Incorporating CO_2 Responses into Crop Simulation Models

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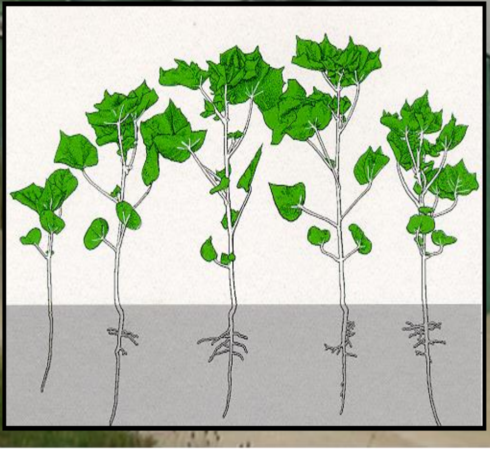
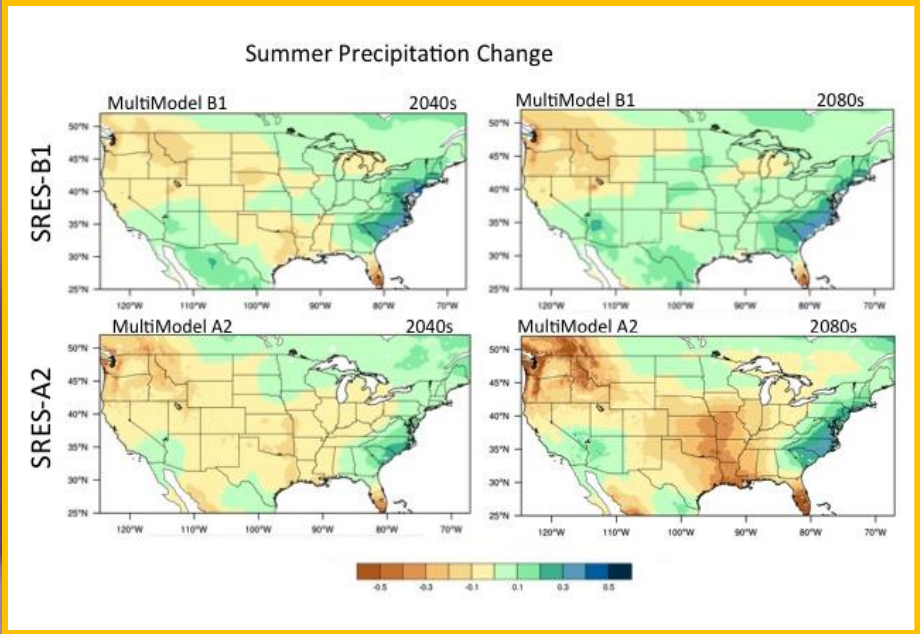
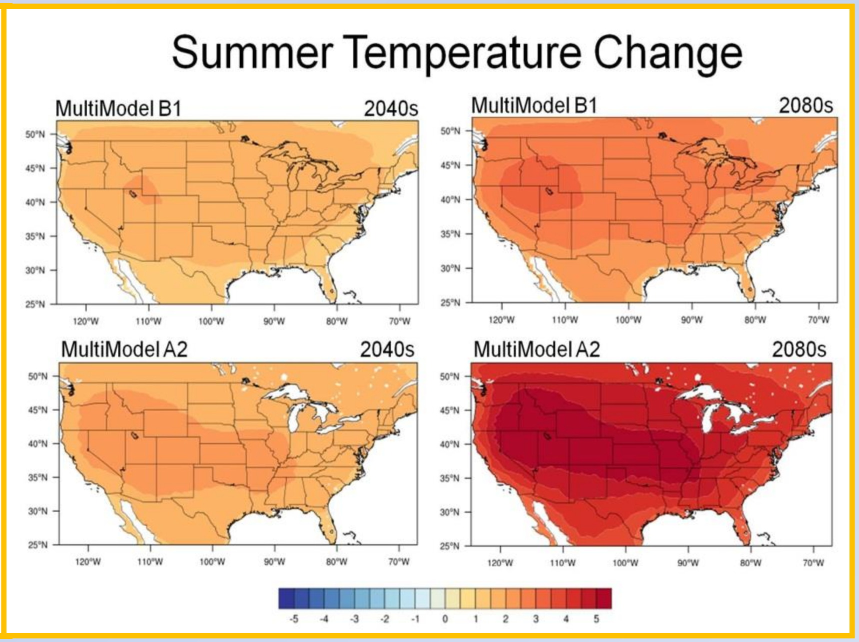


Changing Climate Conditions





- Temperature* increases: longer growing seasons, less frost, warmer nights
- Precipitation* changes: deficits, excesses, timing shifts, changing mix of rain/snow
- Increased intensity of precipitation events*: more flooding and more droughts
- Increasing carbon dioxide concentrations

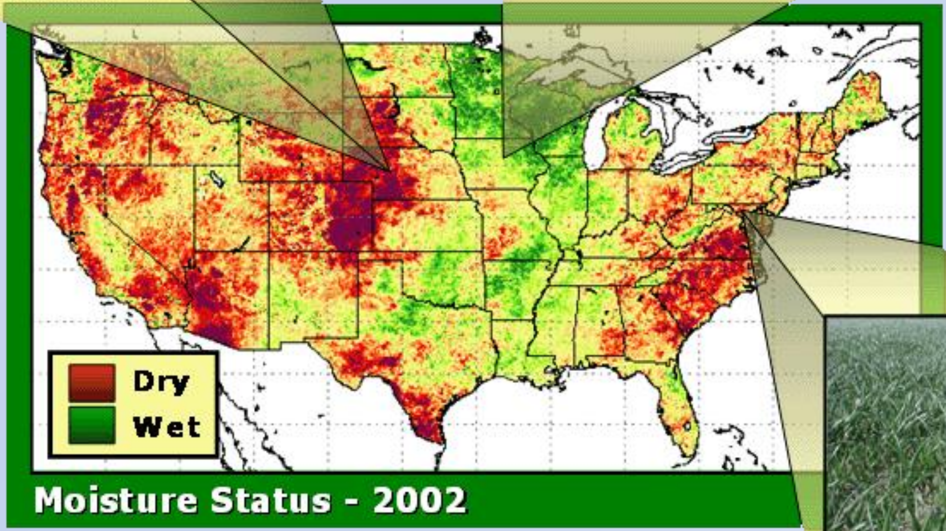
**Variability Increasing*

Source Dr. Charlie Walthall, USDA

Water

Drought

Too much, too fast?



Ground water & soil moisture recharge??

Source Dr. Charlie Walthall, USDA

Crop Modelling in the 21st Century

- Correct temperature and CO_2 responses in crop models are critical
- The crop models that are popular today were developed 20 to 30 years ago. Our understanding of crop physiology and the interaction with the environment is much different today.
- Models were largely engineering tools that captured the most important processes in a mechanistic approach but based on empirical large scale relationships.

Why Develop New Models?

- Many of the current models (DSSAT, EPIC, etc) rely on theories and data from 30-40 years ago
- Empirical and need calibration for any new situation
- New technologies provides better quantification of plant and soil processes
- Theoretical advances in our understanding of plant physiology and environmental physics

How does modeling help?

- It gives us the tools to increase crop yields sustainably
  - Improve resource use efficiency
  - Reduce the environmental footprint of agriculture
  - Investigate GxMxE interactions

Research to Support Simulation models

- There are several key processes that need to be studied in order to develop and test crop simulation models. These include
  - Leaf and canopy development
  - Photosynthesis
  - Reproductive development
  - Root growth
  - Water and nutrient uptake
- Relationships among these processes and nutrient/water stresses

Important Mechanisms for Modeling

- CO_2 content in the atmosphere and sunlight affect
  - the assimilation rate of carbon by a plant leaf, and
  - water relations.
- The magnitude of the response of plant growth to CO_2 depends on plant type (C_4 or C_3) and CO_2 level
- Elevated CO_2 concentrations result in reduced stomatal conductance and an increase in water use efficiency
- Photosynthesis is temperature dependent

Important Mechanisms for Modeling

- Temperature affects growth rate and phenology
- Respiration can be increased or decreased by temperature
- High temperature can increase the rate of plant development and result in a shorter growing season due to early maturity
- Temperature effects on growth are nonlinear

State of the Knowledge

- We know that temperature effects on growth are non-linear. Less is known regarding:
  - the optimums as especially affected by CO_2
  - The mathematical forms of the relationships
- The effect of CO_2 on biomass and yield is often conflicting but often, with C3 plants, increases have been reported. However little is known regarding:
  - the magnitude of daily carbon assimilation rates under different conditions
  - Transpiration under different conditions (water stress, temperature)
  - C3 vs C4 plants

Knowledge Gaps in Crop Models

- Goals:
  - Improve understanding of photosynthesis and canopy development in response to water and temperature stresses, and CO_2
- Approach:
  - Conducted experiments in SPAR facilities to evaluate T, CO_2, H_2O, N, influences

SPAR chambers: “soilbins”

Soil-Plant-Atmosphere-Research Chambers

18 SPAR chambers:

6 Daylits

12 Soilbins

SPAR chambers:

-T, CO_2, RH, irrigation

-Whole plant H_2O and CO_2 fluxes

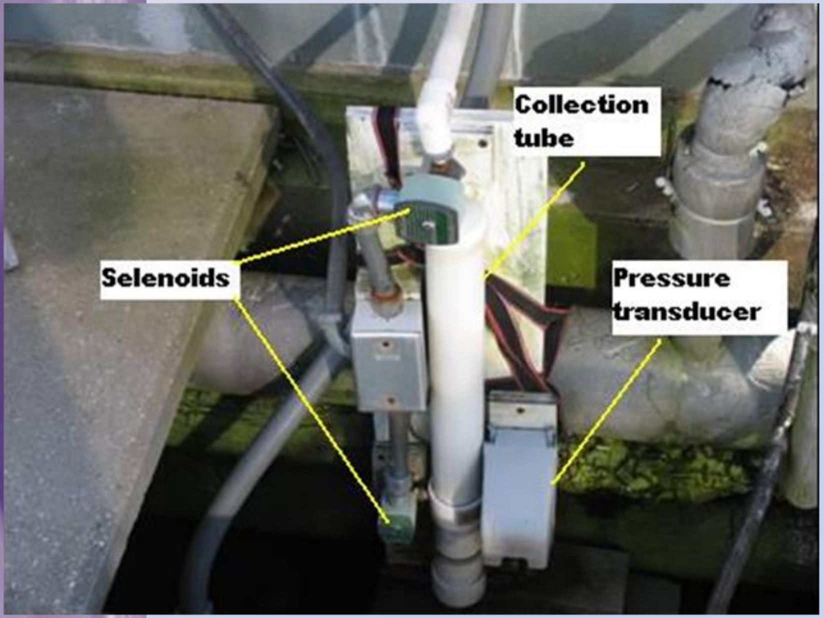
Goal:

Develop process level understanding and modeling of crop responses (Corn, cotton, potato, soybean, wheat, melon) to climate, management, and soil conditions.

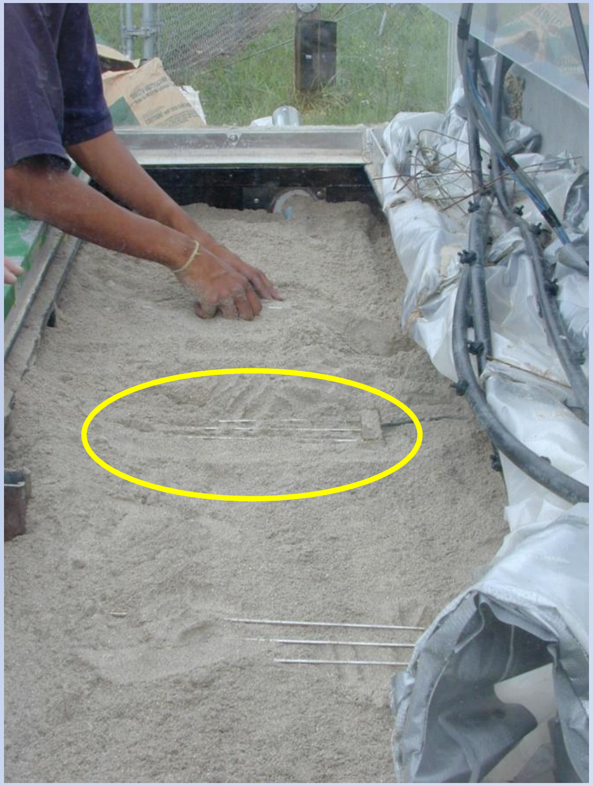
Characteristics of Outdoor Controlled Environment Chambers

- Use natural sunlight and soil volume (larger units)
- Control and monitor aerial and soil environments
- Monitor whole canopy gas exchange (Photosynthesis, Respiration, Transpiration)
- Measure gas leakage rates with a N2O system to maintain accuracy

Evaporation and Transpiration Measurements



Condensate from the cooling coils is collected every 15 minutes

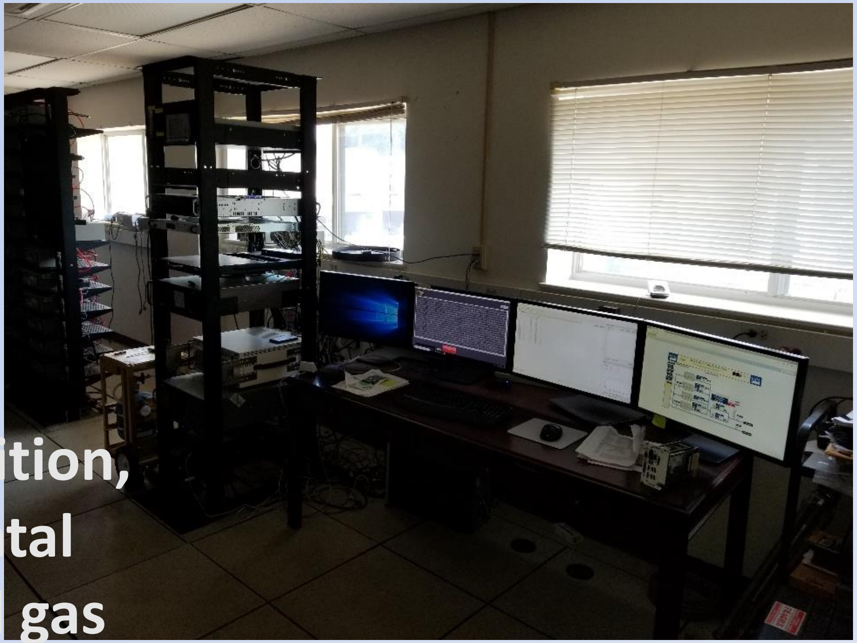


15 Time domain reflectometry waveguides are installed at 5 depths in the soil bins to measure water content

Data Acquisition System

CO2 and temperature monitoring/control

Monitoring and control



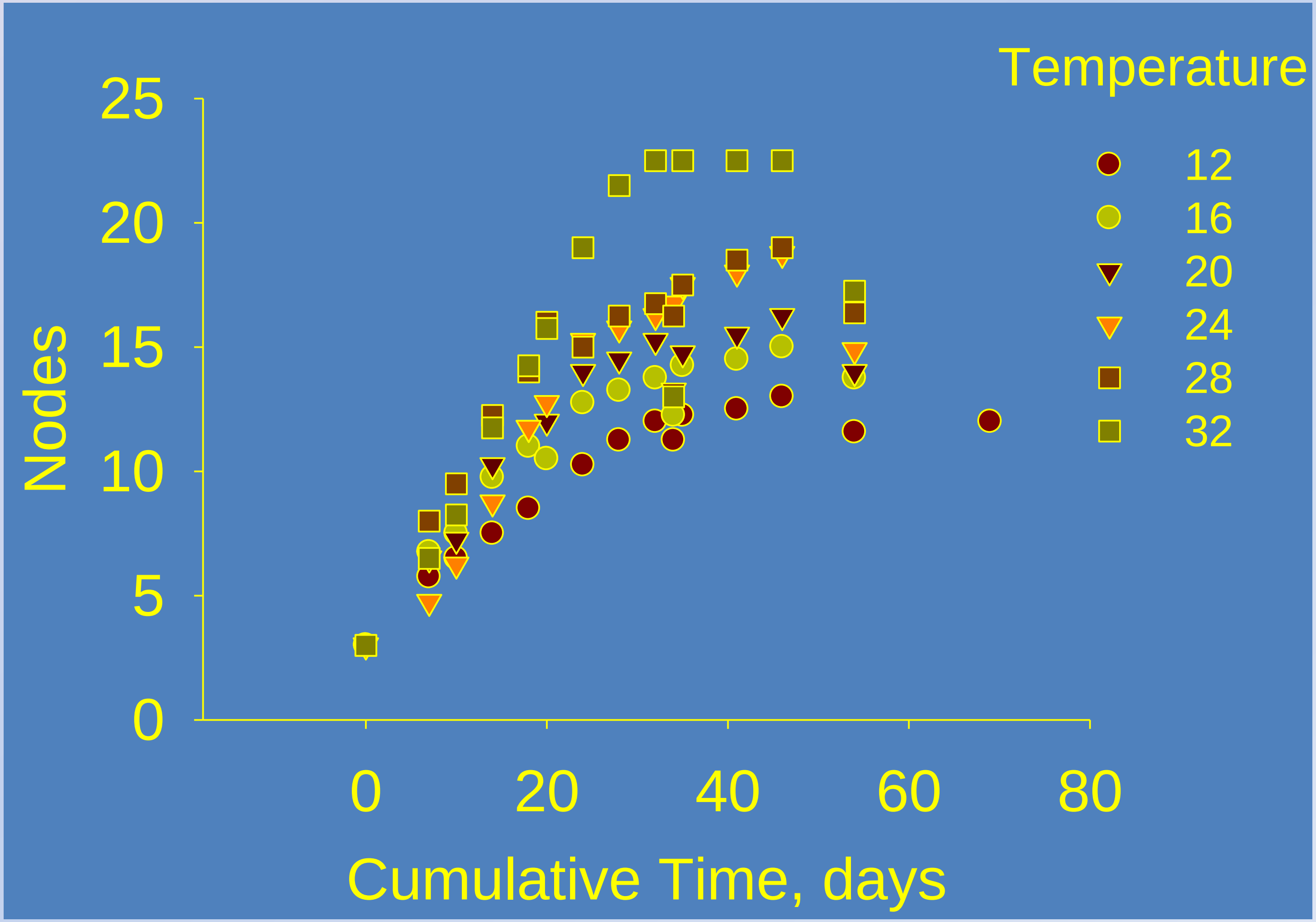
- Data acquisition, environmental control, and gas analysis system for SPAR chambers.

Field Work is Still Important

Instrumentation

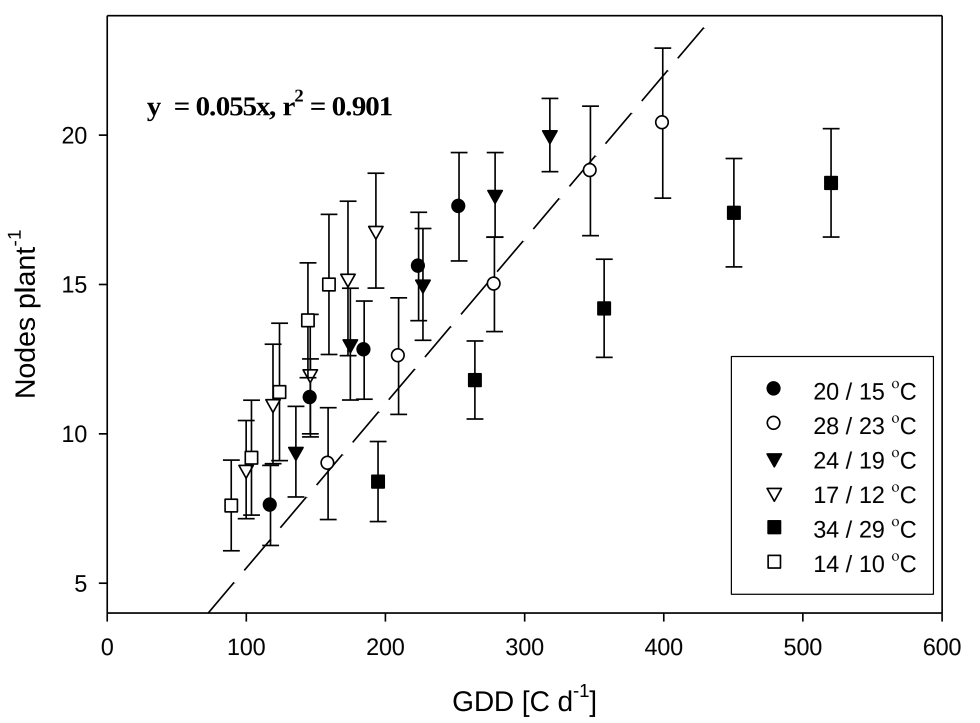
TEMPERATURE RESPONSE

Quantifying Leaf addition Rate in Potato as a Function of Temperature



Thermal Time Approach

- Phyllochron should remain constant regardless of T if between max and min values:



Pooled data from 6 temperature treatments in daylit chambers:

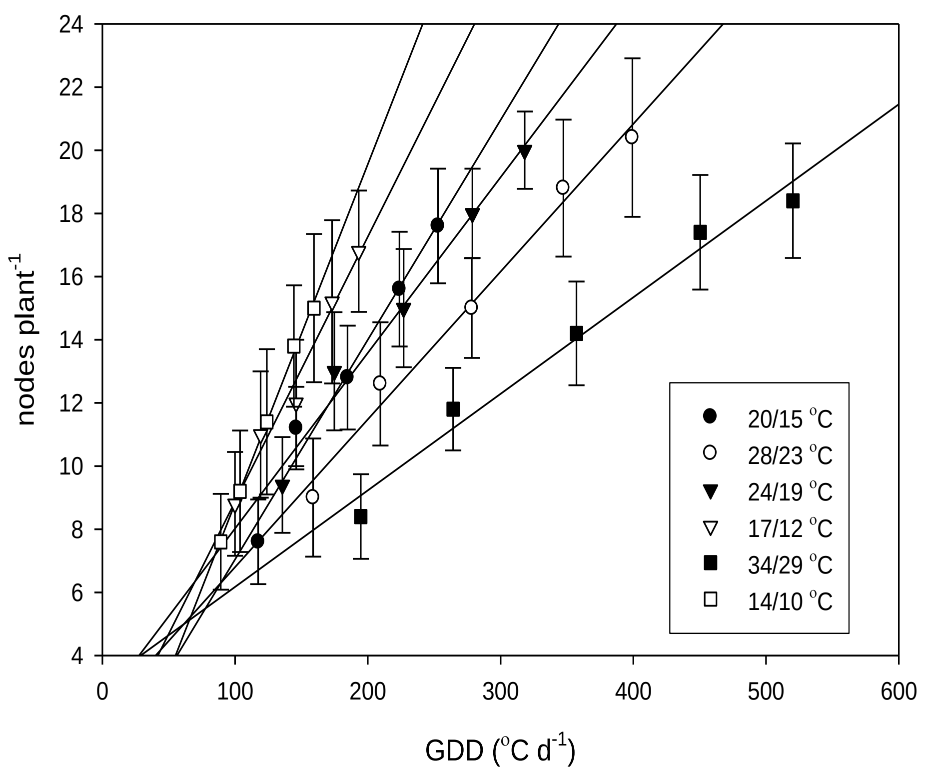
14/10, 17/12, 20/15,
24/19, 28/23, 34/29

Phyllochron = 18.2 GDD_8 leaf^{-1}

Note: Published phyllochrons with 0 base T range from 28.2 to 31.4 at base 0C (28.0)

Thermal Time Approach

- What happens if we don’t pool the data?



Separated treatment data:

	phyllochron*
14/10	10.8
17/12	11.5
20/15	14.3
24/19	15.2
28/23	18.6
34/29	26.0

* slopes are statistically different from one another

Non-linear temperature dependence vs thermal time (GDD)

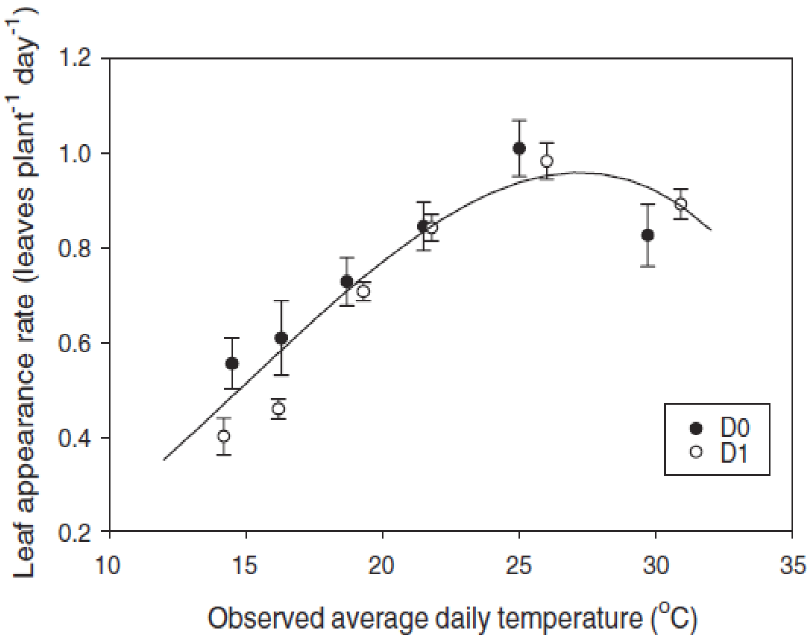


Fig. 1. Leaf appearance rates with standard errors vs. observed average daily temperature for experiments D0 and D1. The nonlinear temperature response model based on the modified β distribution parameters (Table 3) is shown as the solid line.

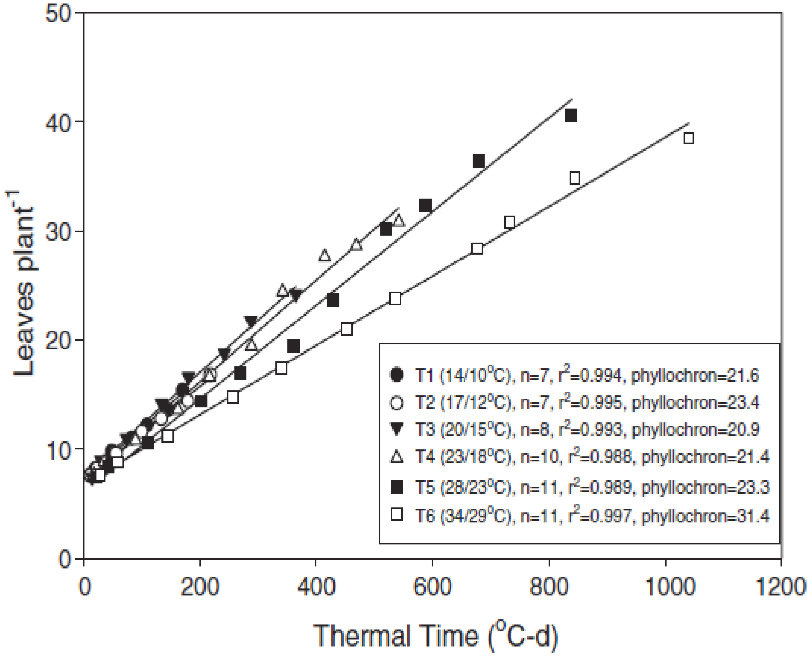
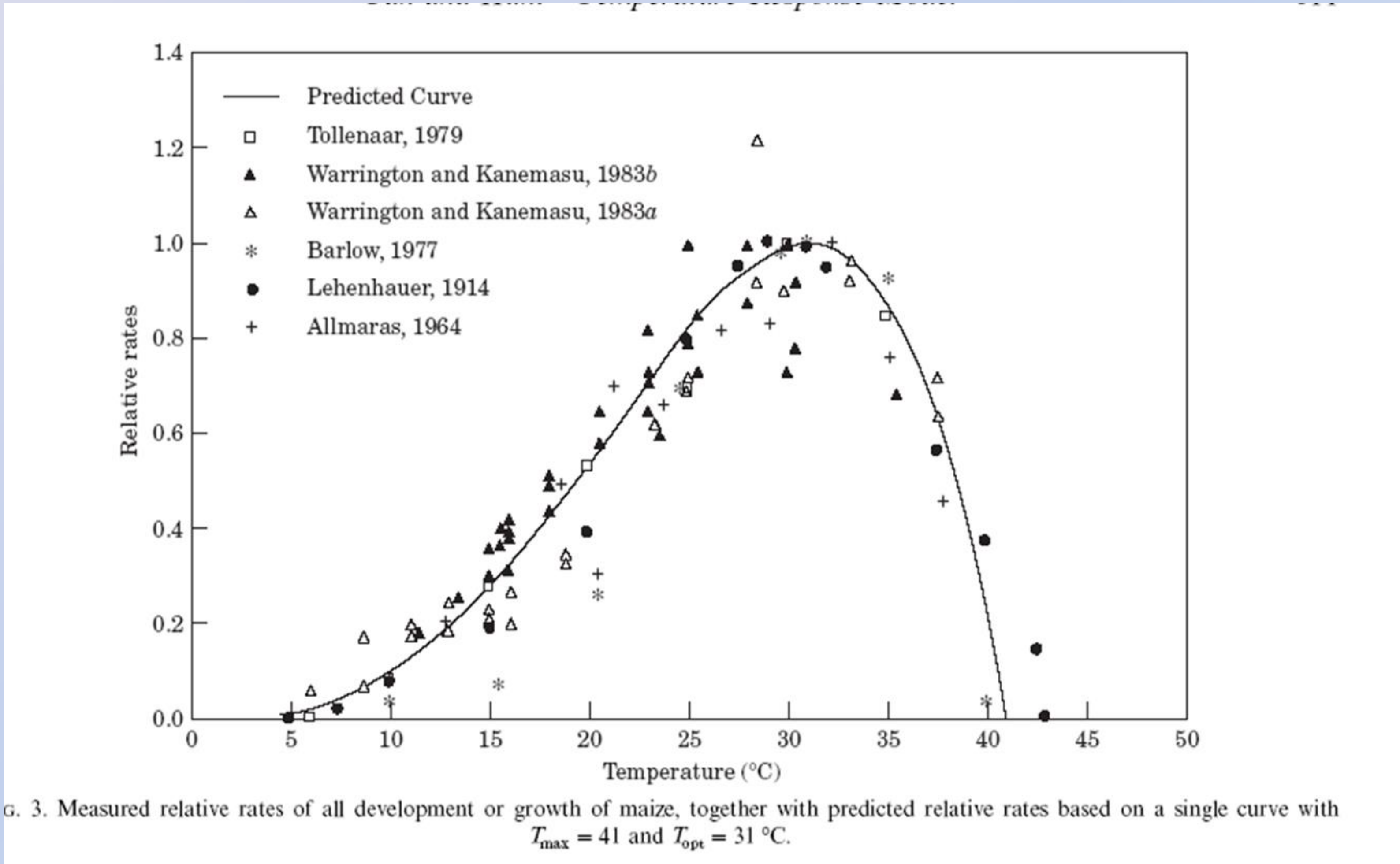


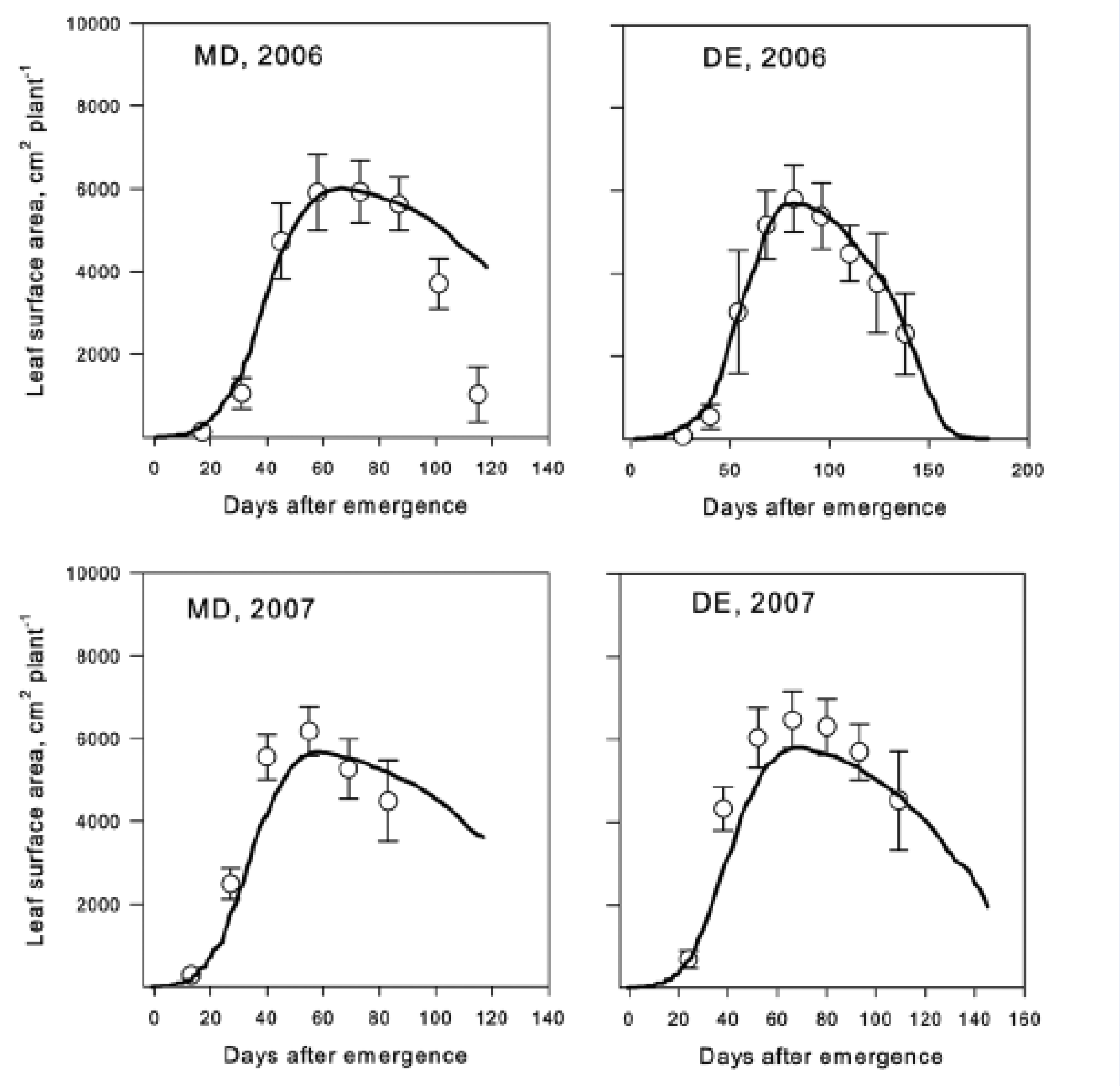
Fig. 3. Leaf appearance data separated for each temperature treatment (T1 through T6) in experiment D1. Data points are the averaged value of five observations at each measurement date (error bars not shown for clarity).

Beta function for maize leaf addition rate is consistent over a large number of studies



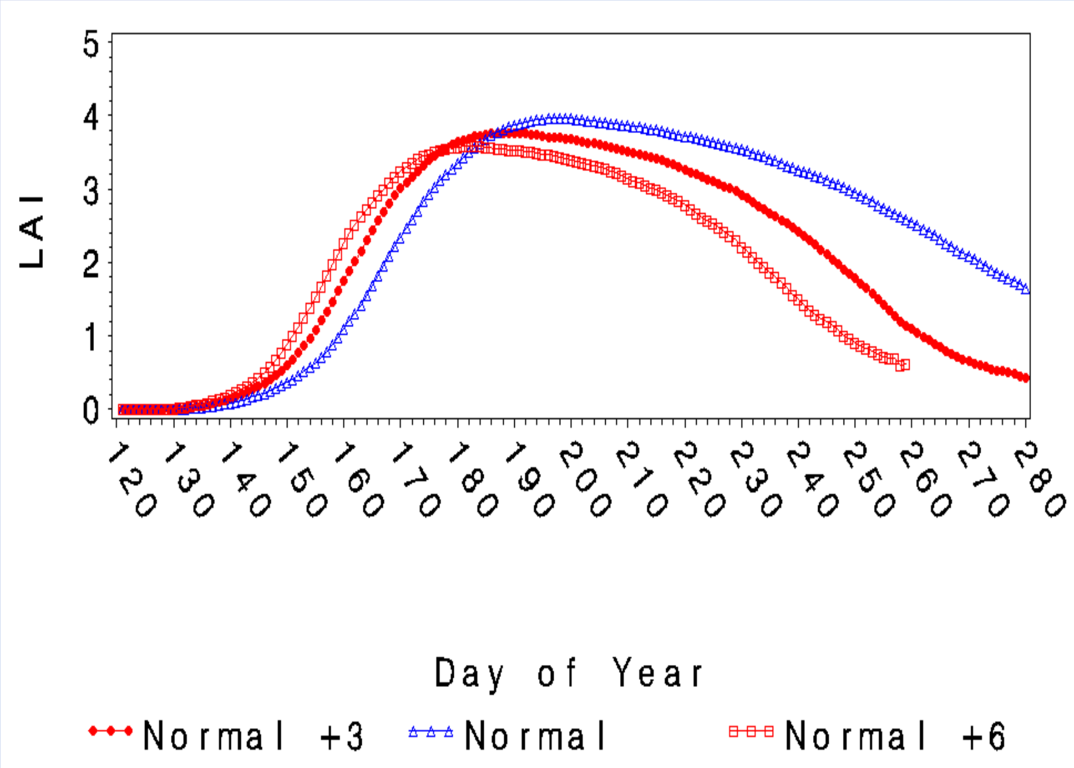
G. 3. Measured relative rates of all development or growth of maize, together with predicted relative rates based on a single curve with $T_{max} = 41$ and $T_{opt} = 31$ °C.

MAIZESIM Calculated Leaf Area for Field Data



Effect of increased temperature on development processes

1. Exposure to higher temperatures will cause faster rate of development
2. This doesn't translate into maximum production because shorter life cycle creates smaller plants, shortened reproductive duration, and reduced yield potential because of reduced light interception during the growing season.
3. At higher temperatures plant leaves grow and age faster.

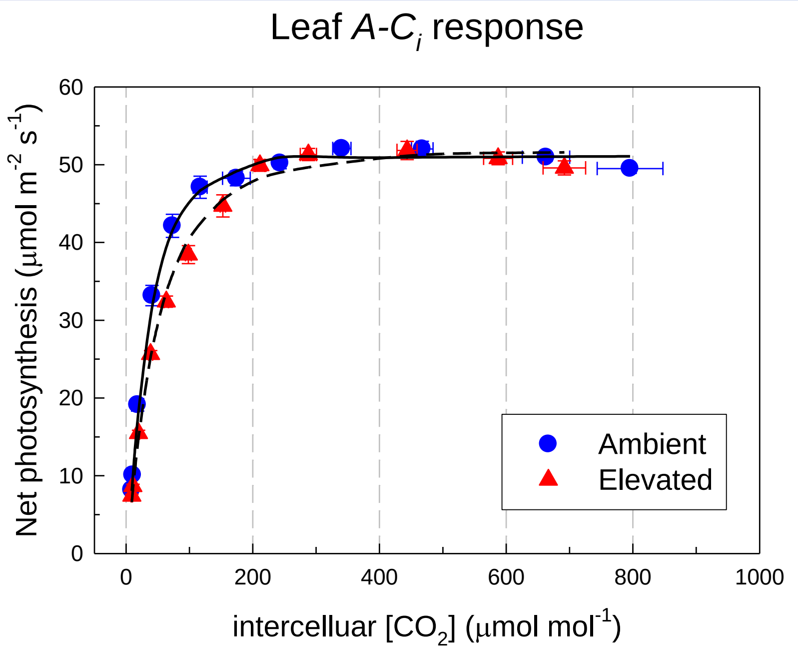


This figure shows the decrease in the lifetime of a corn crop as temperature increases. LAI is Leaf Area Index, leaf area per unit ground area.

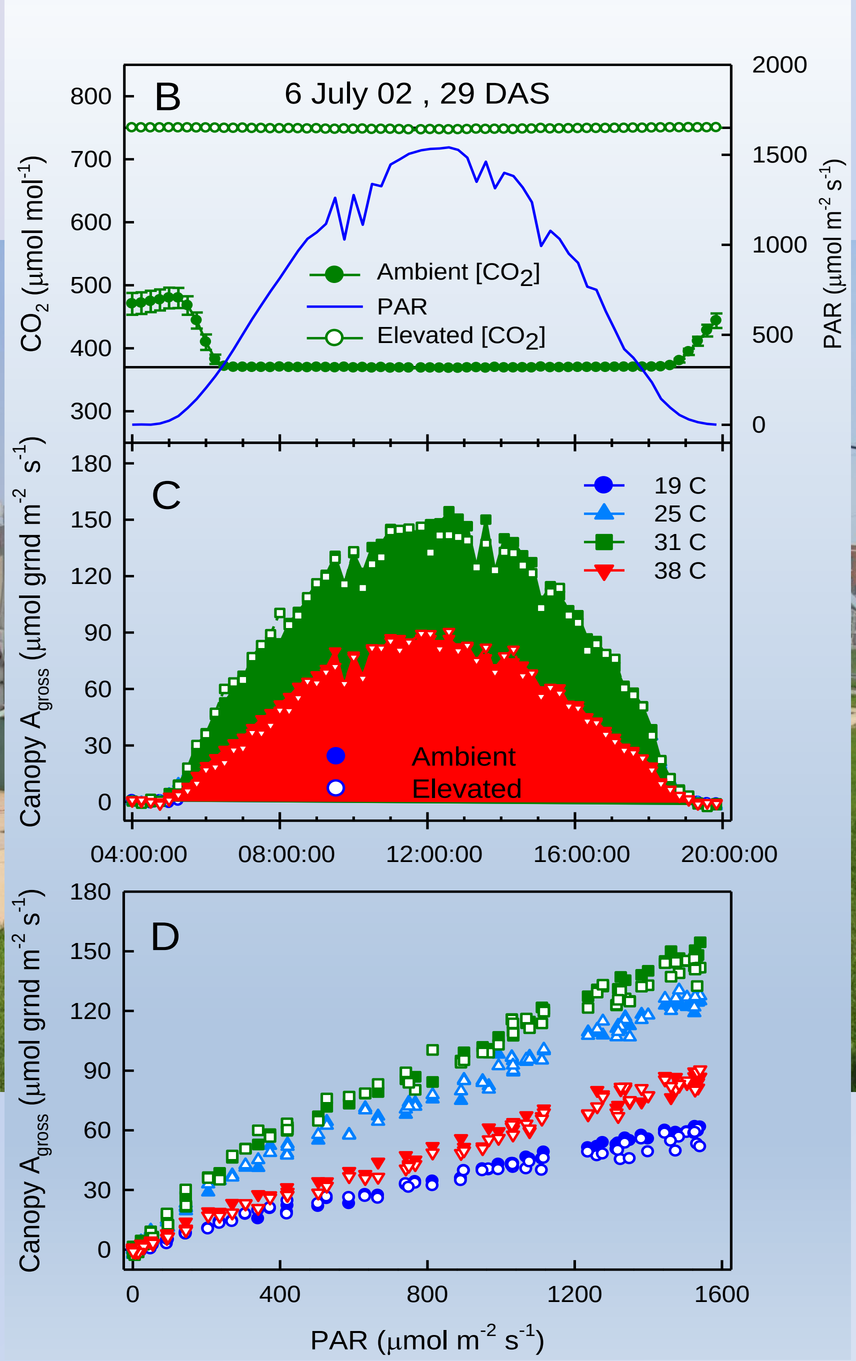
PHOTOSYNTHESIS AND WATER

Carbon assimilation rate in corn (C$_4$) in a leaf

C$_4$ - corn

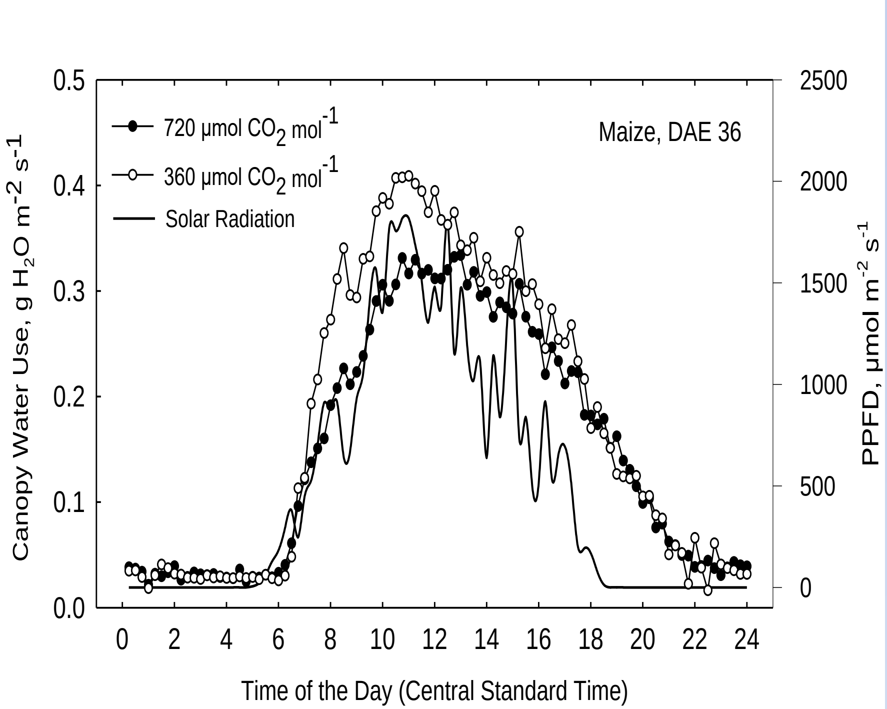


Temperature response of photosynthesis



Maize response – CO_2

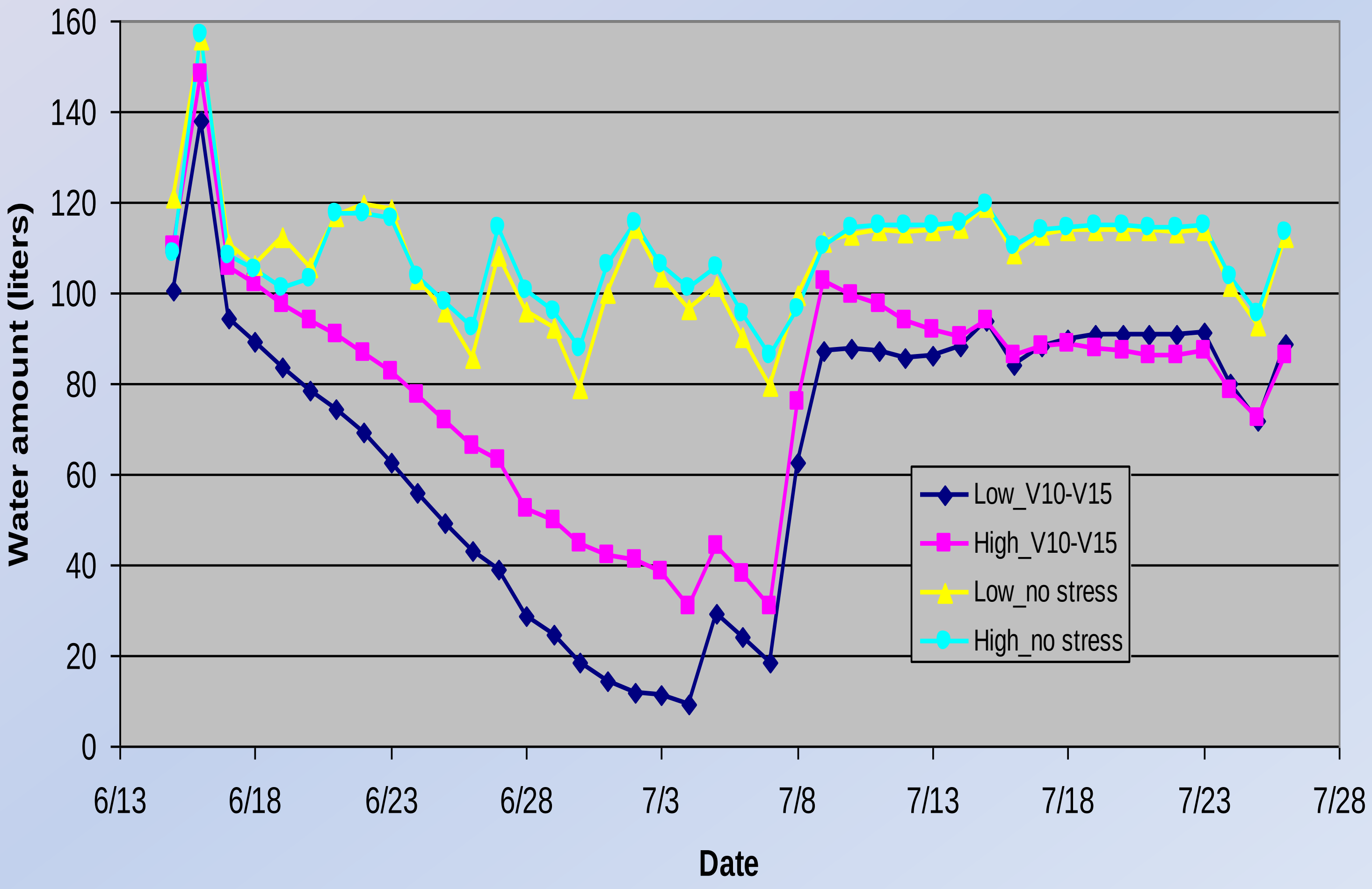
- ☐ Canopy Evapotranspiration (Diurnal, DAE 36)



- ☐ Reduced ET rates under elevated CO_2
- ☐ Daily and season WUE higher with elevated CO_2

Adapted from: Kim, S.-H., Sicher R.C., Bae H., Gitz, D.C., Baker, J.T., Timlin, D.J. and Reddy. V.R. Canopy photosynthesis, evapotranspiration, leaf nitrogen, and transcription profiles of maize in response to CO2 enrichment. Global Change Biol. 12:588-600. 2006.

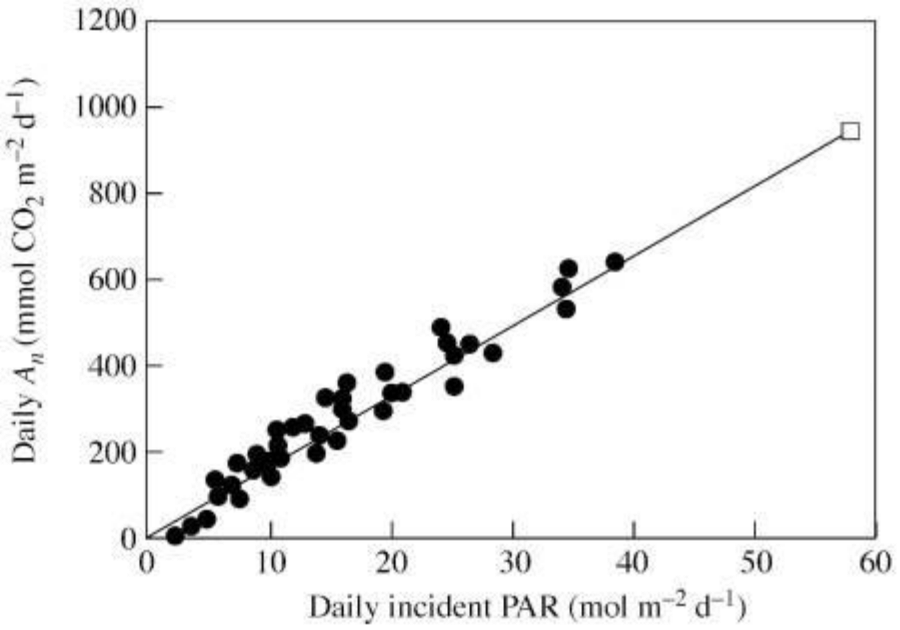
Water Uptake by Corn



PHOTOSYNTHESIS MODELS

Radiation Use Efficency

- Simple to use
- Temperature and CO2 dependence are added empirically
- Varies with vapor pressure density
- Often requires calibration for different locations

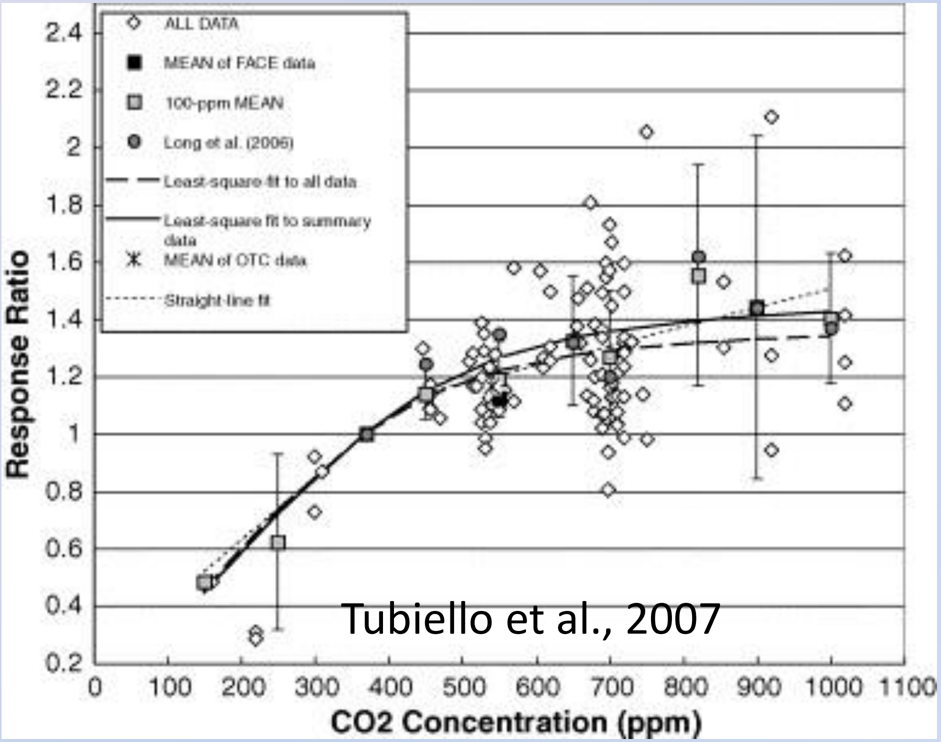


Rosati, A., et al. (2004). "A Simple Method to Estimate Photosynthetic Radiation Use Efficiency of Canopies." Annals of botany **93(5): 567-574.**

Models for Plant Response to CO_2

- Farquhar biochemical model of gas exchange
- Scaling CO_2 response in a radiation use efficiency equation

Simple approach – scale CO2 response



Tubiello et al., 2007

- This can be applied to a light response curve or to Radiation Use Efficiency (Mg C MJ^{-1} light)

Model for Leaf Gas-Exchange

- Biochemical demand for CO_2
  - C_4 (von Caemmerer and Furbank, 1999) and C_3 Photosynthesis model (Farquhar and von Caemmerer, 1981)
- Physical supply of CO_2
  - Stomatal conductance model Ball, Woodrow and Berry (1987)
- Transpiration and leaf temperature: Penman’s linearized energy budget equation

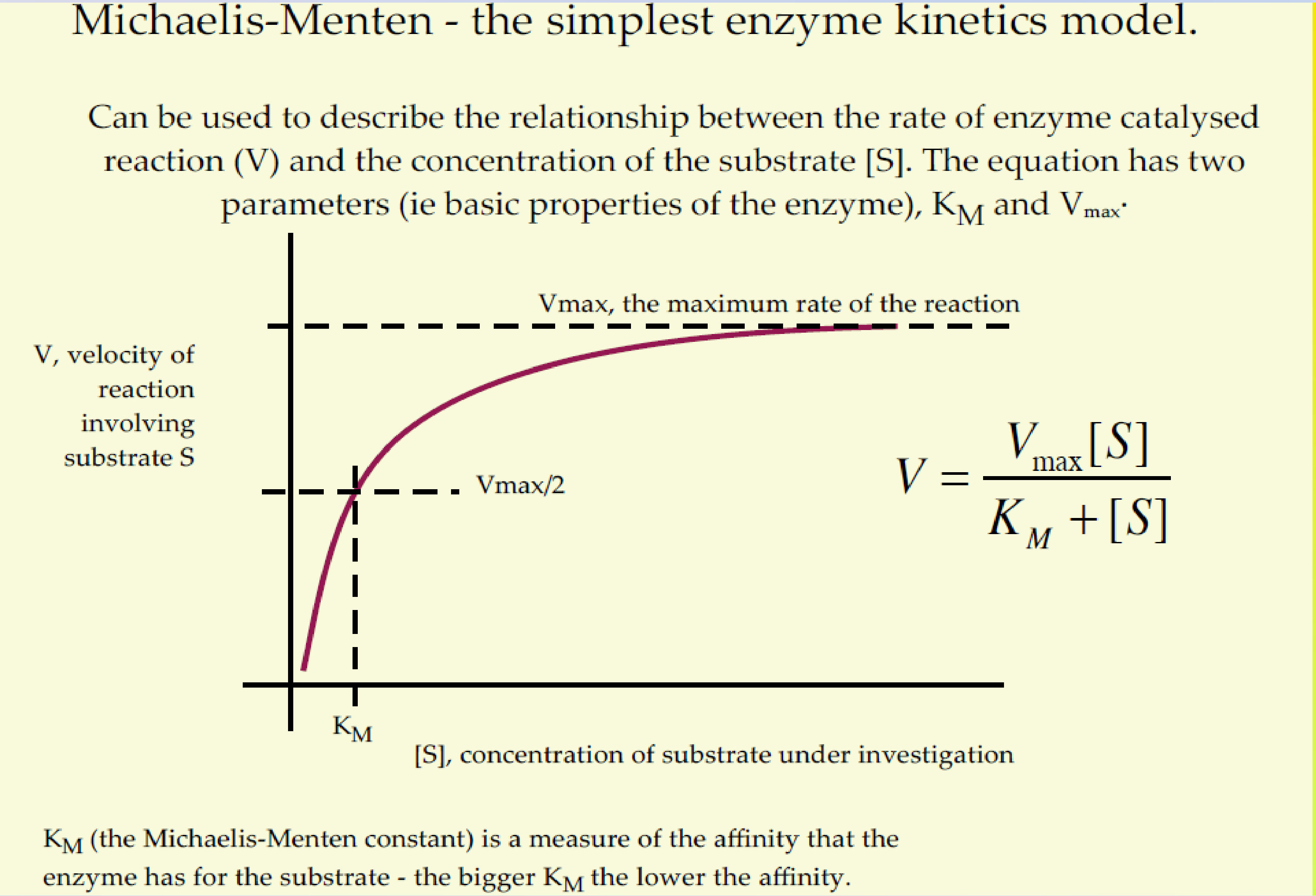
Model components (processes) to simulate photosynthesis

- Photosynthesis (carbon assimilation): response to PAR, CO_2 and temperature
- Conductances and transpiration: response to vapor pressure deficit and wind.
- Canopy radiative transfer: response to sun angle, and canopy size/structure

Dependent Variables

- Light intensity [PAR umol m^{-2} s^{-1} photons]
- CO_2 Concentration [umol CO_2 mol^{-1} air]
- Temperature [°C]
- Relative humidity – vapor pressure deficit [kPa]
- Nitrogen [mg gr^{-1}]
- Leaf water status [kPa water potential]

Farquhar - von Caemmerer - Berry (FvCB) model (C_3)



Michaelis-Menten - the simplest enzyme kinetics model.

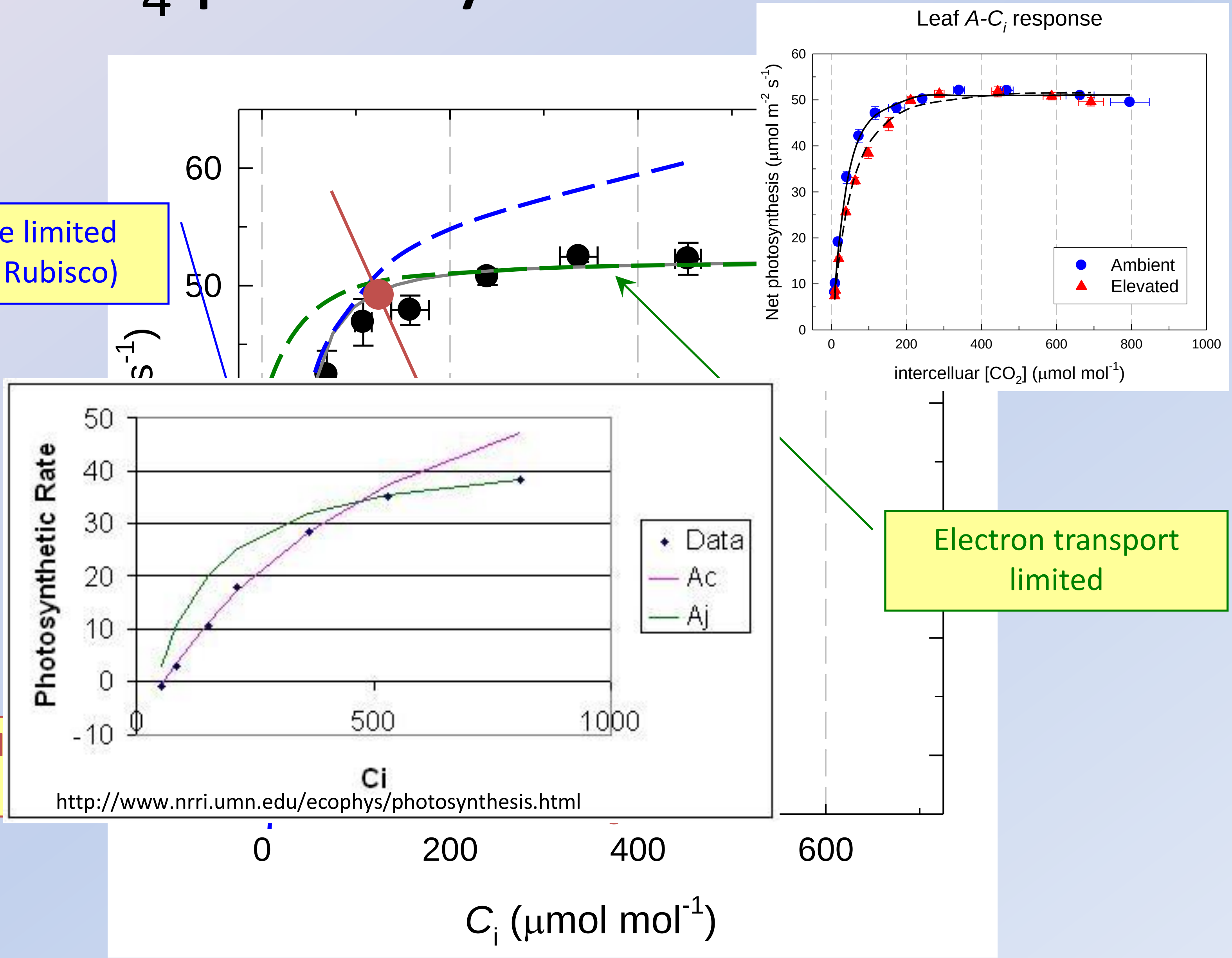
Can be used to describe the relationship between the rate of enzyme catalysed reaction (V) and the concentration of the substrate [S]. The equation has two parameters (ie basic properties of the enzyme), K_M and V_{max}.

$$V = \frac{V_{\max}[S]}{K_M + [S]}$$

K_M (the Michaelis-Menten constant) is a measure of the affinity that the enzyme has for the substrate - the bigger K_M the lower the affinity.

Source:
http://www.tbi.univie.ac.at/~raim/harvest/workshop.brno/presentations/harbinson.pdf

C_4 photosynthesis model



http://www.nrri.umn.edu/ecophys/photosynthesis.html

Enzyme limited (PEPC, Rubisco)

Electron transport limited

Physical

2. Stomatal Conductance and Water Relations

Stomatal conductance

- Ball, Woodrow, Berry (1987)

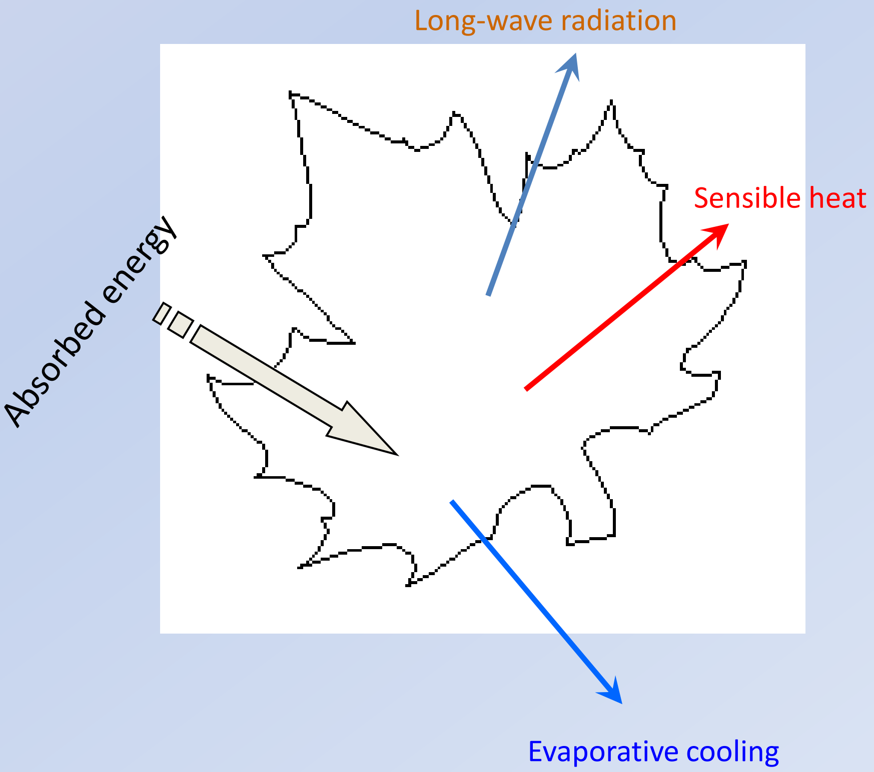
$$g_s = b + \boxed{m}(Ah_s/C_s)$$

  - g_s: stomatal conductance for water vapor
  - b, m: empirical coefficients
  - A: net CO_2 assimilation rate
  - h_s: relative humidity at leaf surface
  - C_s: leaf surface $[CO_2]$
- Requires photosynthetic rate (A) as input
- Lacks stomatal response to water stress

3. Energy balance equation

$$R_{abs} = L + H + \lambda E$$

- R_{abs}: Absorbed radiation
- L: Long-wave radiation
- H: Sensible heat loss
- λE: Latent heat loss (evaporative cooling)

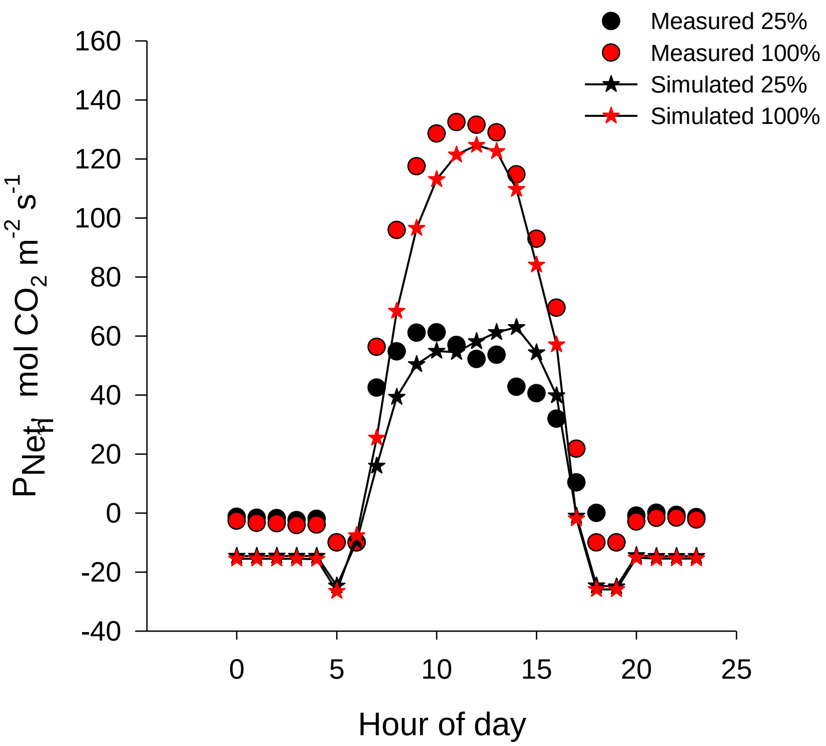


Coupled gas exchange model

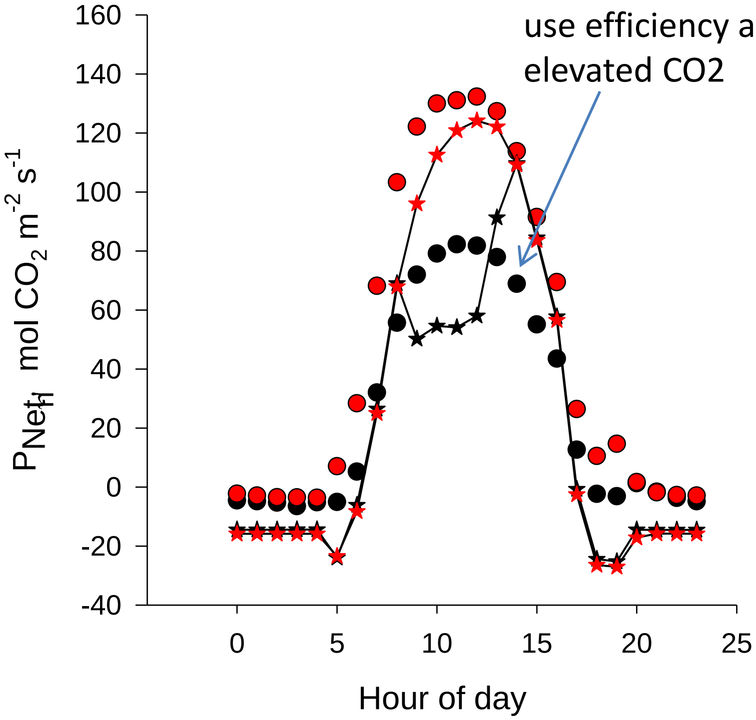
- Component models are coupled numerically which requires iteration.
- Scaling up to canopy
  - Sunlit and shaded leaf class method
- Validation
  - Tested against independent data

Simulation of Canopy Photosynthesis Response to Water Stress and CO_2 in Corn

400 ppm

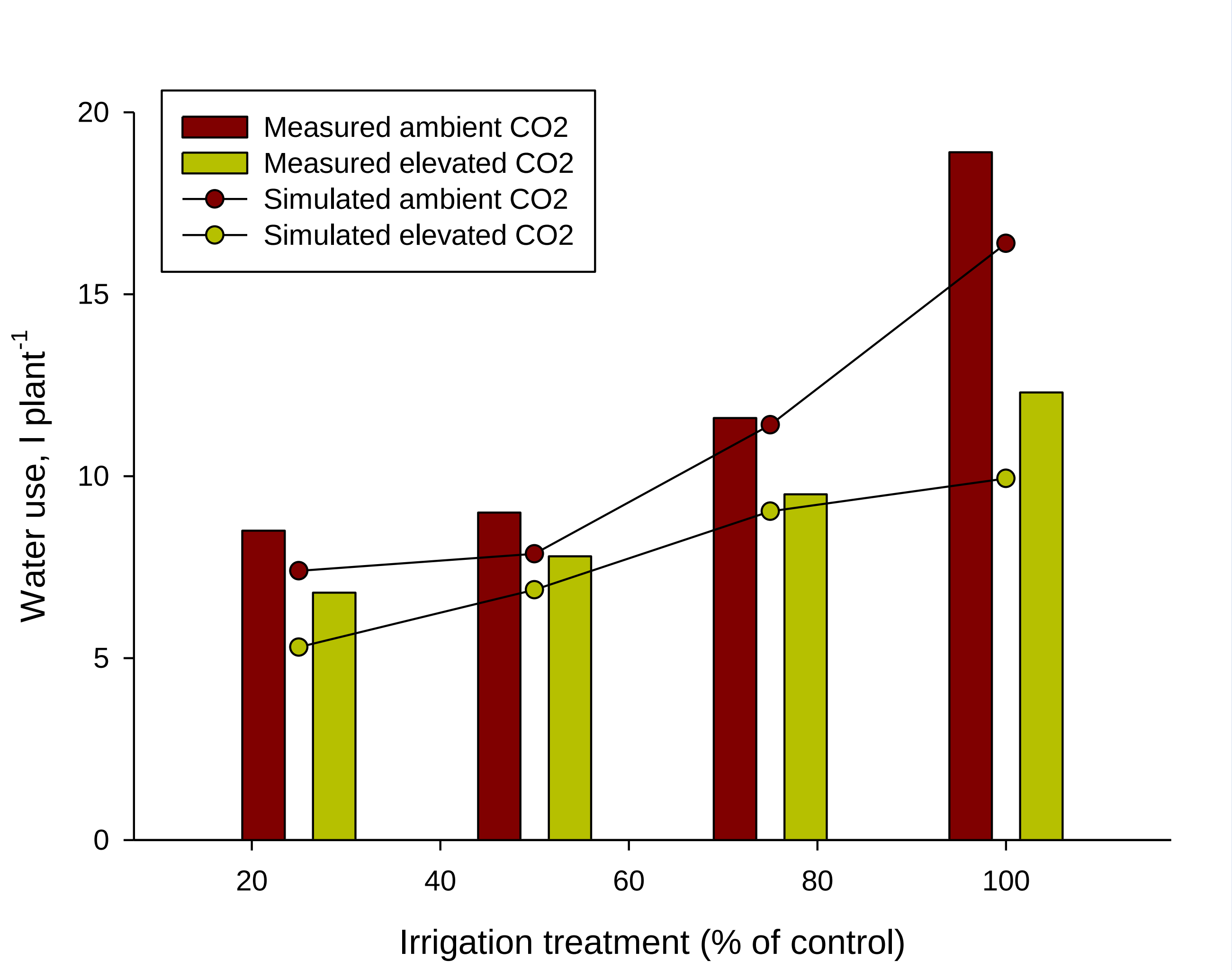


800 ppm



Improved water use efficiency at elevated CO2

Water Use, Observed and from Simulations with SPAR Environment Data



Simulation Results - Yield and Water Use No Irrigation

Temperature	Grain Yield Kg/ha		Transpiration mm		Water in Soil, mm	
	CO$_2$					
	amb	elv	amb	elv	amb	elv
Normal	10.2	14.5	471.1	417.1	40.7	63.9
+3 C	8.0	11.9	456.3	412.7	53.2	68.0
+6 C	6.5	9.9	429.7	400.4	50.9	62.9

With Irrigation

Temperature	Grain Yield Kg/ha		Transpiration mm		Water in Soil, mm	
	CO_2					
	amb	elv	amb	elv	amb	elv
Norm	14.9	15.2	609.8	430.5	51.7	68.9
+3 C	12.5	12.8	613.3	434.8	61.6	73.0
+6 C	10.8	11.0	610.5	433.5	60.6	67.7

Summary and Conclusions

- Temperature effects on growth are non-linear
- Temperature dependent rates are best modeled using a non linear function such as a beta-function
- GDD are sensitive to the mean growth temperature during the measurement period.

Summary and Conclusions

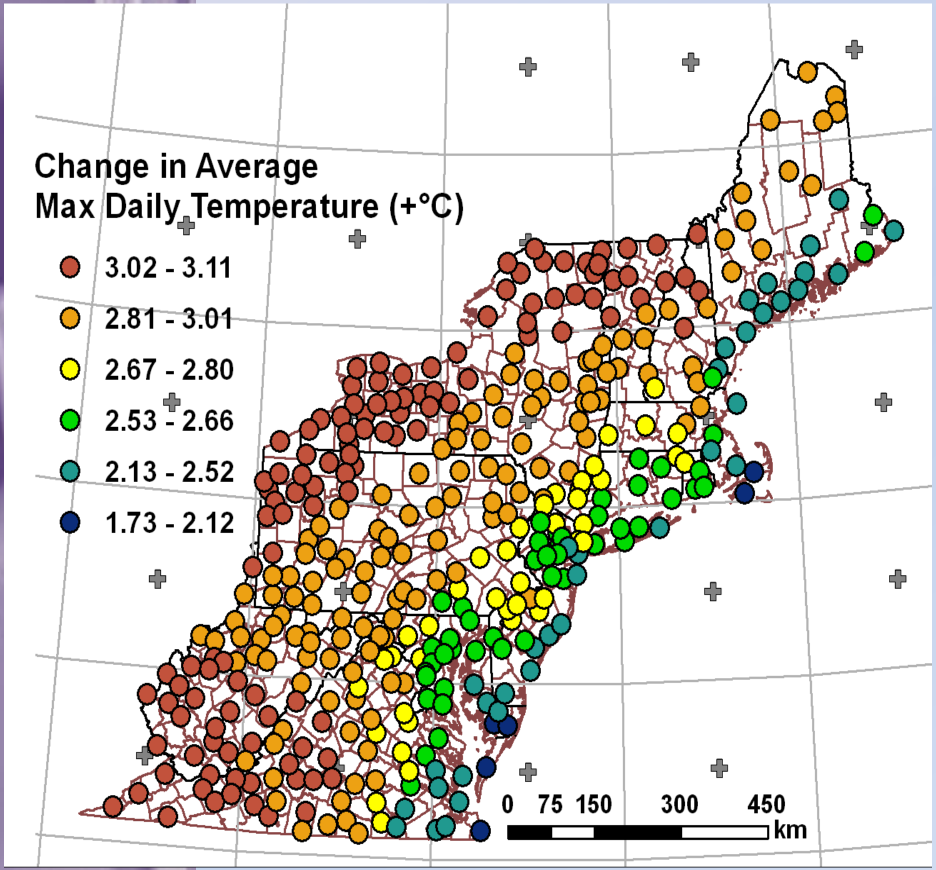
- A biochemical model of photosynthesis is a useful approach to modeling the effects of elevated CO_2 on photosynthesis
- Parameters can be fit with data from leaf gas exchange equipment but fitting the parameters has some numerical problems
- Mechanisms for adaptation by leaves to CO_2 are missing.

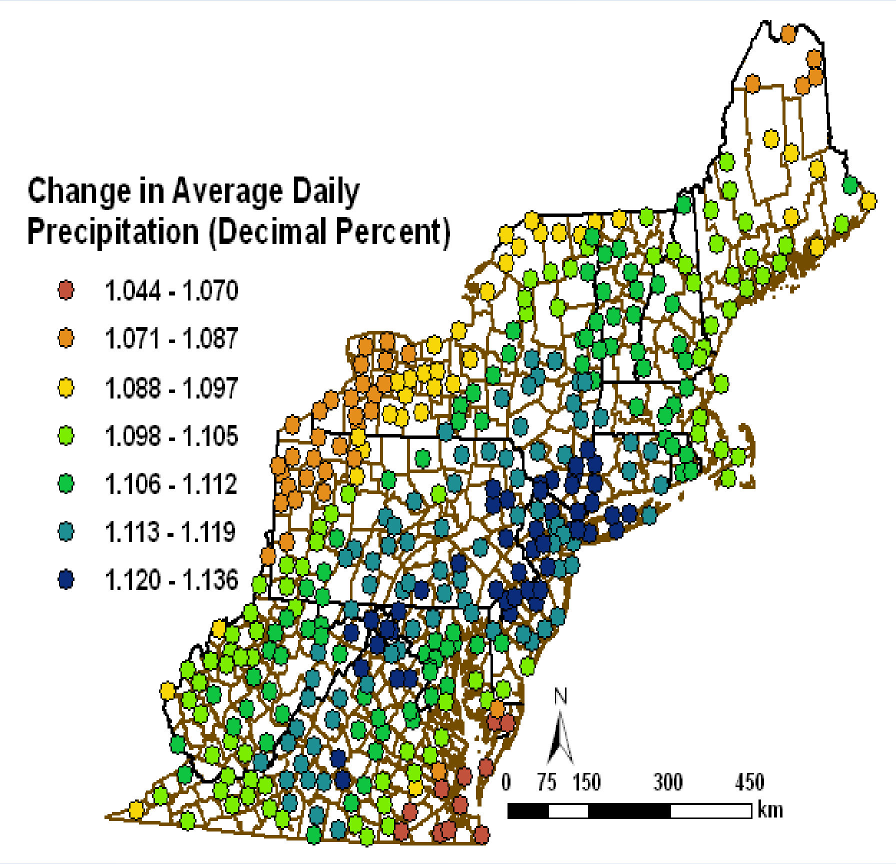
Summary

- Growth chamber research is an important tool to better incorporate temperature and CO2 effects into crop models in a mechanistic manner.
- Allows measurements at fine time scales
- Good separation of temperature and water effects (also nutrients).

Case study 3 – ESR & Climate Change

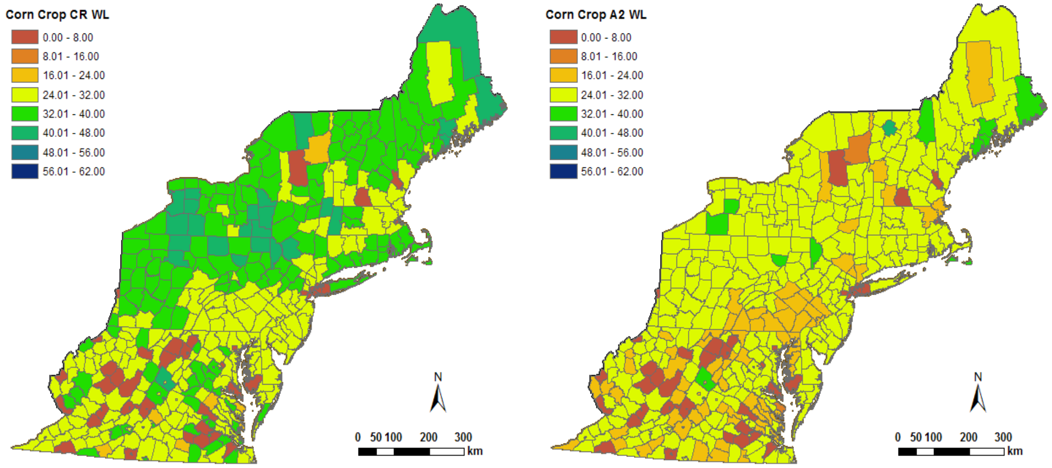
- GCM data downscaled using IDW method to the NOAA CLIGEN parameters
- Future predictions are averaged over the time frame 2050 to 2080
- Climate Scenarios = A2 (Focus on Economic Development, High CO_2 ~600 ppmv)





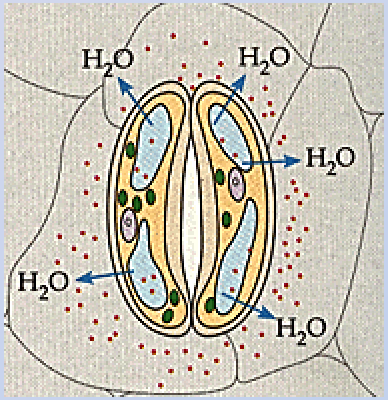
Projected Impacts - 3

- Corn crop-land: Current vs A2



Percent Yield Declines	
Corn	
State	WL->A2
ME	-23
VT	-24
RI	-20
NH	-19
MA	-20
CT	-19
NY	-21
PA	-20
NJ	-18
MD	**-17**
DE	-14
WV	-22
VA	-17
MEAN	**-20**

THANK YOU!



Applying Systems Theory

To Complex

Agricultural Problems