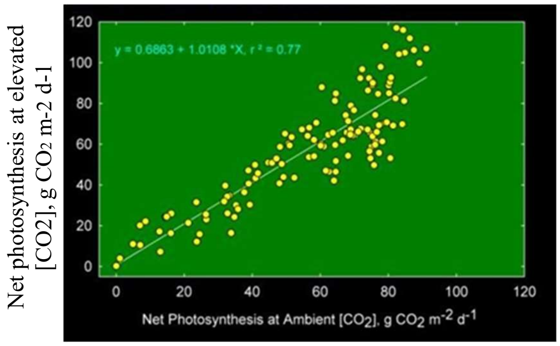
Environmental Stresses and Crop Productivity

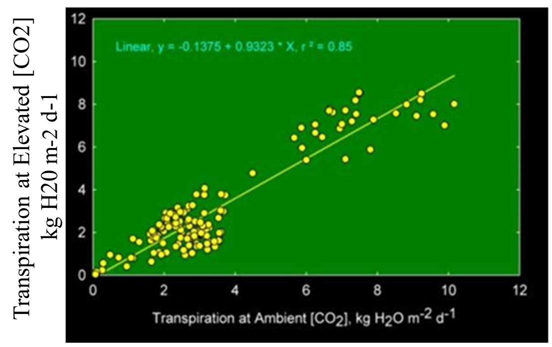
Sorghum (C_4 Crop) - Canopy Photosynthesis and Transpiration

- For sorghum, a C_4 crop, elevated CO_2 didn’t enhance photosynthesis.
- However, elevated CO_2 caused a 5% reduction in transpiration rate.

Canopy Photosynthesis

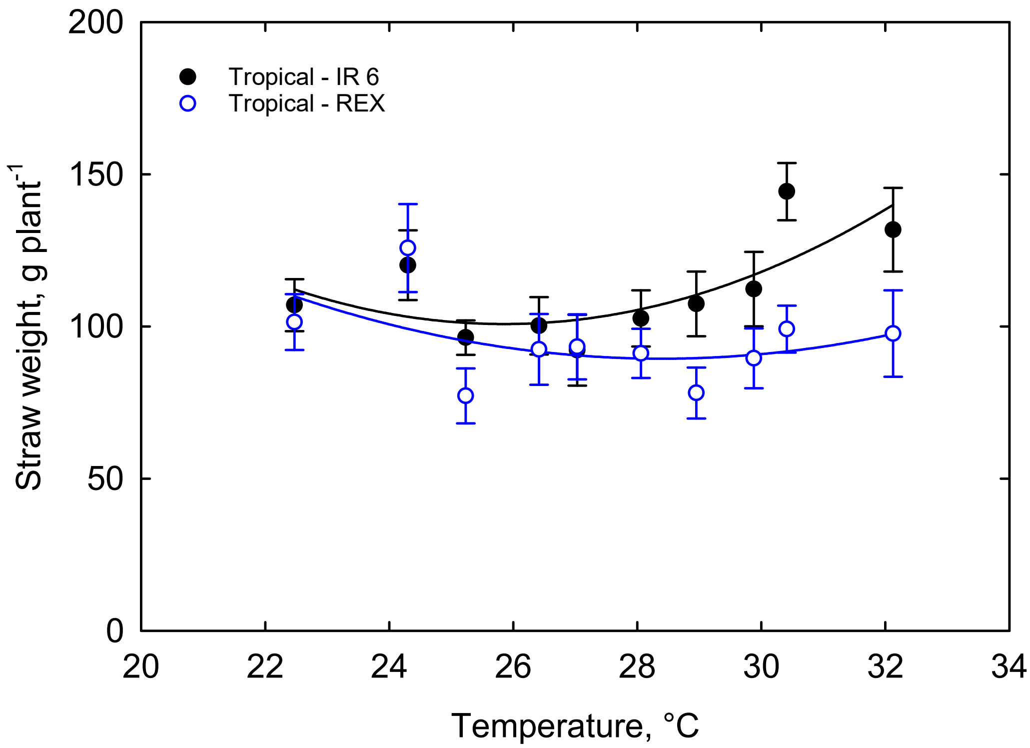


Canopy Transpiration



Environmental Stresses and Crop Productivity

Temperature and CO_2 – Rice Straw Growth



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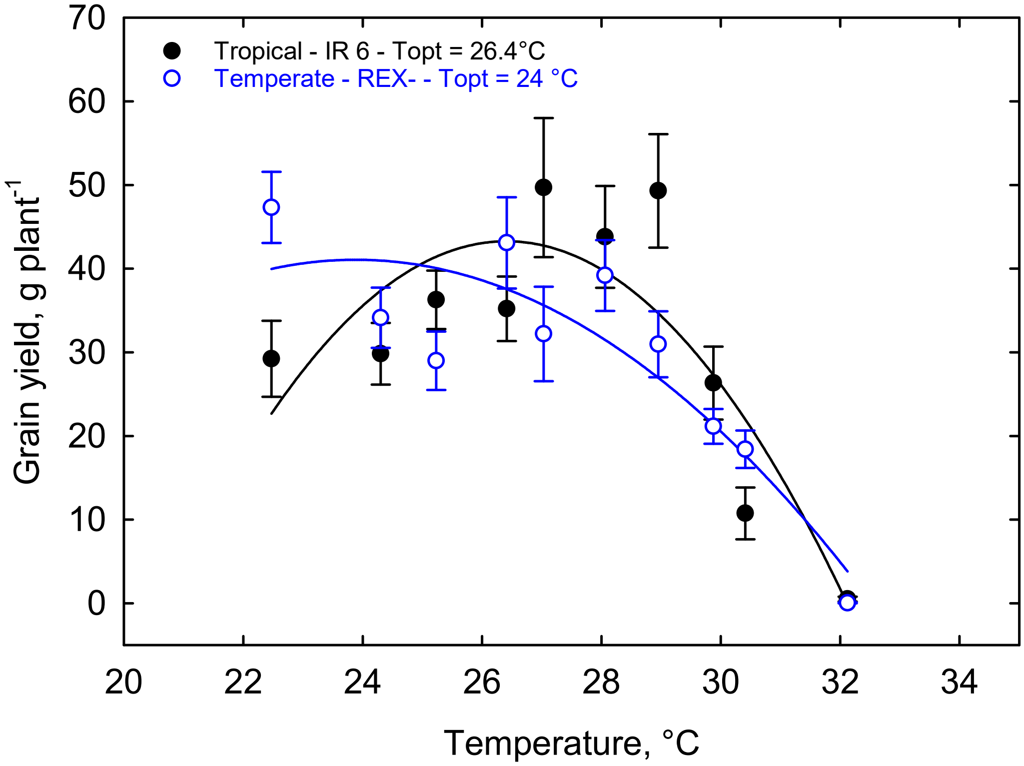
Environmental Stresses and Crop Productivity
Temperature and CO_2 – Rice Grain Yield



Results

Impact of high nighttime temperatures on rice

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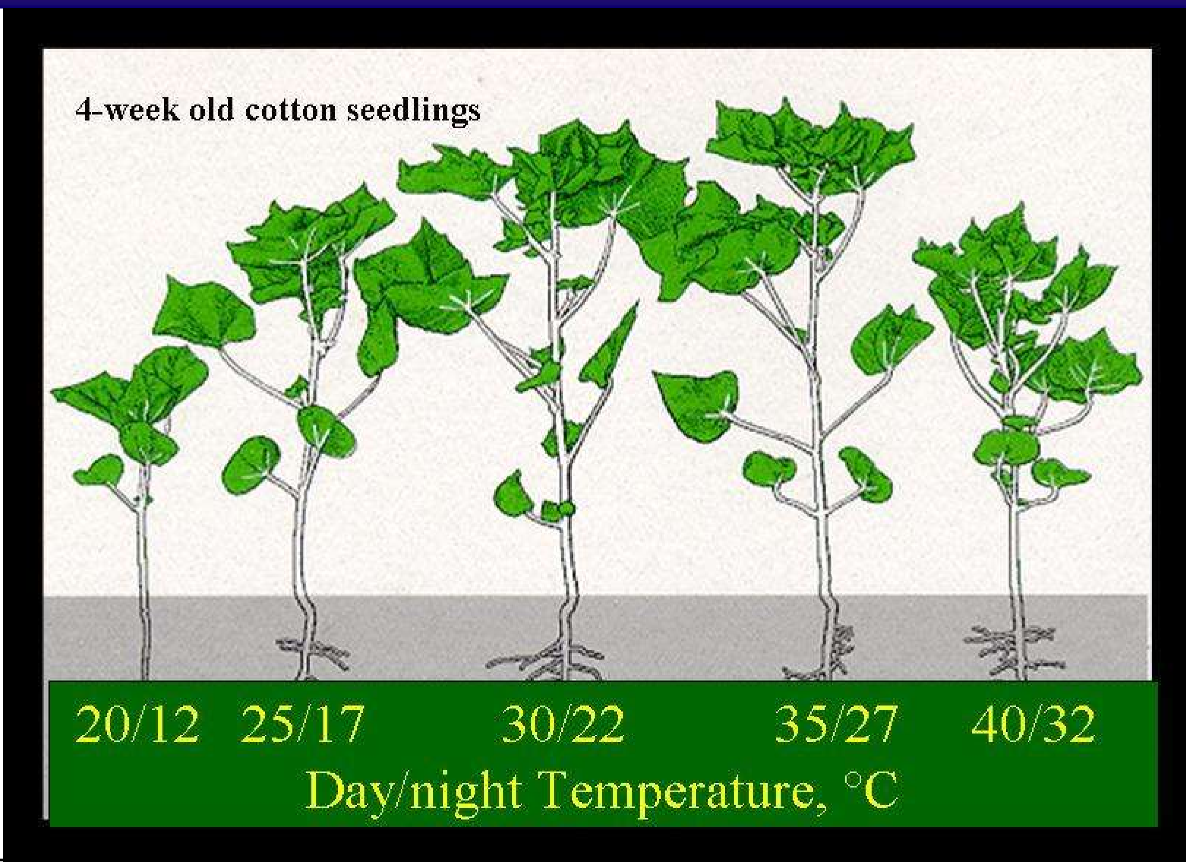
Environmental Stresses and Crop Productivity

Temperature and Cotton Vegetative Growth and Development



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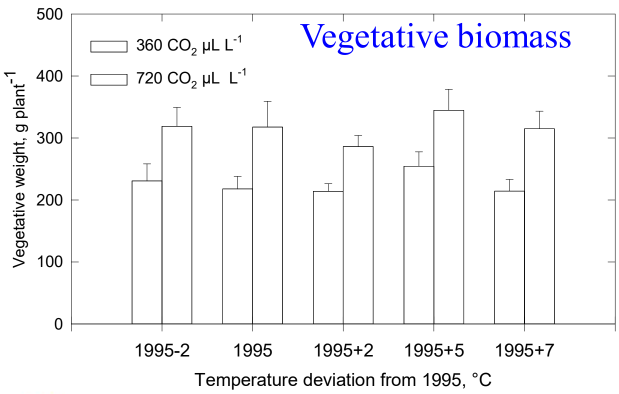
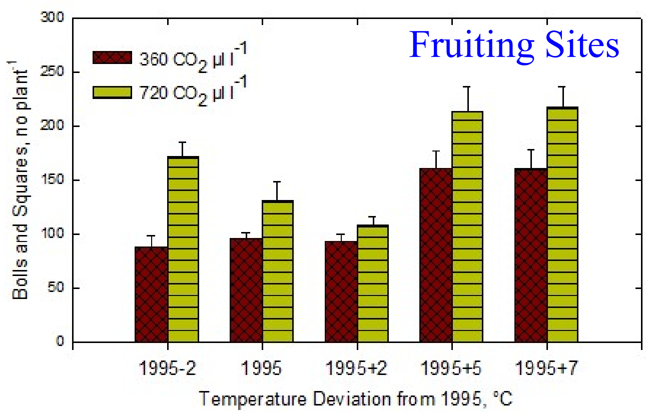
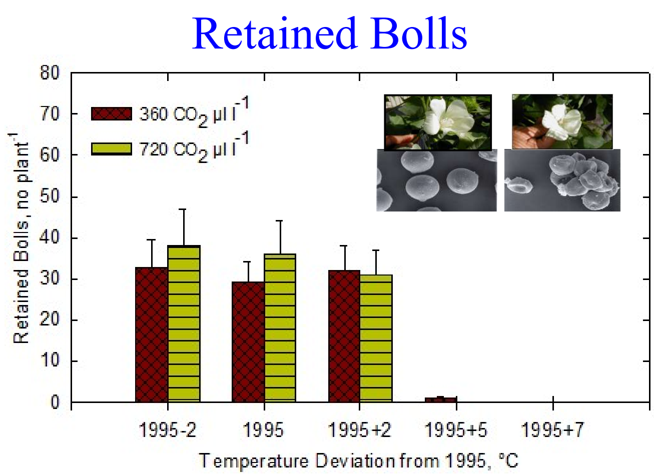
Environmental Stresses and Crop Productivity

Temperature and CO2 – Cotton Growth& Development



Can 2-7 °C change in temperature affect yield?





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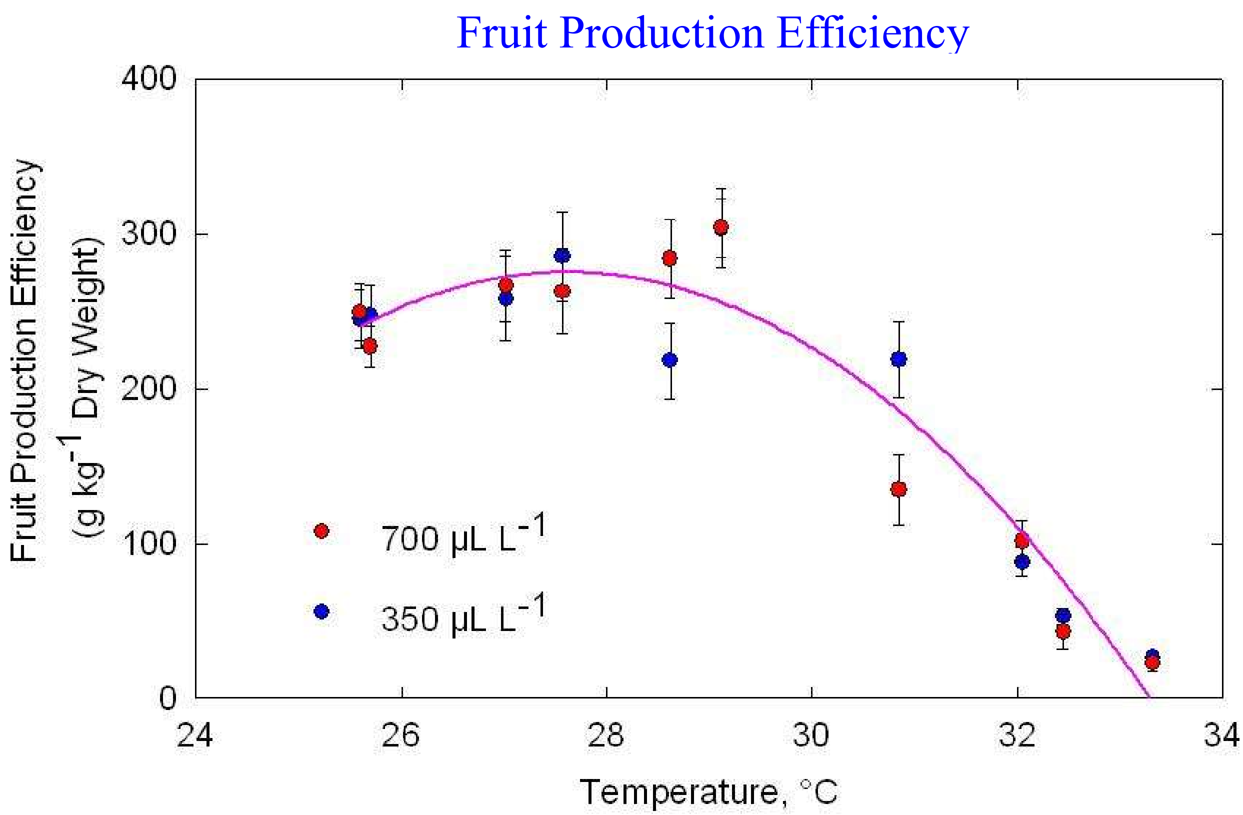
Environmental Stresses and Crop Productivity

Temperature and CO_2 – Cotton Reproductive Growth



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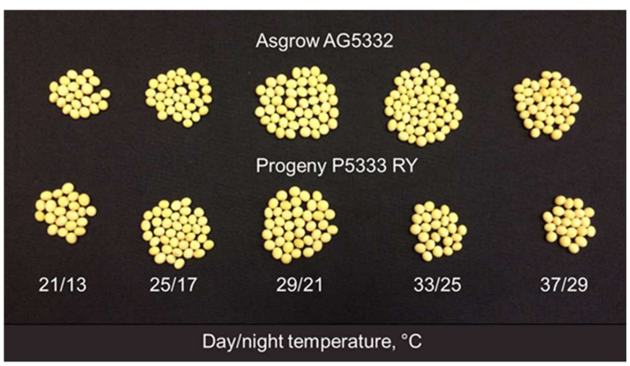
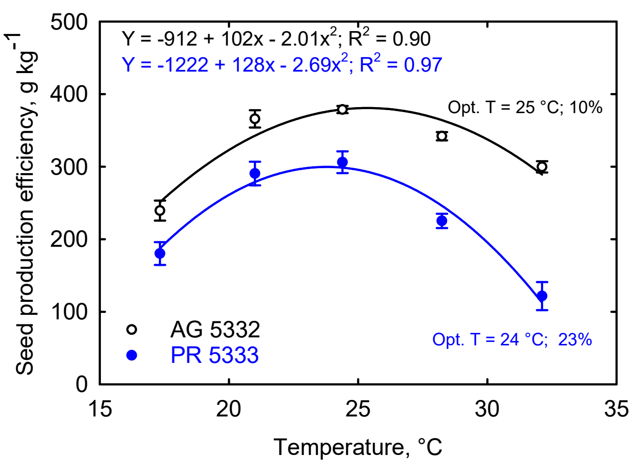
Environmental Stresses and Crop Productivity

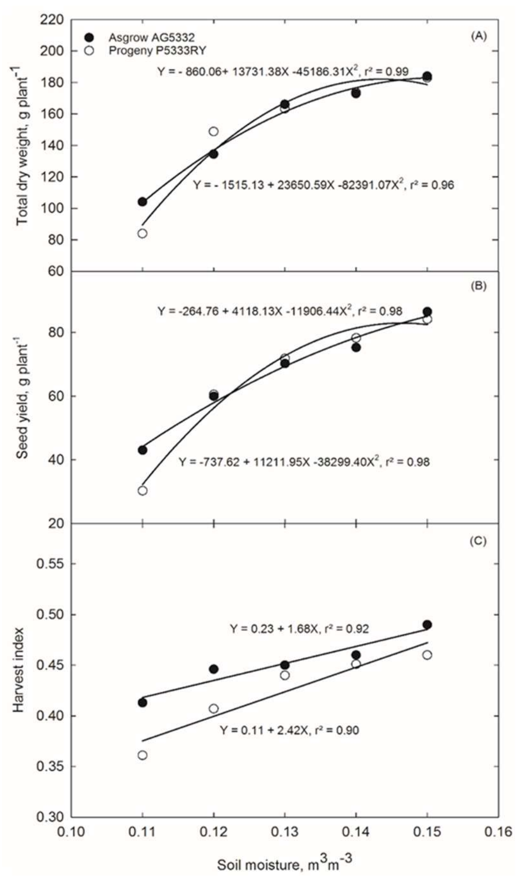
Temperature – Soybean Yield





Environmental Stresses and Crop Productivity

Soil Moisture Stress – Soybean Growth and Yield



- ❑ All the traits' values declined with soil moisture stress, including harvest index.

Optimum ⟷ Drought Stressed

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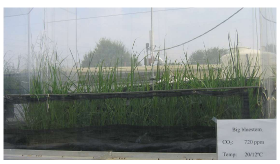
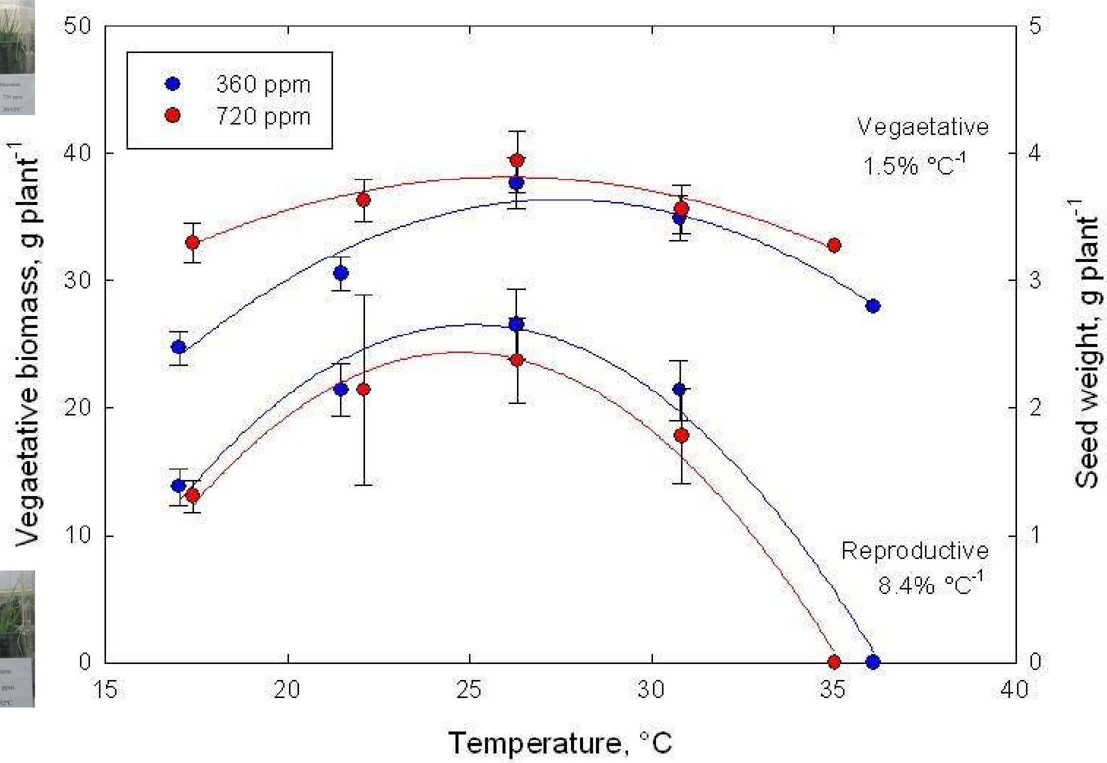
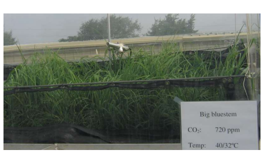
Environmental Stresses and Crop Productivity

Temperature and CO_2 – Rangeland C4 Grass – Big Bluestem



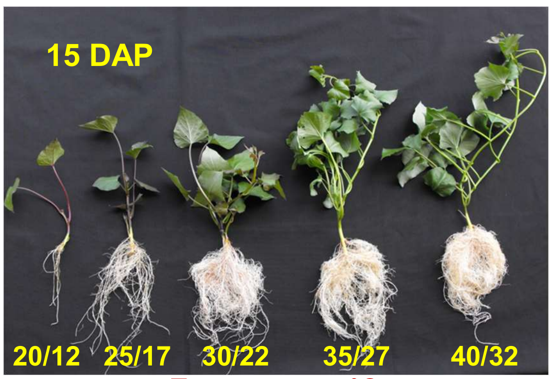
Vegetative Weight and Seed Weight





Environmental Stresses and Crop Productivity

Temperature and CO_2 – Tuberous Crops – Sweetpotato



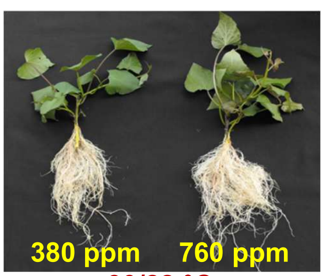
Temperature, °C

380 ppm

760 ppm

20/12 25/17 30/22 35/27 40/32

Temperature, °C



30/22 °C

Process	Temperature optima, °C	
	Ambient	Elevated
Total biomass	29.0	31.5
Storage root biomass	26.5	27.0

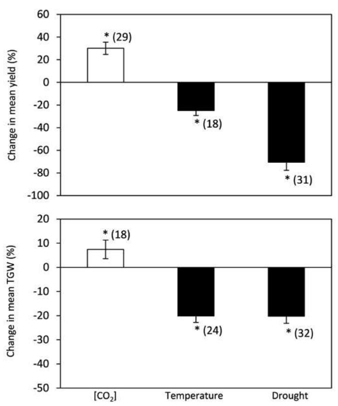
Similar to grain crops, bulking process was affected by high temperatures and thus lower yield.

Environmental Stresses and Crop Productivity
Soil Waterlogging and Corn Growth

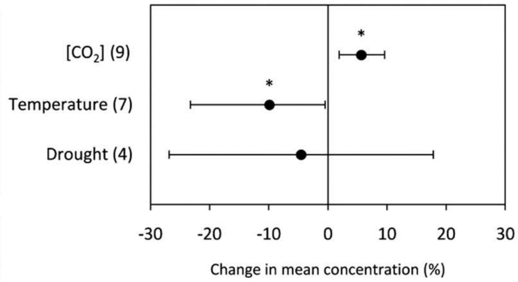
0 2 4 6 8 10 12 14
Days of Flooding

Atmospheric [CO_2] Grain & Yield Quality

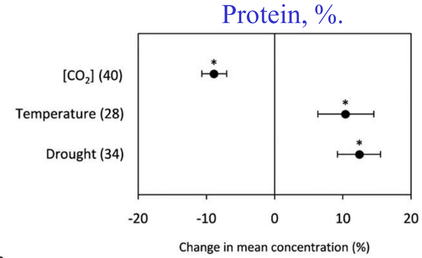
Yield and 1000 Grain wt.



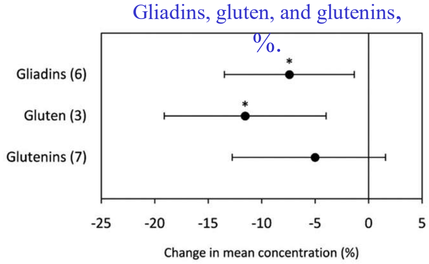
Starch, %.



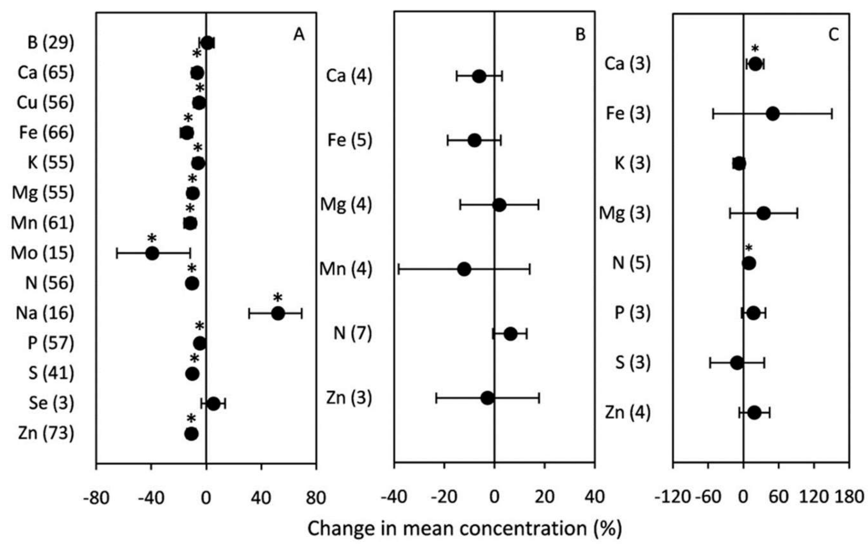
Protein, %.



Gliadins, gluten, and glutenins, %.



Minerals, %.



Citation: Ben Mariem, S.; Soba, D.; Zhou, B.; Loladze, I.; Morales, F.; Aranjuelo, I. Climate Change, Crop Yields, and Grain Quality of C3 Cereals: A Meta-Analysis of [CO2], Temperature, and Drought Effects. Plants 2021, 10, 1052. https://doi.org/10.3390/plants10061052

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Environmental Stresses and Crop Productivity
Genetic Variability

Let us peek into the current genetic variability among major crops to gain some perspectives

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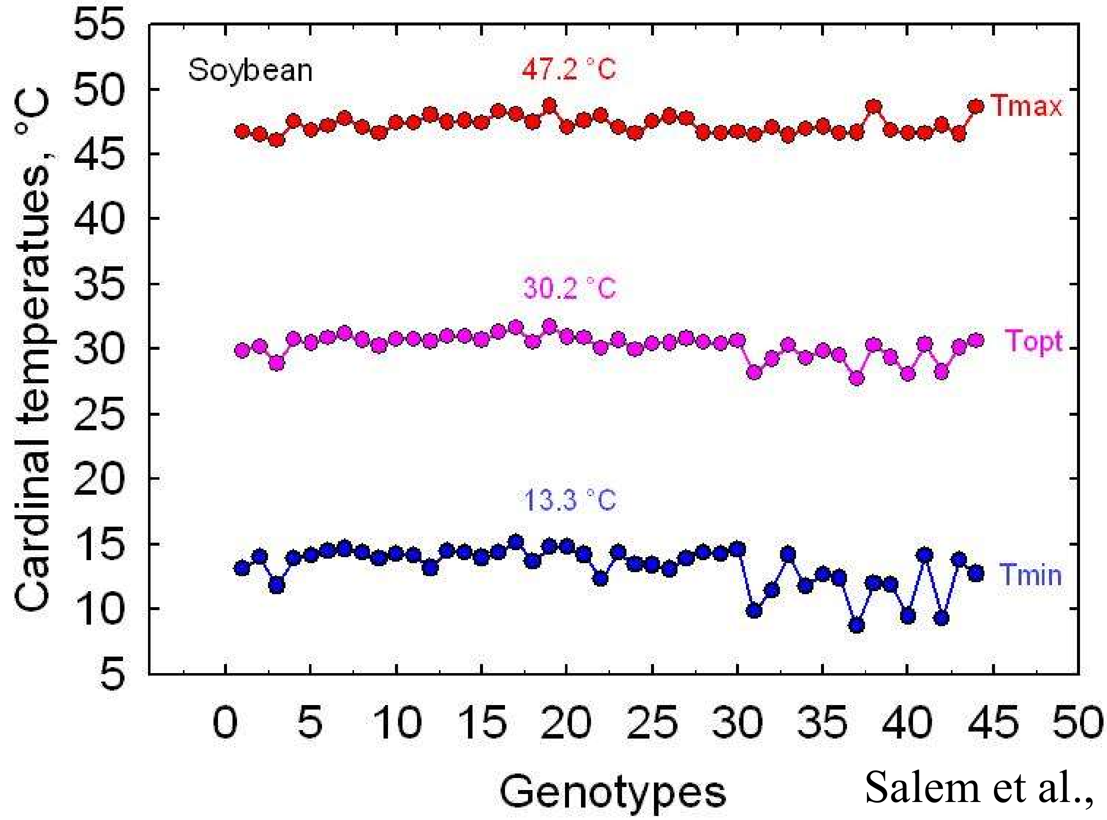
Environmental Stresses and Crop Productivity

Soybean – Pollen Germination – Cardinal Temperatures
Genotypic Variability



Salem et al., 2006

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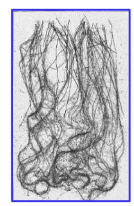
Rapid Screening of Rice Genotypes

Classification of 100 rice breeding lines based on cumulative drought response indices (CDSRI)

Very low tolerant CDSRI = (14.701-16.989)	Low tolerant CDSRI = (16.990- 19.278)	Moderate tolerant CDSRI = (19.279-21.567)	High tolerant CDSRI = (21.568-23.855)	Very high tolerant CDSRI = (23.856 <)
CHENIERE (14.701) CL Jazzman (15.397) LA 2008 (16.012) RU1504157 (16.662) RU1403126 (16.731) 5   50 % 100 %	JUPITER (17.001) RU0603075 (17.178) RU1504114 (17.181) 14CVPYT144 (17.251) . . . ANTONIO (18.865) RU1304114 (19.046) Bowman (19.062) IRGA409 (19.079) 14CVPYT094 (19.100) RU1504100 (19.195) CL151 (19.269) 28	RU1305001 (19.293) CL152 (19.314) LA 2134 (19.319) RU1302192 (19.425) RU1304122 (19.431) . . . Sabine (21.266) RU1204156 (21.314) RU1402189 (21.422) 14CLPYT108 (21.427) CLJZMN (21.457) RU1404122 (21.518) RU1201024 (21.526) RU1401161 (21.557) 45	RU1504193 (21.831) RU1401067 (21.884) RU1504156 (21.910) . . . Cocodrie (22.998) RU1402149 (23.074) LAKAST (23.076) Presidio (23.225) GSOR101758 (23.472) GSOR101758 (23.472) 16	INIA Tacuari (23.989) RU1402195 (24.527) CL163 (24.709) RU1401145 (25.376) N-22 (25.638) RU1402174 (27.955) 6   50 % 100 %

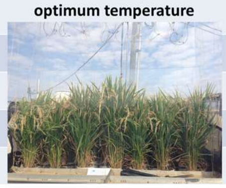
Variability = 14.7 to 27.9

Environmental Stresses and Crop Productivity
Temperature and CO_2 – Rice Yield

Variability = 1.43 to 2.09

Temperature tolerance groups of rice cultivars			
Heat sensitive	Moderately heat sensitive	Moderately heat tolerant	Heat tolerant
ANTONIO (1.43)	CL142-AR (1.62)	CL111 (1.80)	CLXL745 (1.99)
NIPPONBARE (1.49)	TO 517/8-4-9-5-1 (1.63)	R41104191 (1.82)	CL151 (2.07)
R41004197 (1.51)	REX (1.64)	XP753 (1.91)	CHENIERE (2.09)
CL162 (1.56)	N-22 (1.66)		
COLORADO (1.56)	TAGGART (1.68)		
CL152 (1.60)	BOWMAN (1.69)		
	R41104122 (1.72)		
	R41004053 (1.74)		
	MERMENTAU (1.77)		

21 rice cultivars grown at optimum temperature



CLXL745 at optimum temperature

CLXL745 at high temperature

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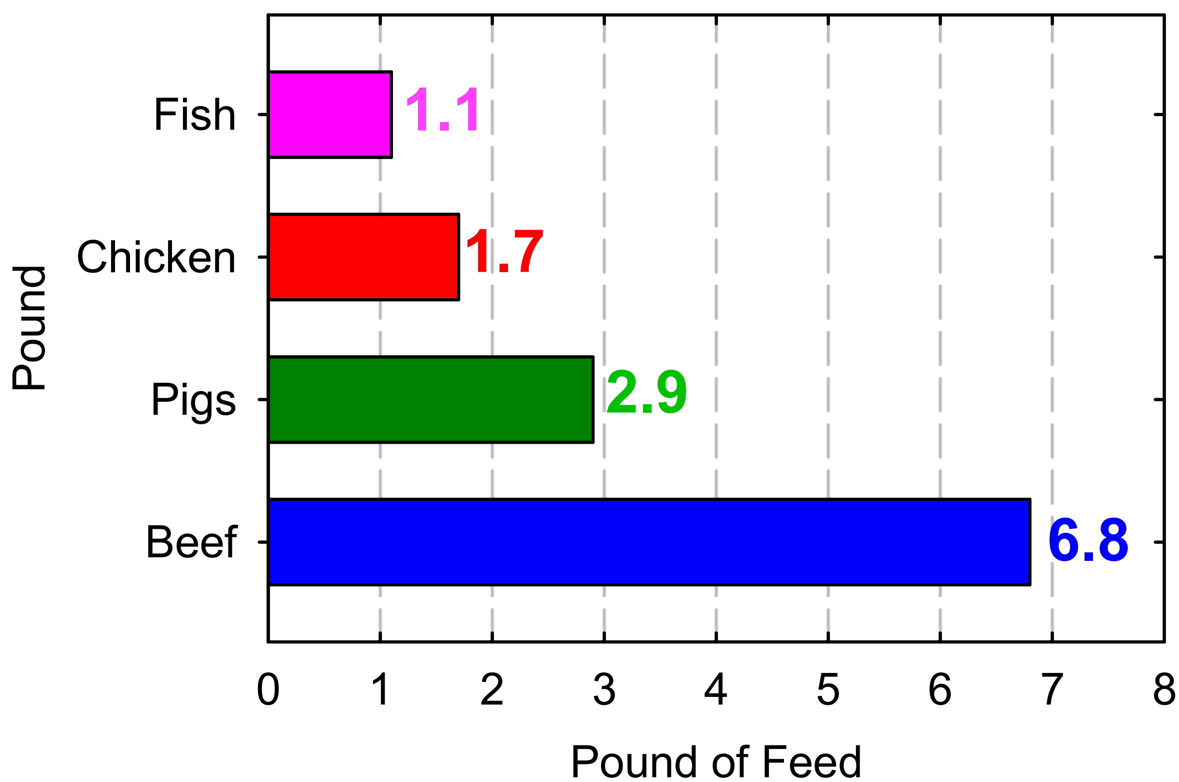
Some Solutions for the Hungry Planet

- Freeze the climate and agriculture footprint and halt agriculture expansion.
- Growing more on the farms and closing yield gaps on underperforming lands.
- Increasing cropping and resource use efficiencies.
- Shift diets.
- Reduce waste (1/3rd of the food produced is lost).
- Use all sources of technology to increase productivity.

Some Solutions for the Hungry Planet

Shift Diets – Feed Utilization efficiency



Some Solutions for the Hungry Planet

Shift Diets – Feed Utilization efficiency

- If we don’t know the long-term effects of human-induced changes on our climate, then, we shouldn't mess with it.
- For now, the long-term consequences are darn challenging to predict.
- We need to hand over the planet that we have given by the previous generation to the next generation, at least in the same shape and quality.

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Think about this?
We will be over 9.8 billion by 2050 and over 11.2 billion by 2100 in a much different climate than what we have today
We need to produce enough goods and have ecosystem services in a sustainable way
www.spar.msstate.edu

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Questions?

Thank You All