Incorporating CO2 Responses into Crop Simulation Models

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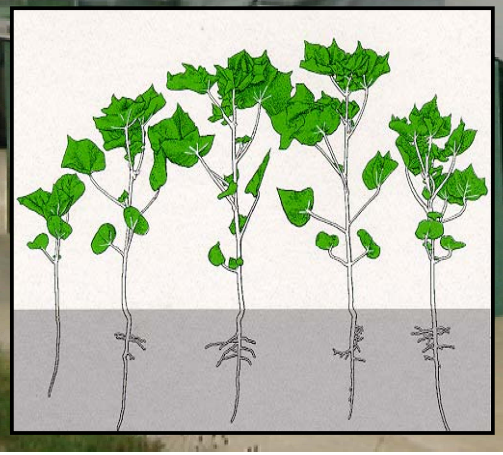


Important Mechanisms

- CO_2 content in the atmosphere and sunlight affect the assimilation rate of carbon by a plant leaf.
- 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

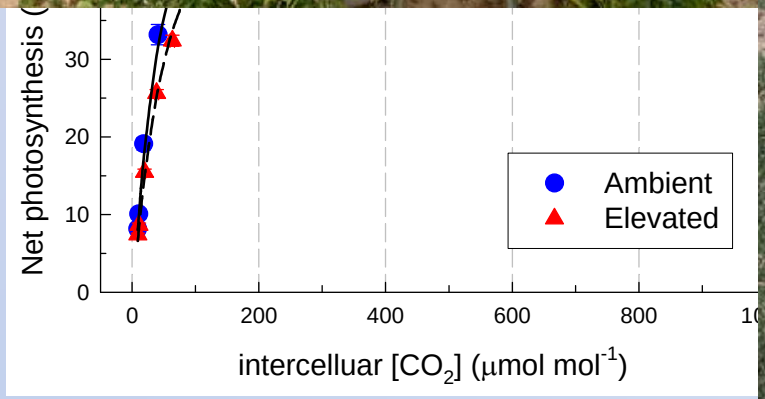
Input Variables

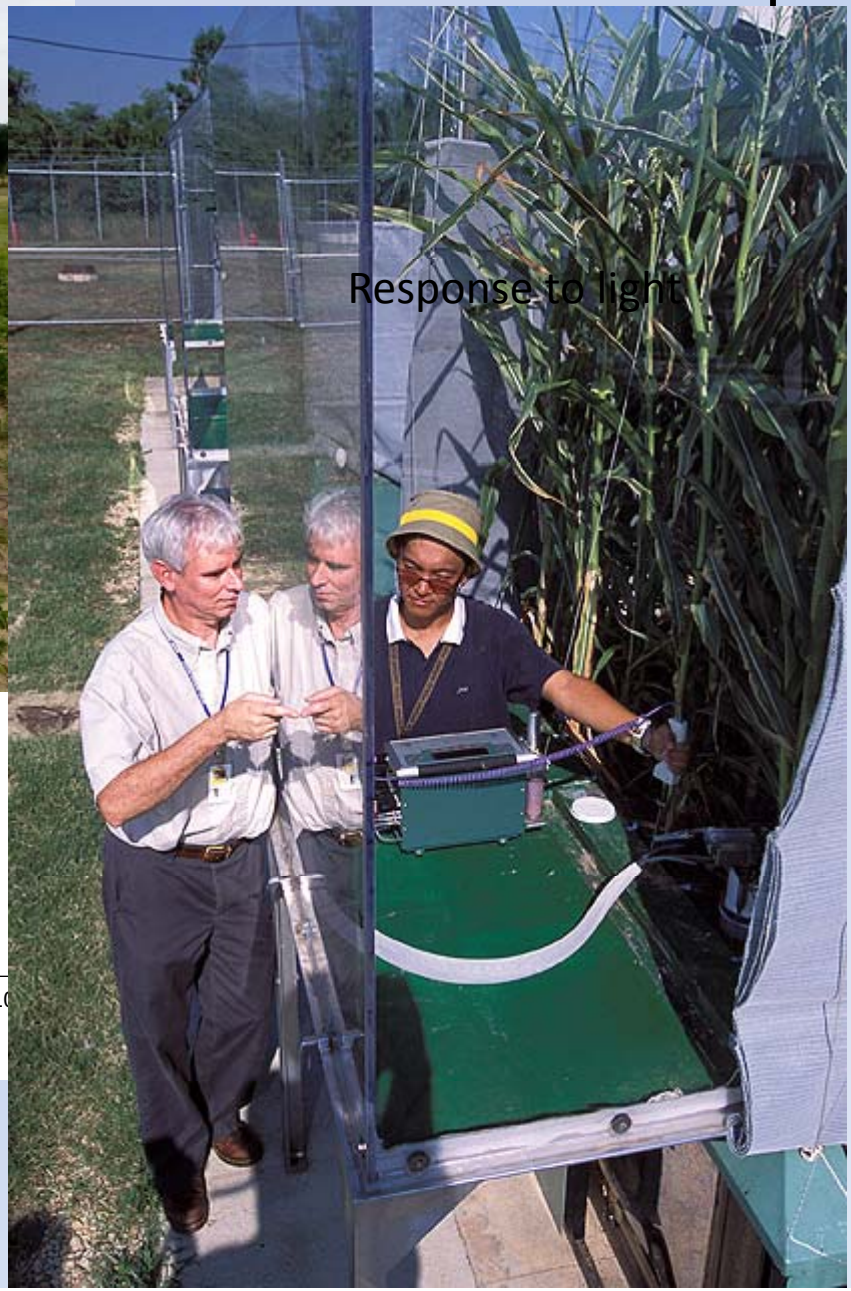
- Light intensity [PAR umol m^{-2} s^{-1} photons]
- CO_2 Concentration [umol CO_2 mol^{-1} air]
- Temperature [°C]
- Relative humidity – vapor pressure deficit [kPa]
- Nitrogen [mgr gr^{-1}]
- Leaf water status [kPa water potential]

Model components (processes) to simulate photosynthesis

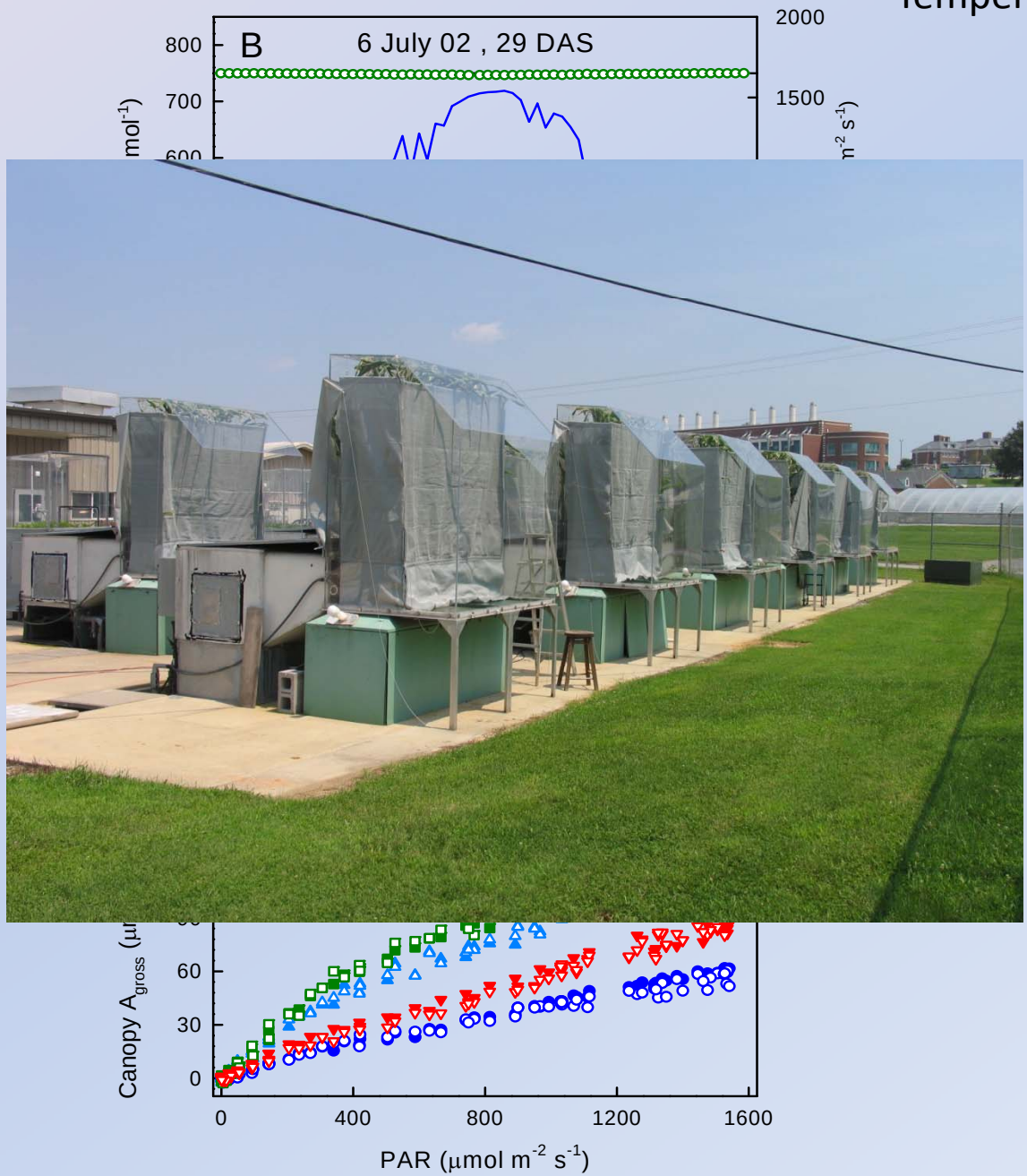
- Photosynthesis (carbon assimilation): response to PAR, CO_2 and temperature
- Conductances and transpiration: response to vapor pressure deficit and wind.
- Canopy radiative transfer: response to sun angle, and canopy size/structure

Carbon assimilation rate in corn (C_4)



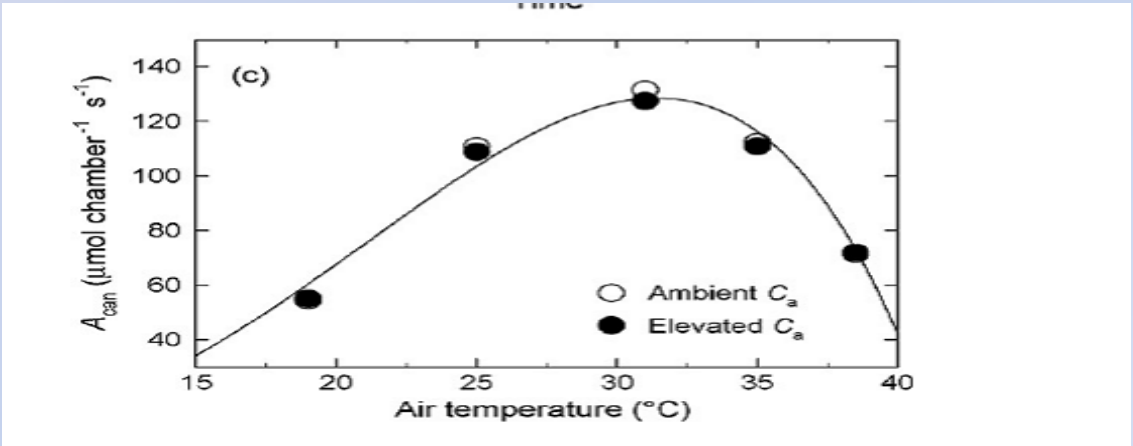


Temperature response



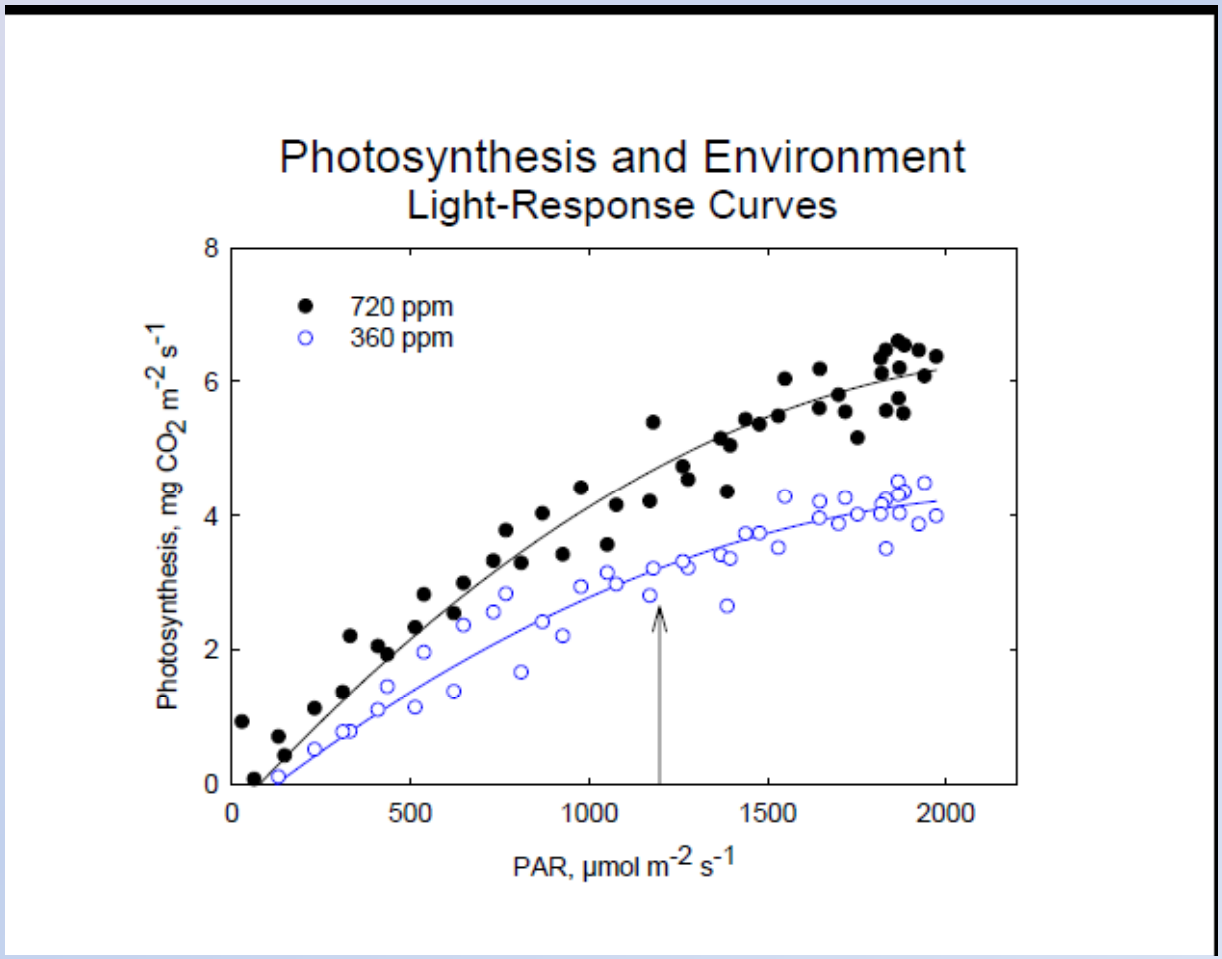
Temperature dependence of photosynthesis in corn

Diurnal Pnet@1800 μmol m^{-2} s^{-1}, DAP29



Kim et al. 2007. Temperature dependence of growth development and photosynthesis in maize under elevated CO2. Env. and Exp. Bot., 61: 224-236

Photosynthesis response to light and CO_2 in cotton (a C_3 plant)



Models for Plant Response to CO_2

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

1. Photosynthesis

- CO_2 supply (source)
  - Diffusion equation
  - Function of external CO_2 (gradient)
  - Stomatal control (conductance)
- CO_2 biochemical demand (sink)
  - Michaelis-Menten kinetics model
  - C_3 model
  - C_4 model
    - Accounts for the CO_2 concentrating mechanism and related leakage
- C_i, leaf temperature and PAR tie the two processes together

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

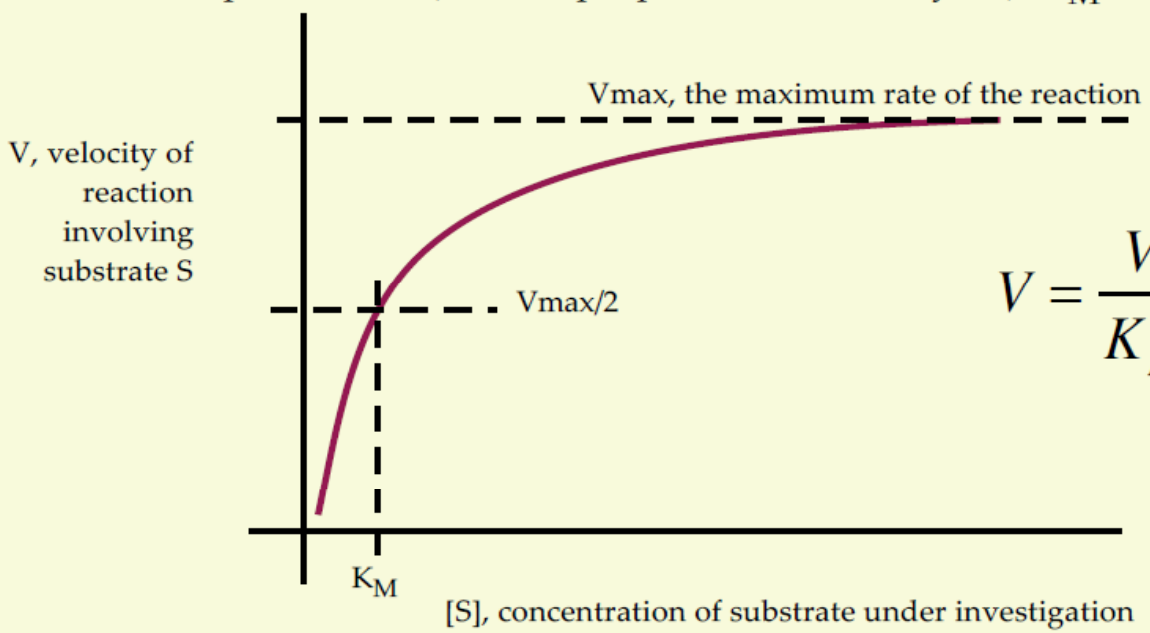
$A_c = V_c - 0.5V_o - R_D$

- A_c = Net carbon assimilation rate due to carboxylation
- V_c= Rate of carboxylation
- V_o= Rate of oxygenation
- R_D= Rate of respiration

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}.



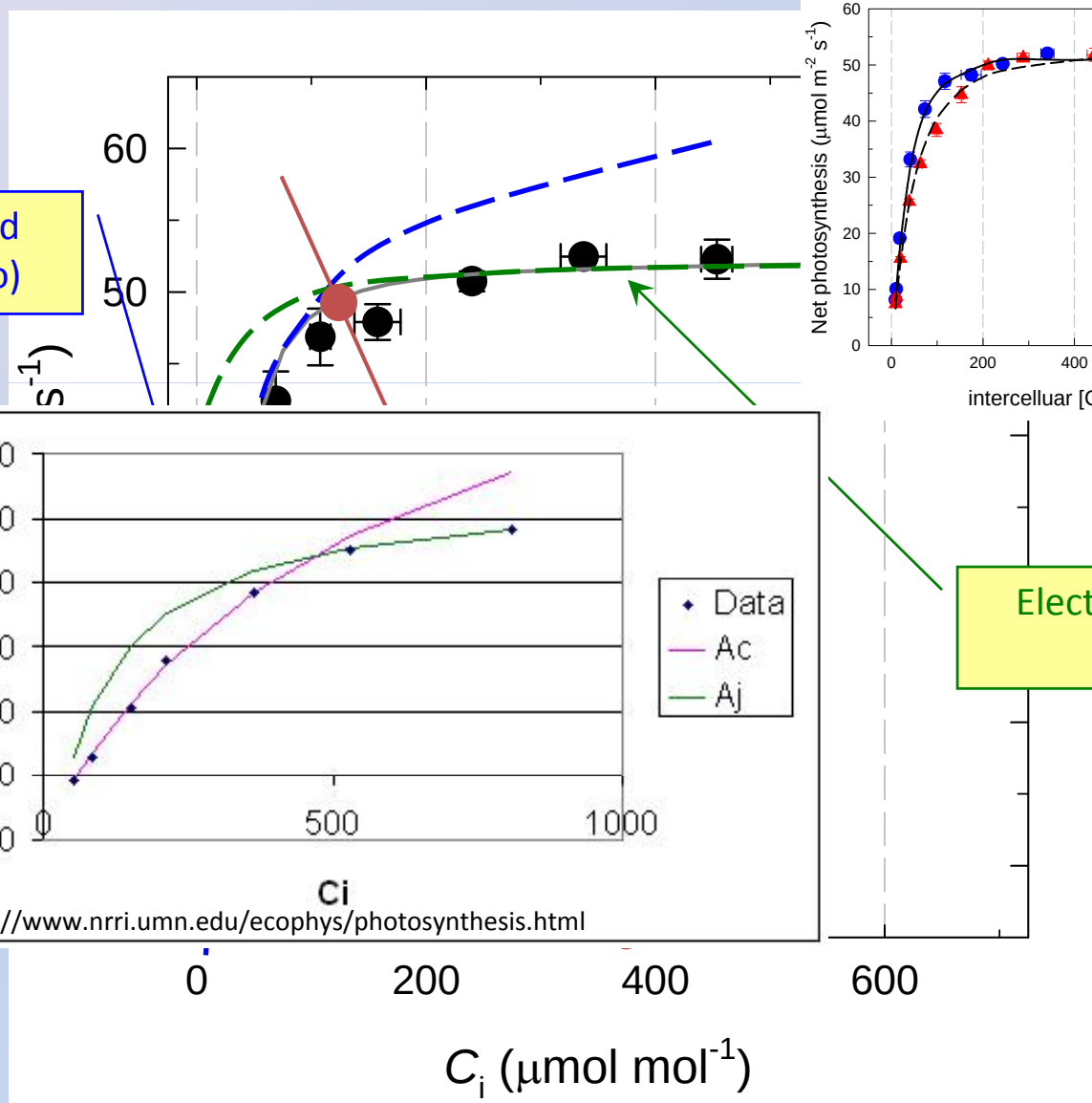
$$V = \frac{V_{max}[S]}{K_M + [S]}$$

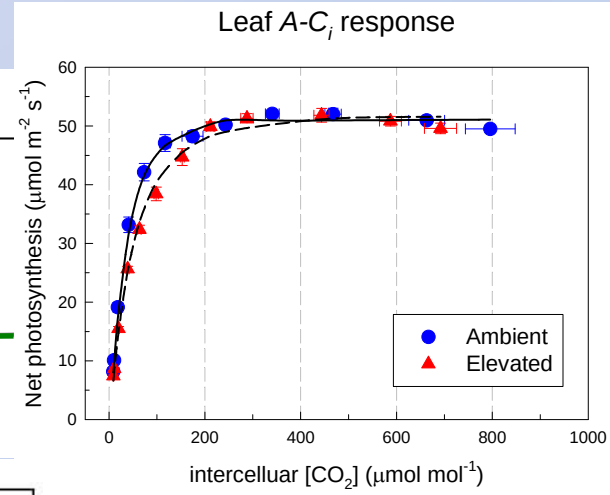
K_M (the Michaelis-Menten constant) is a measure of the affinity that the enzyme has for the substrate - the bigger K_M the lower the affinity.

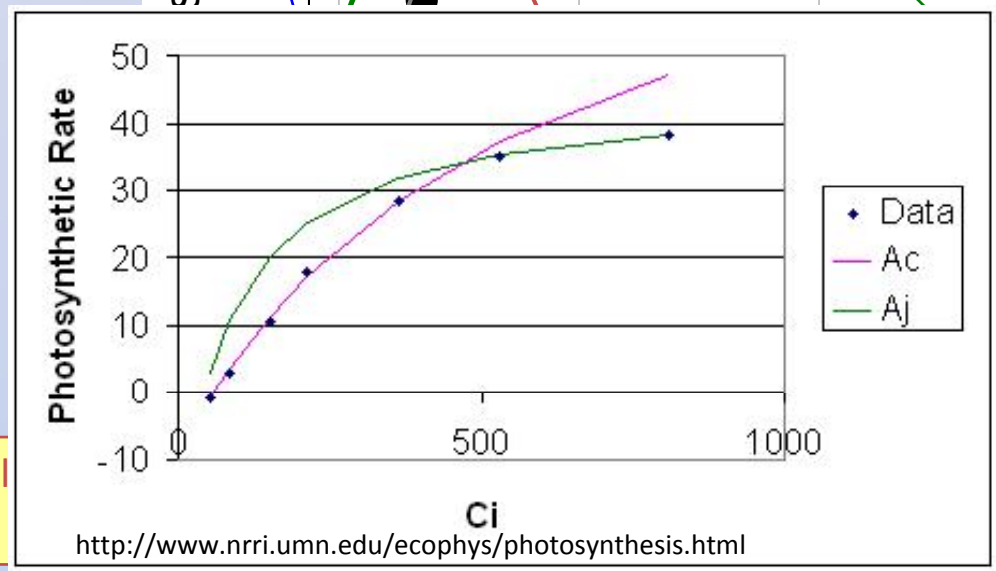
Source:
http://www.tbi.univie.ac.at/~raim/harvest/workshop.brno/presentations/harbinson.pdf

C_4 photosynthesis model

Enzyme limited
(PEPC, Rubisco)





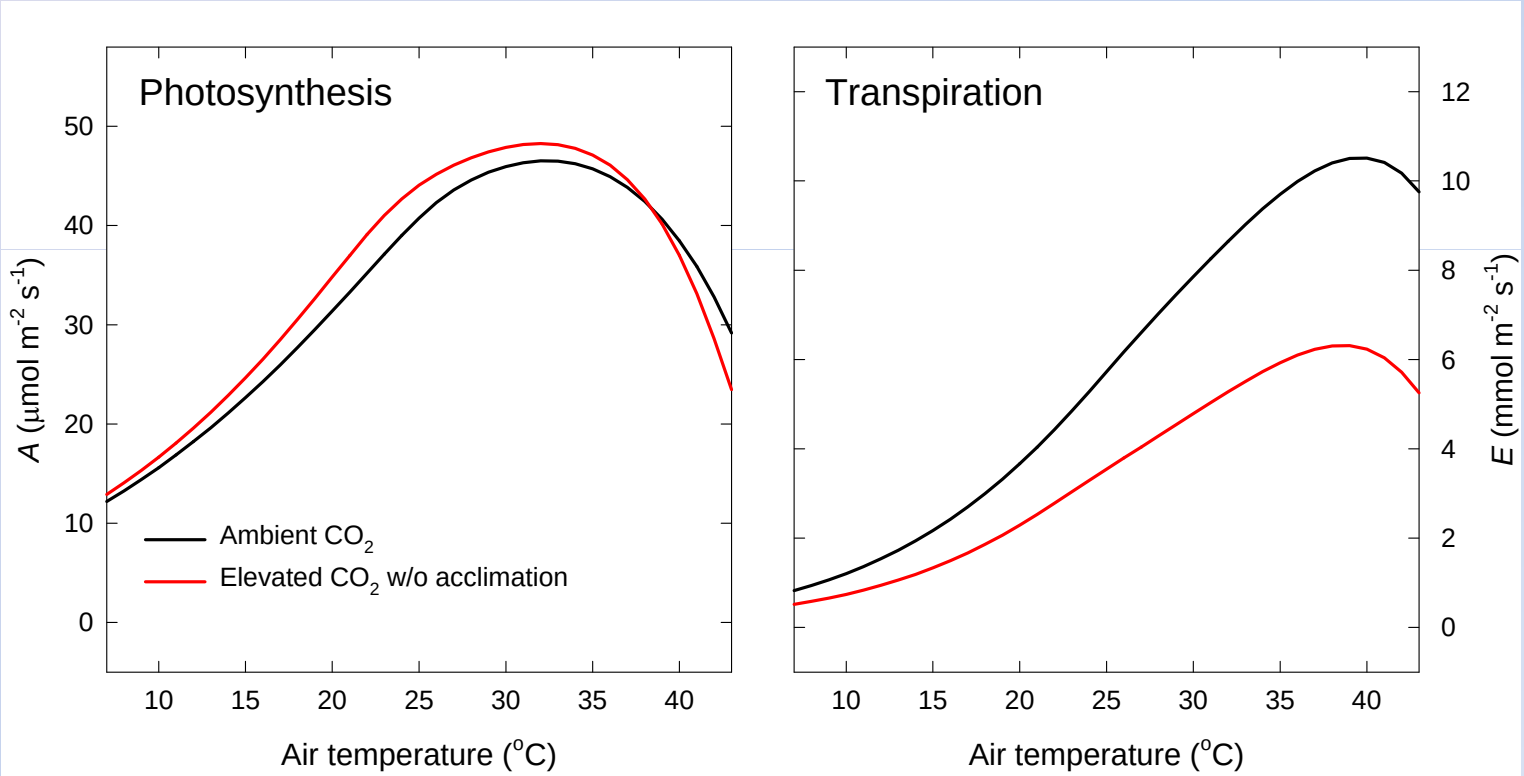


http://www.nrri.umn.edu/ecophys/photosynthesis.html

Electron transport
limited

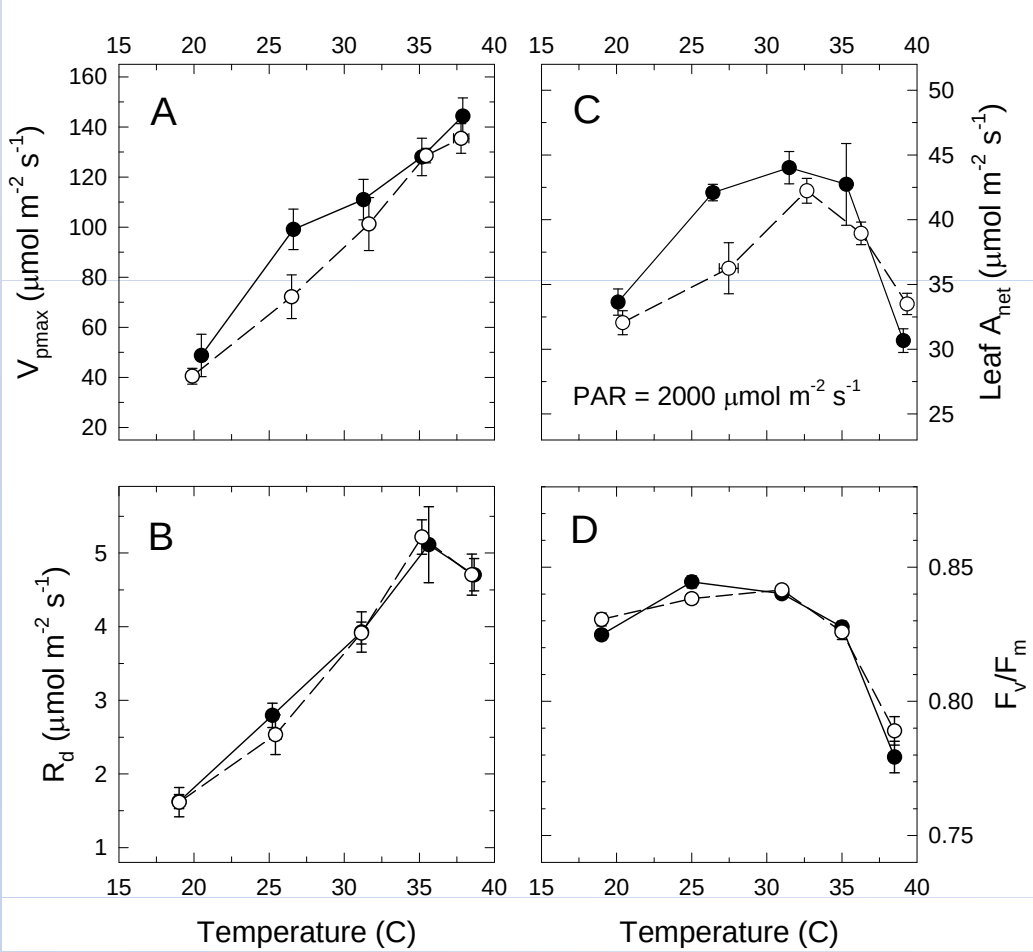
Physical

Modeling C_4 temperature dependence at elevated CO_2



- Temperature optimum is unchanged under elevated CO_2. Photosynthetic rate may increase in part due to increased leaf temperature at low temperatures

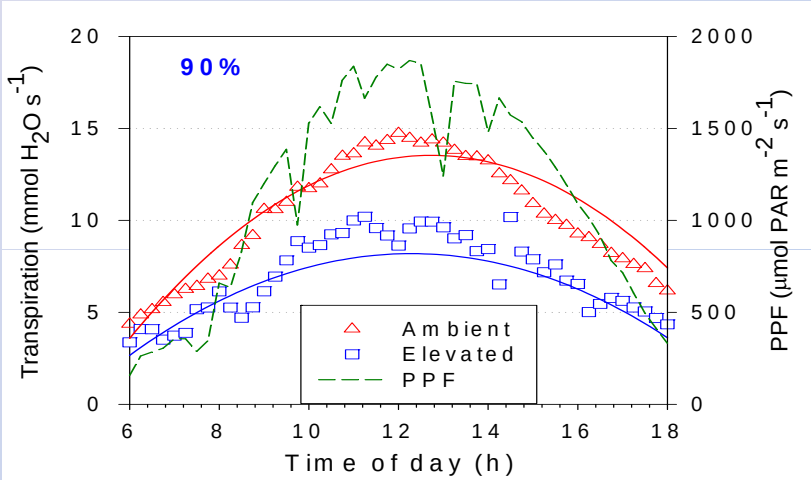
Temperature responses of leaf photosynthetic parameters. Maximum PEP-Case activity estimated by initial slope of A-C_i response (A), leaf dark respiration (B), Leaf A_{net} at saturating PAR (C), and quantum efficiency of PSII measured as F_v/F_m (D).

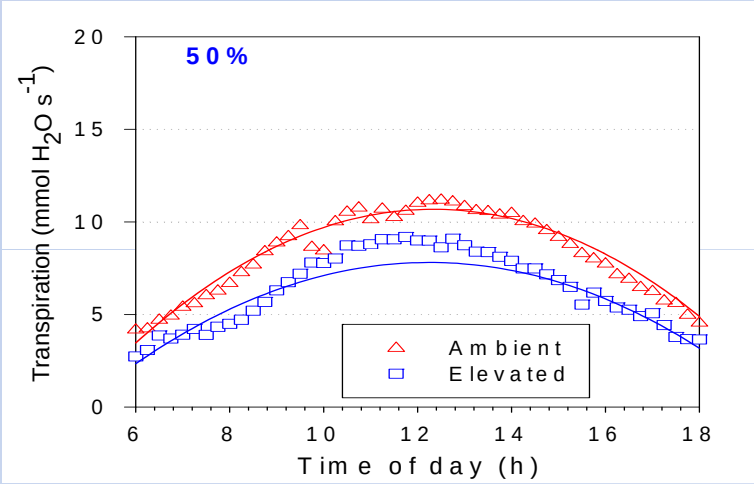


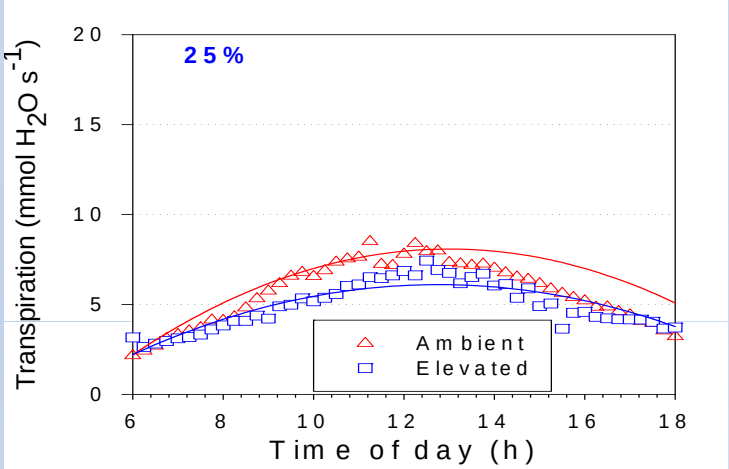
2. Stomatal Conductance and Water Relations

Daily transpiration as a function of water stress and CO_2 in potato

Diurnal transpiration values at 45 DAE







- Transpiration significantly reduced by elevated CO_2 at most water stress treatments.
- Transpiration also decreased with water stress.

Stomatal conductance

- Ball, Woodrow, Berry (1987)

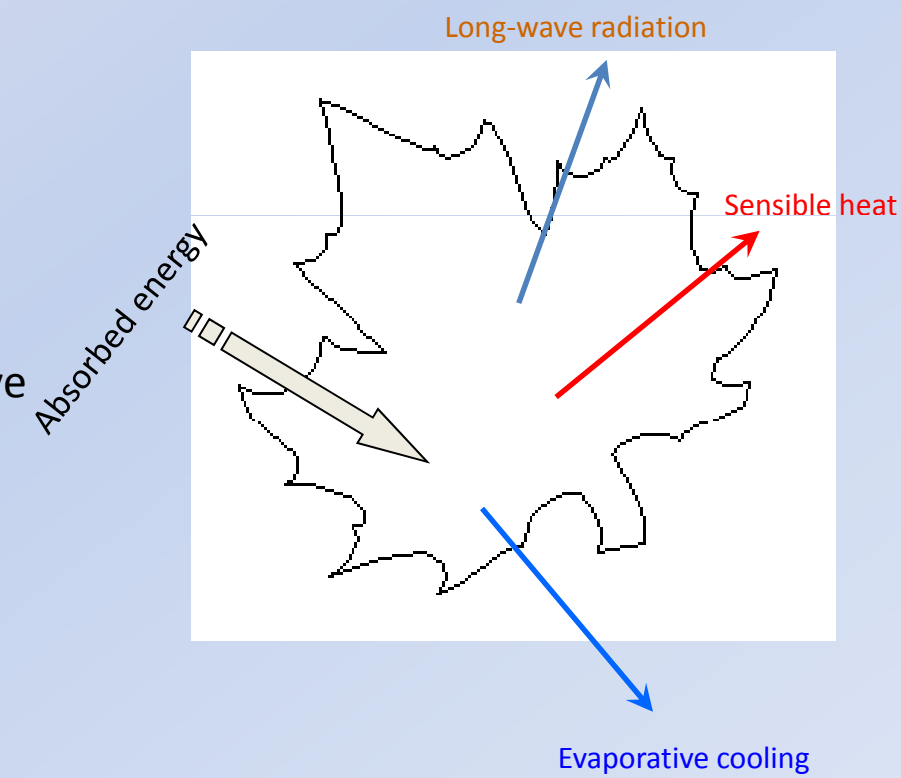
$$g_s = b + m(Ah_s/C_s)$$

  - 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)



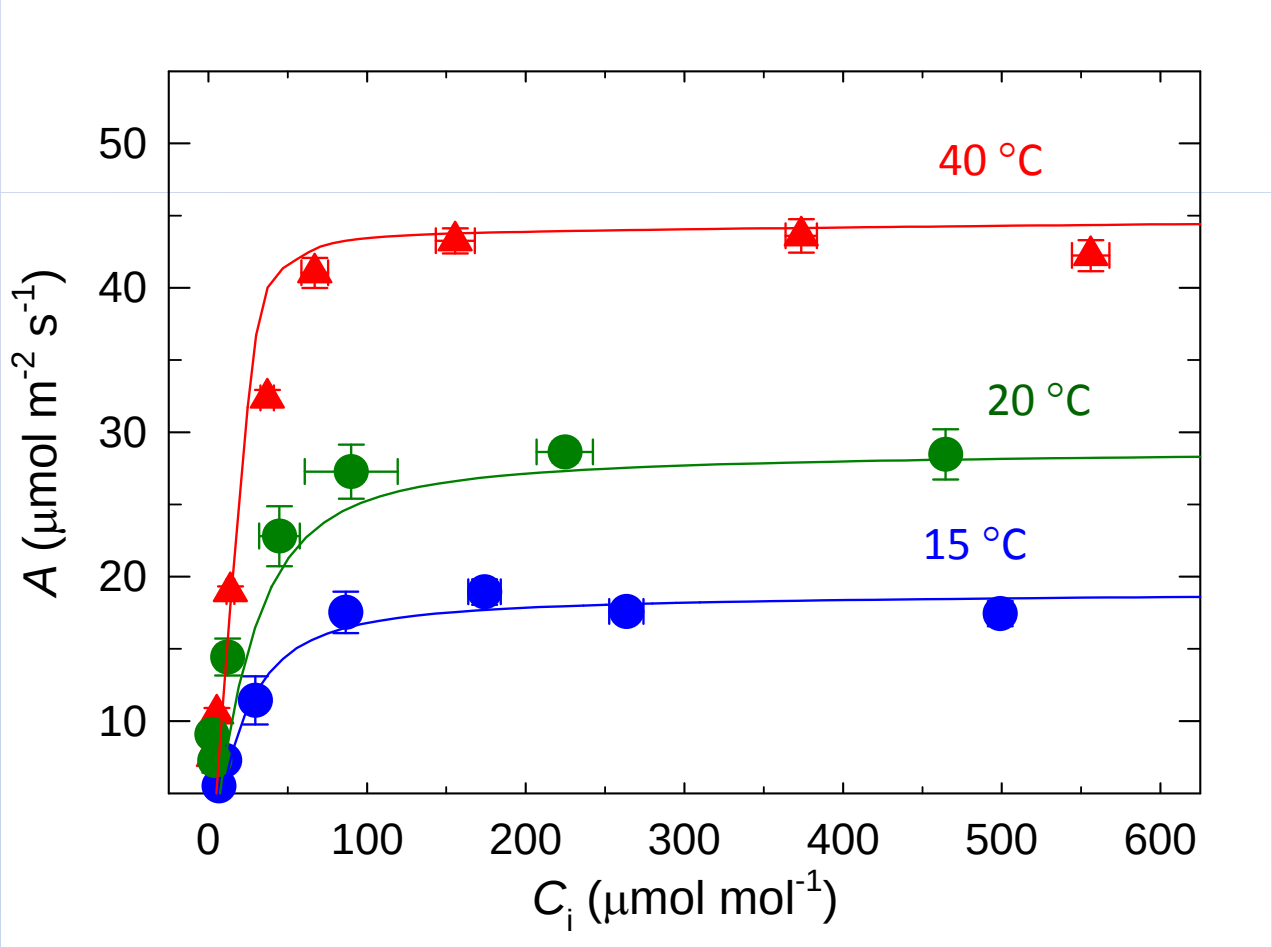
Model for Leaf Gas-Exchange

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

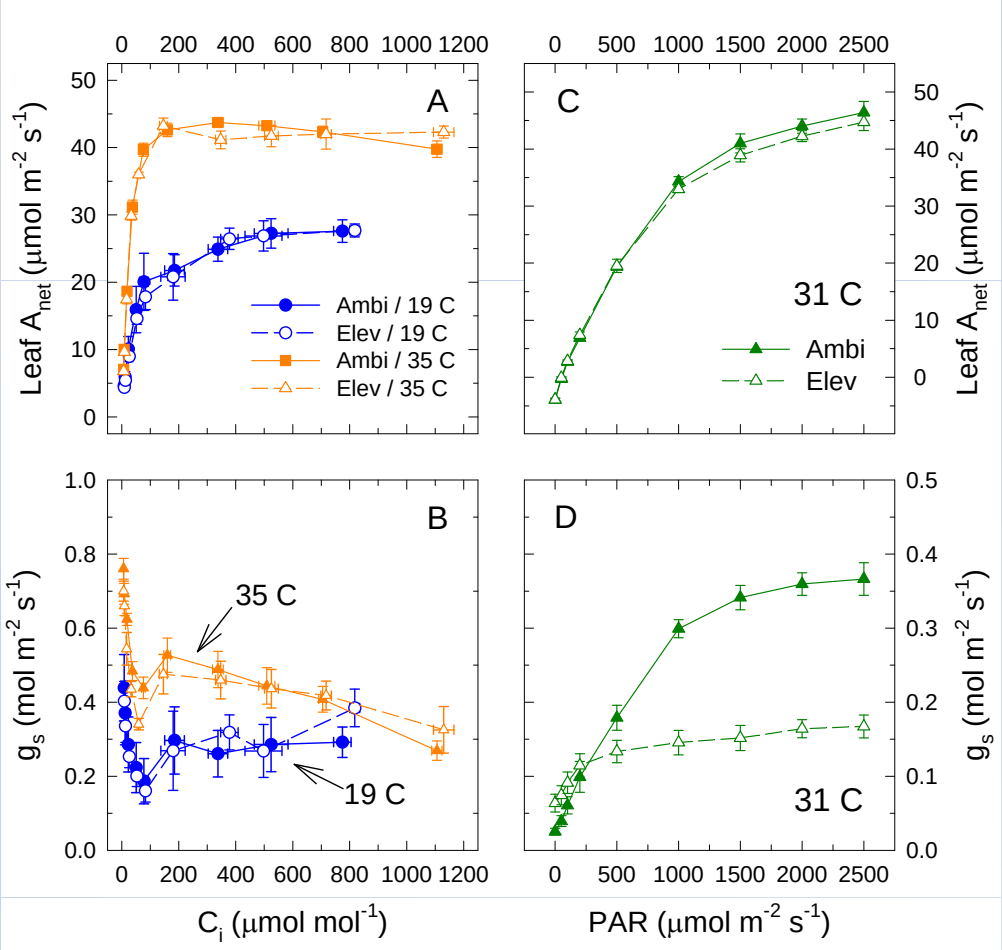
Coupled gas exchange model

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

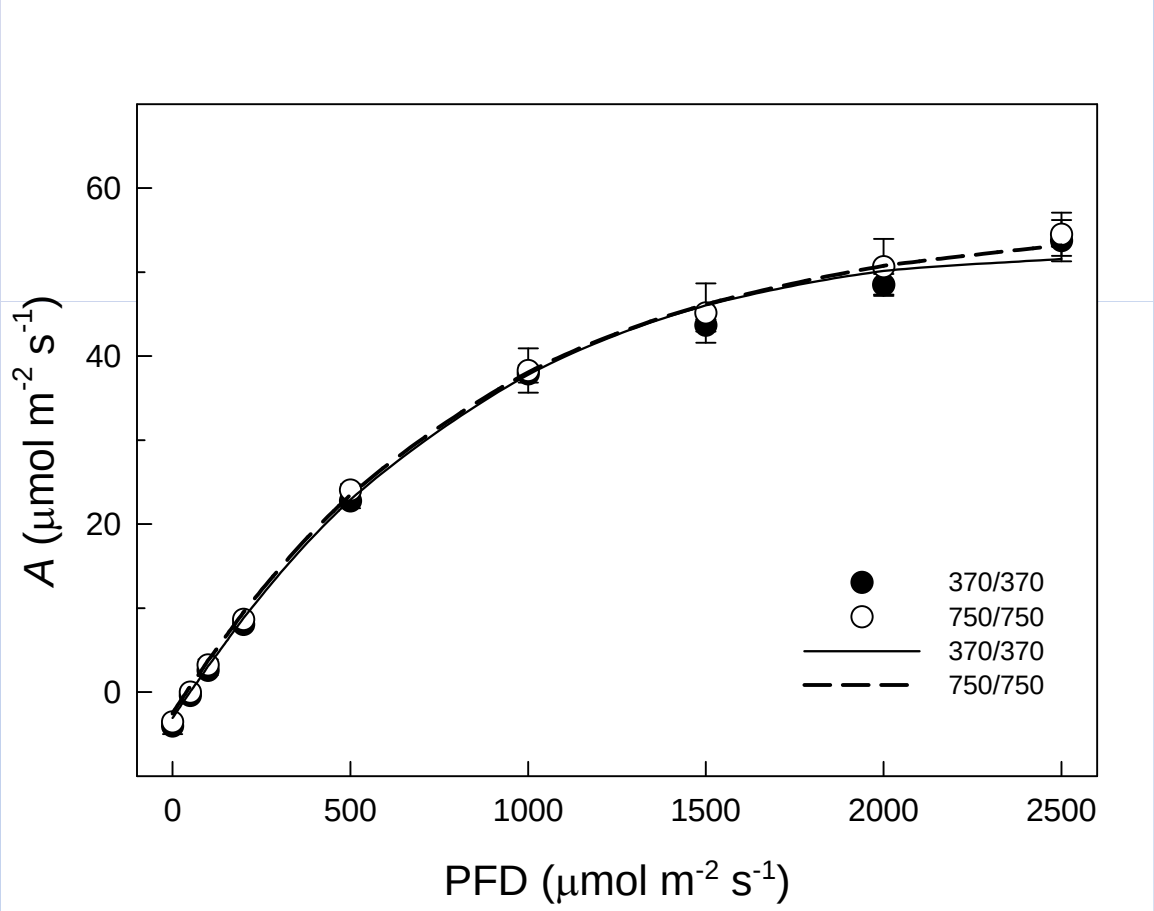
Temperature response (leaf level) for corn



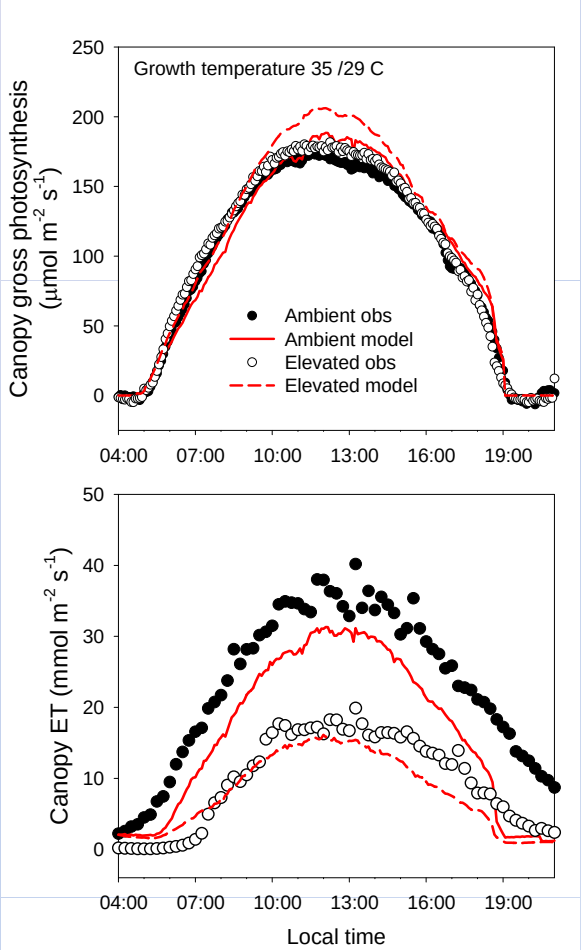
A_{net} and Stomatal Conductance Response to Temperature and CO_2

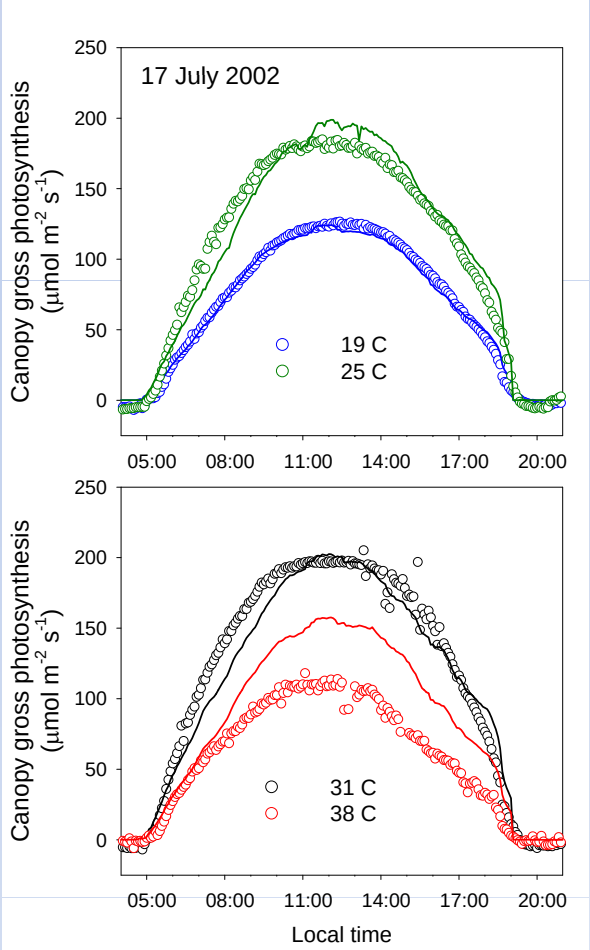


Calibrated leaf level light response for corn

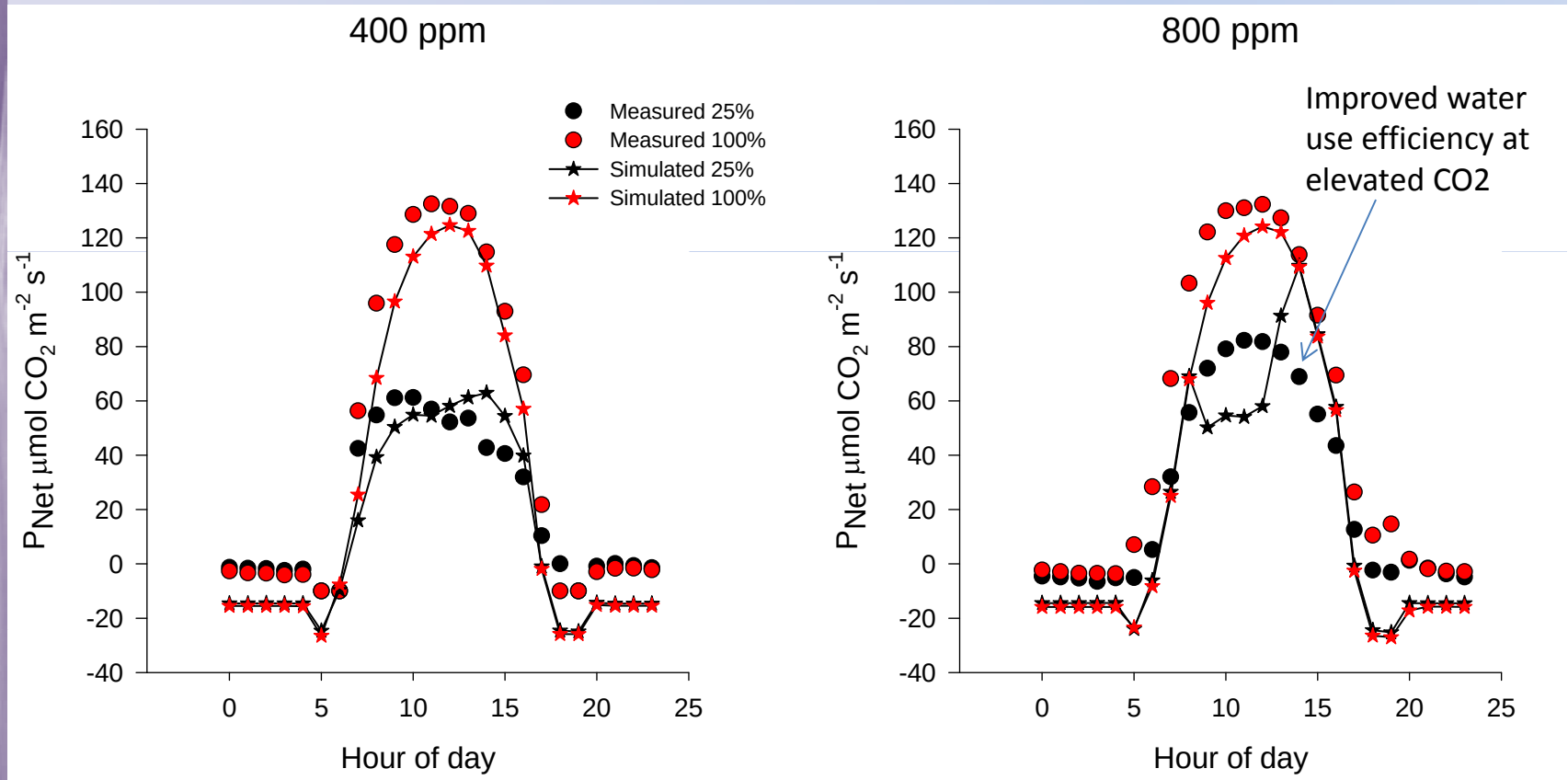


Temperature response of observed and simulated canopy photosynthesis for corn in growth chambers

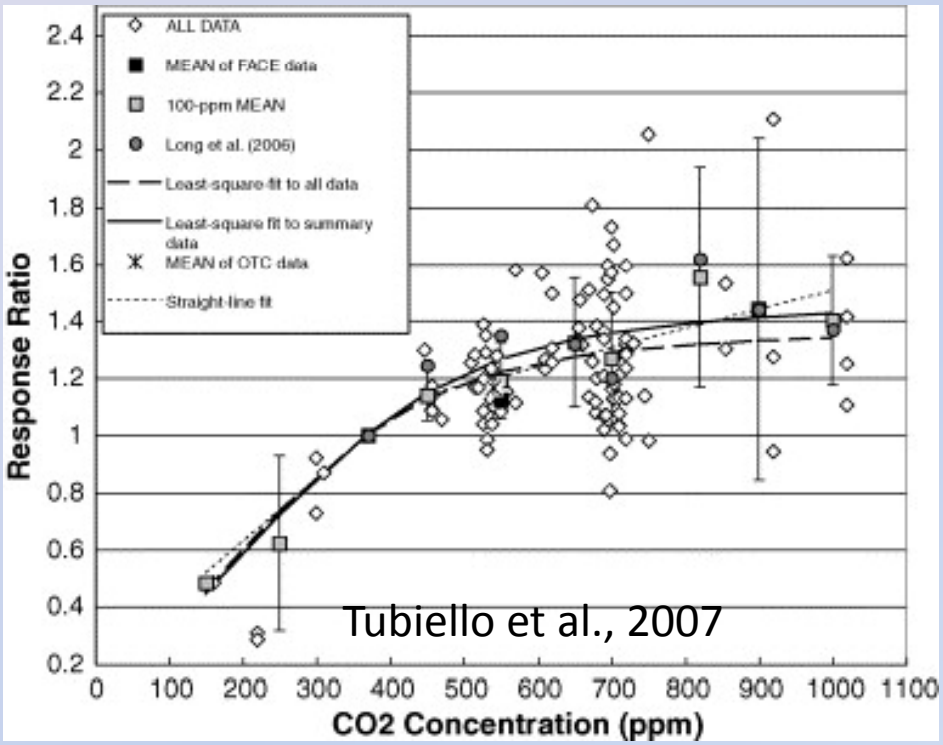




Simulation of canopy photosynthesis response to water stress in corn



Simple approach – scale CO2 response

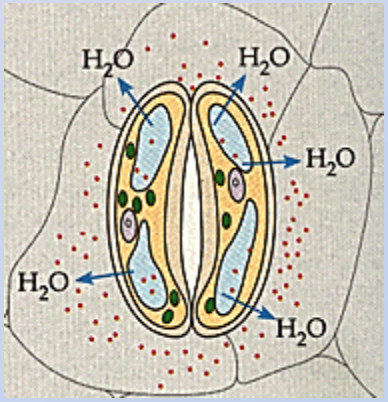


- This can be applied to a light response curve or to Radiation Use Efficiency (Mg C MJ^{-1} light)

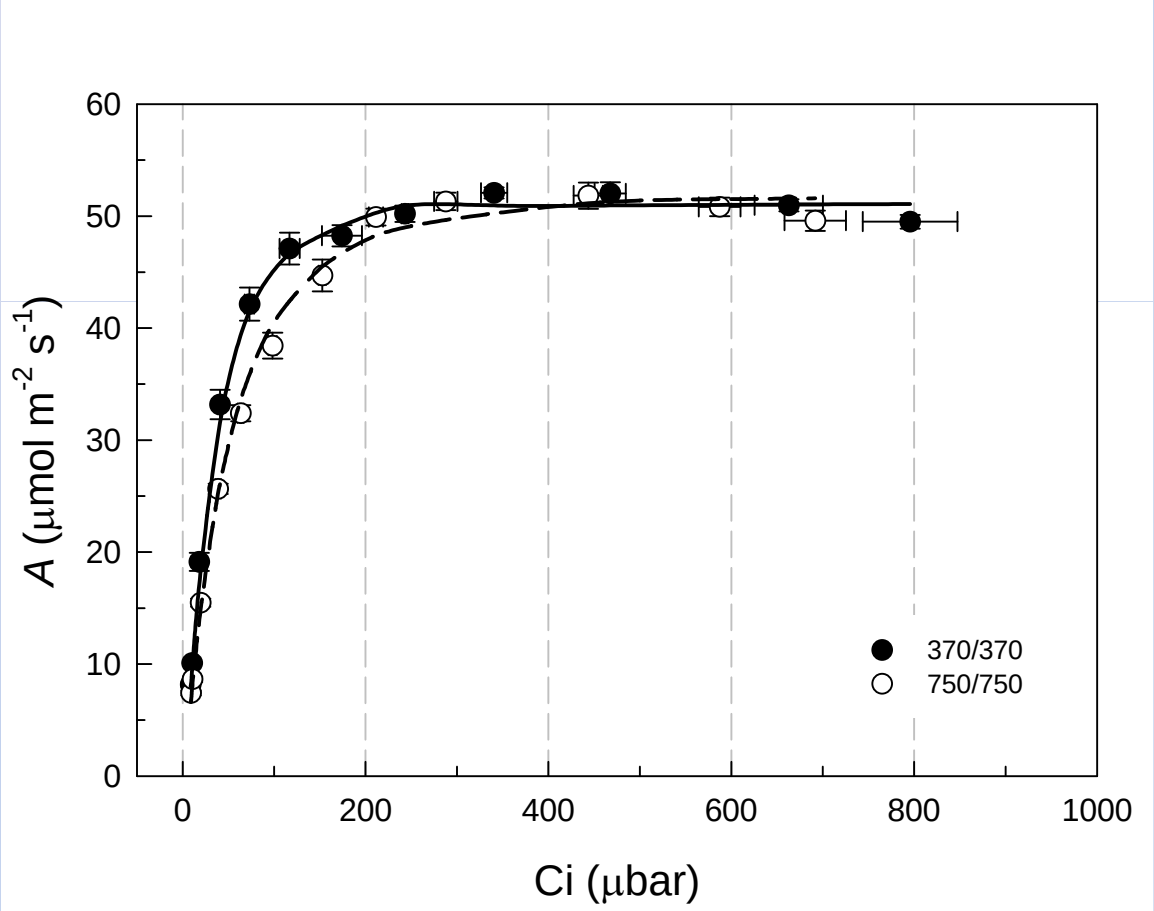
Summary and Conclusions

- A biochemical model of photosynthesis is a useful approach to modeling the effects of elevated CO2 on photosynthesis
- Parameters can be fit with data from leaf gas exchange equipment but fitting the parameters has some problems
- Mechanisms for adaptation by leaves to CO2 are missing.

THANK YOU!

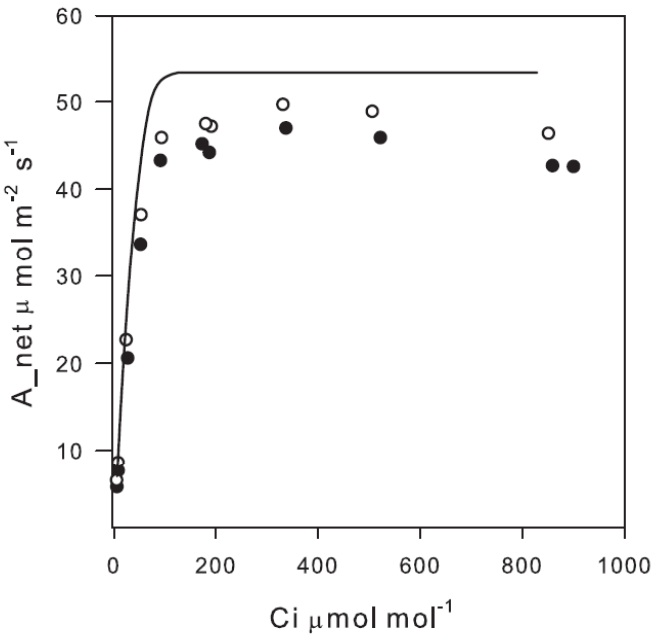
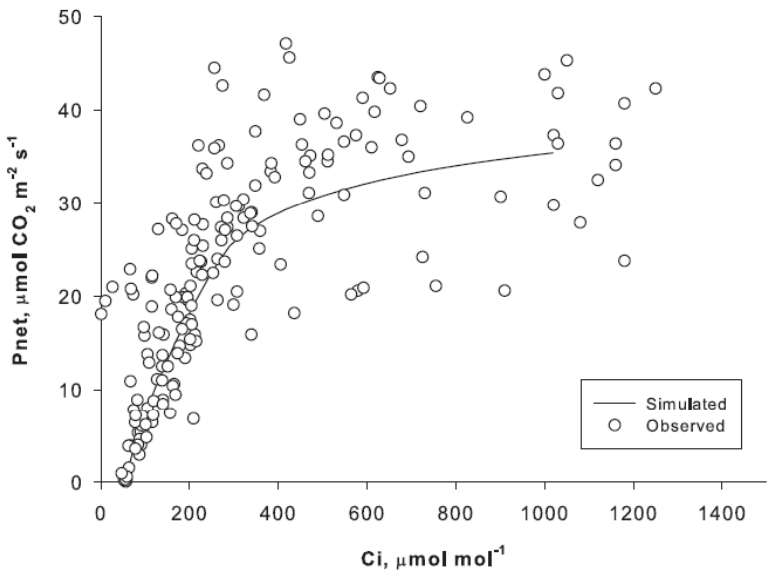

H_2O
H_2O
H_2O
H_2O
H_2O

Applying Systems Theory
To Complex
Agricultural Problems


60
50
40
30
20
10
0
0
200
400
600
800
1000
A (µmol m-2 s-1)
Ci (µbar)
370/370
750/750

Simulated carbon Assimilation rate and intracellular [CO2]

Maize, C4



Potato, C3