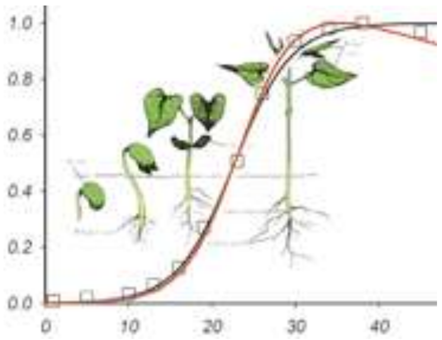
Toward a More Comprehensive and Mechanistic Approach to Simulation of Interacting Plant and Soil Processes

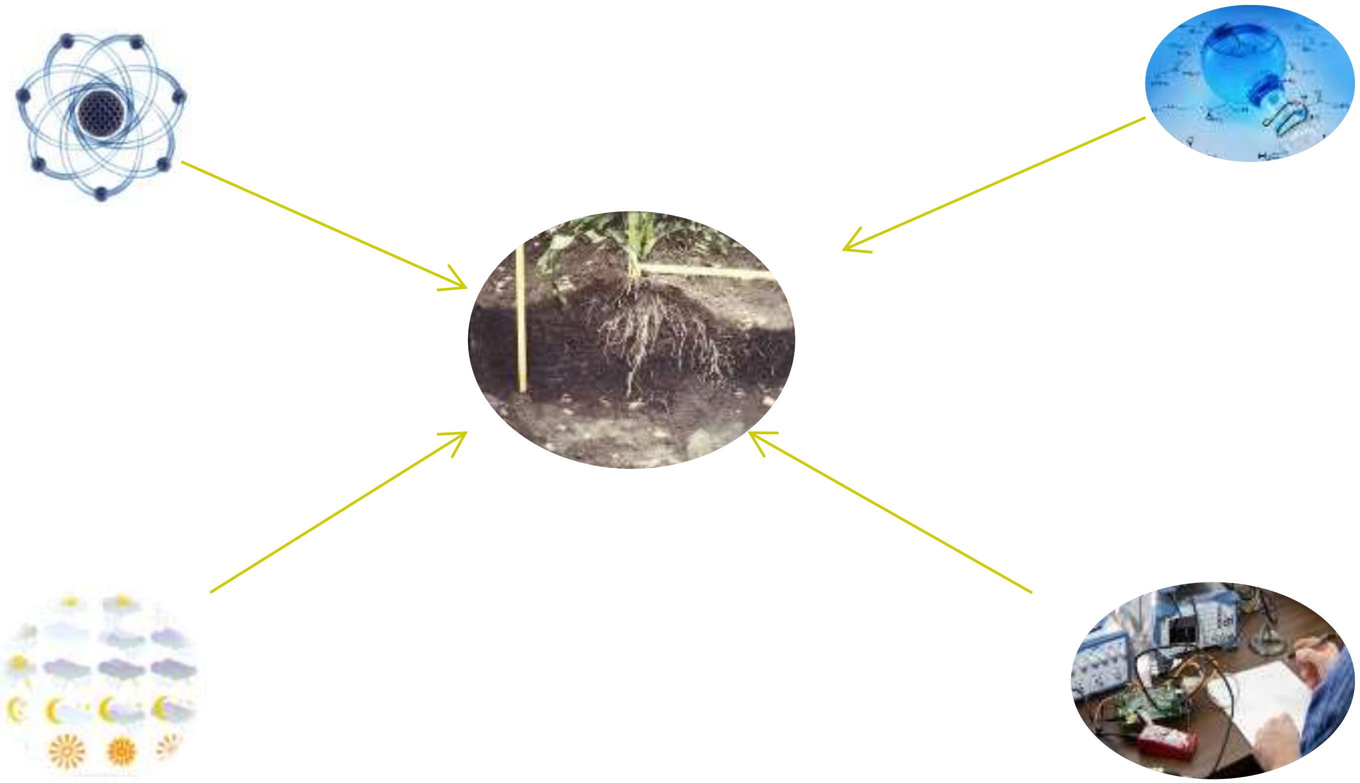


Dennis Timlin[1], David Fleisher[1], Soo-Hyung Kim[2], V.R. Reddy[1]

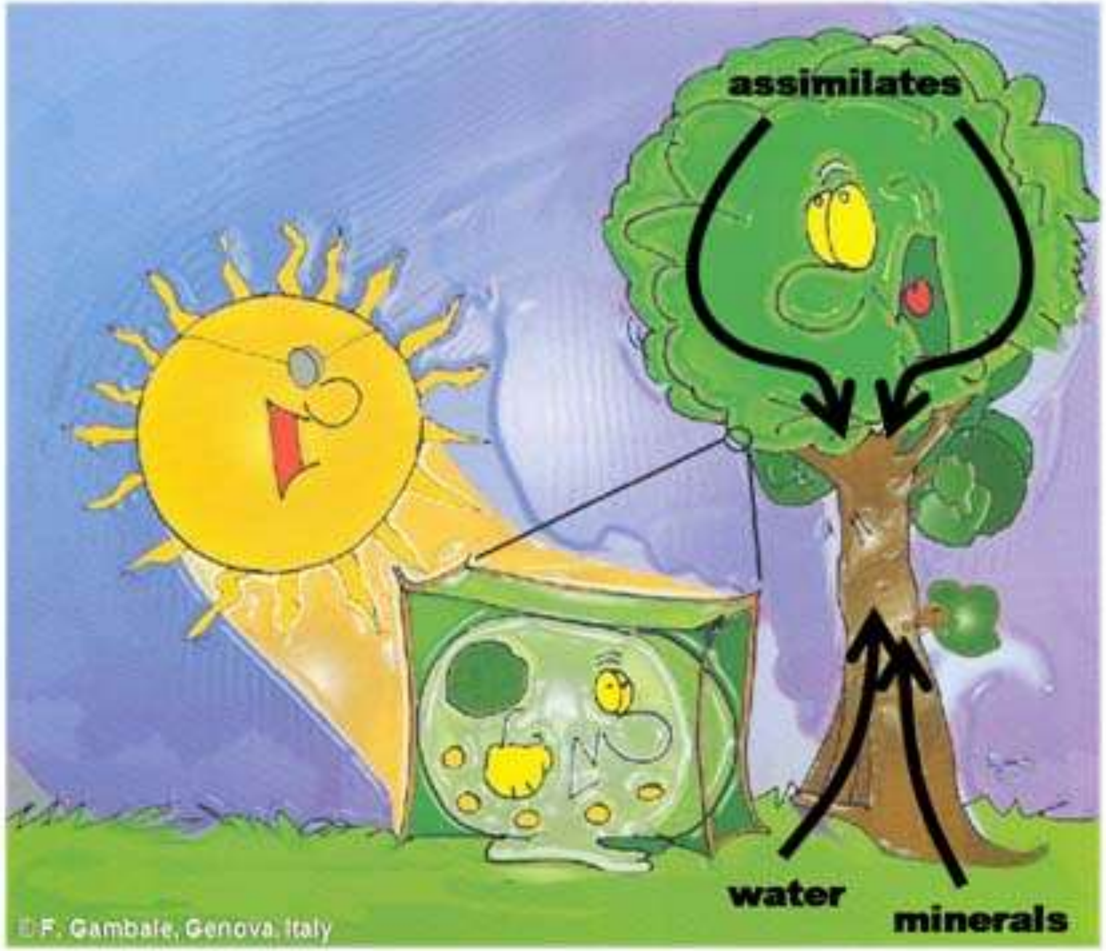
[1]USDA-ARS Crop Systems and Global Change Laboratory

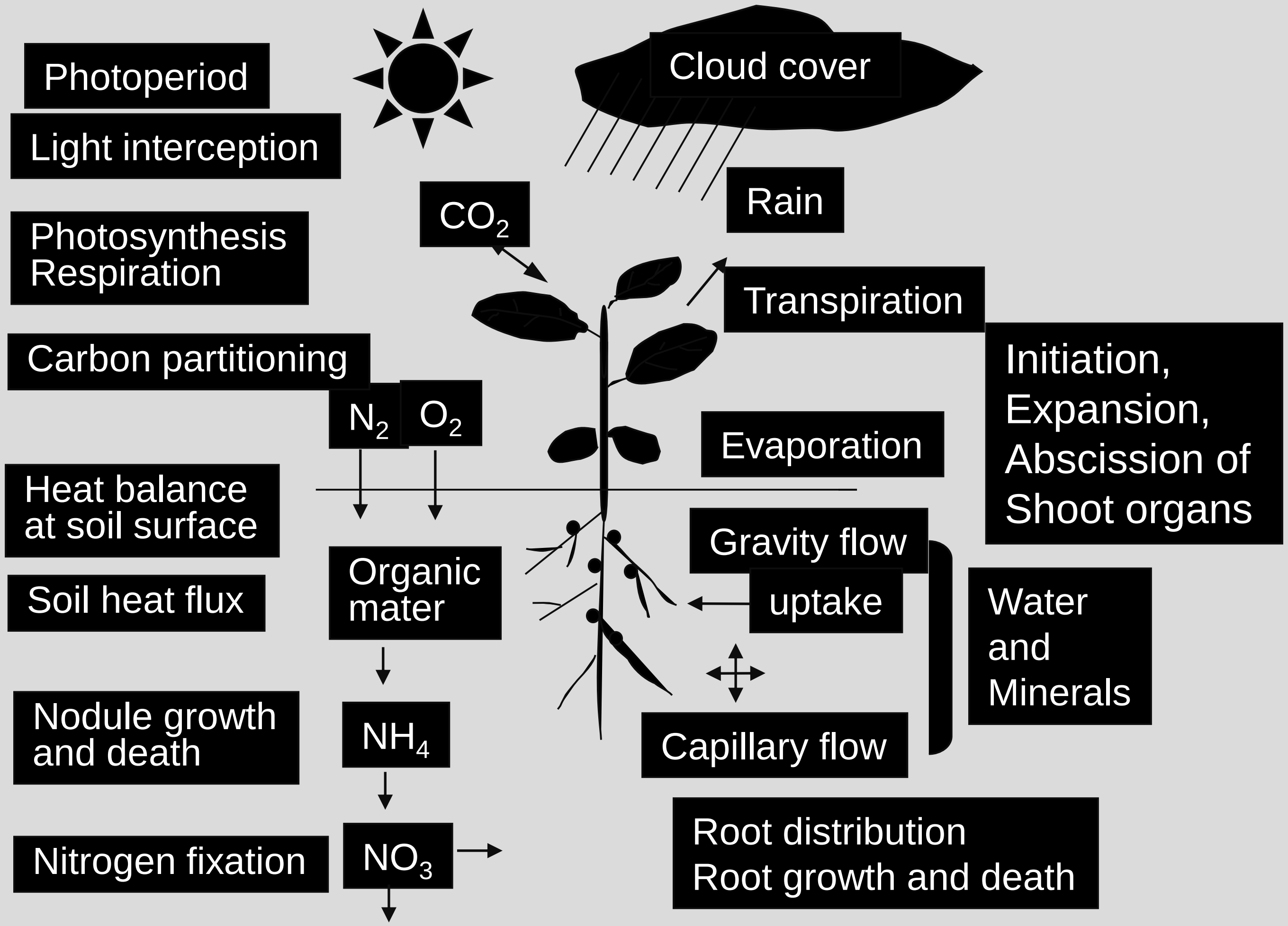
[2]University of Washington

How can Soil Physics Contribute to Crop Modelling?



You also need to know about Biology and how the components interact





Photoperiod

Light interception

Photosynthesis
Respiration

Carbon partitioning

Heat balance
at soil surface

Soil heat flux

Nodule growth
and death

Nitrogen fixation

CO_2

N_2

O_2

Organic
mater

NH_4

NO_3

Cloud cover

Rain

Transpiration

Evaporation

Gravity flow

uptake

Capillary flow

Initiation,
Expansion,
Abscission of
Shoot organs

Water
and
Minerals

Root distribution
Root growth and death

Overview

- Research Approach
- Quantification of temperature effects
- Coupled gas exchange models for photosynthesis and energy balance
- Water stress effects on plants
- Some examples

MODELING STARTS WITH DATA AND QUANTIFIABLE RELATIONSHIPS

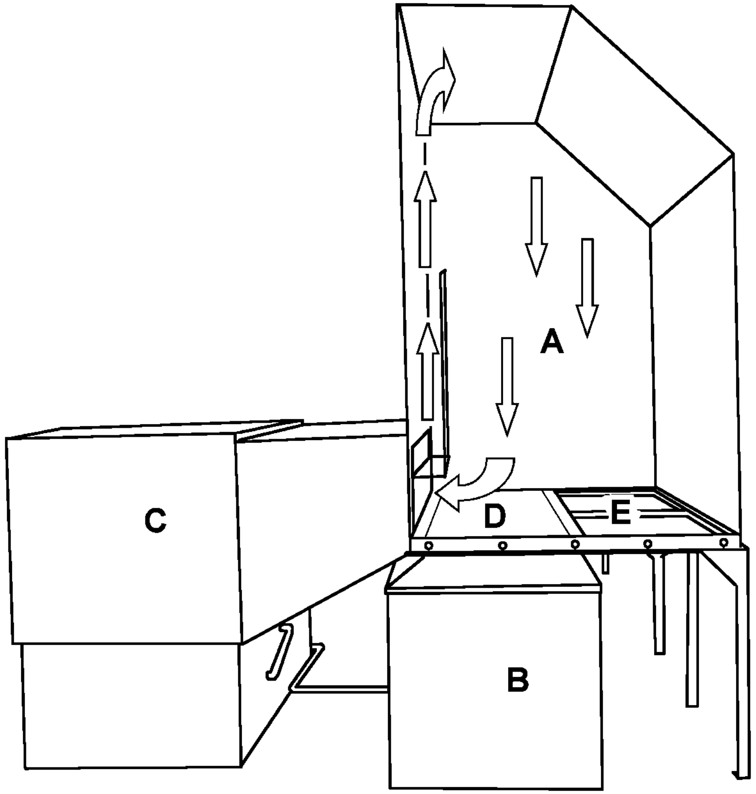
Data Are First Obtained from Controlled Experiments in Growth Chambers

Characteristics of Sunlit Controlled Environment Chambers

- Use natural sunlight and soil volume (larger units)
- Control and monitor aerial and soil environments
- Monitor whole canopy gas exchange (Pg, Respiration, Transpiration)
- Measure gas leakage rates with a N_2O system to maintain accuracy

SPAR chamber

- Sunlit; controls air T, CO_2, RH, fertigation; measures CER, ET, canopy T, soil water content, root growth
  - A: Clear plexiglas cuvette (2.2 *1.4*2.5 m)
  - B: One cubic meter soil bin
  - C: Air handler
  - D: Soil surface
  - E: Doors

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12

Field Experiments Are Also Carried Out

Collecting Potatoes for a Spatial Nitrogen Study

Sampling is a Busy Time

TEMPERATURE RESPONSE

Temperature Response Functions

- Temperature is a key environmental variable regulating growth and development of plants
- Biological organisms respond to temperature in nonlinear fashion
- Temperature responses best modeled using **non-linear** temperature functions

Non-linear temperature dependence vs thermal time (GDD)

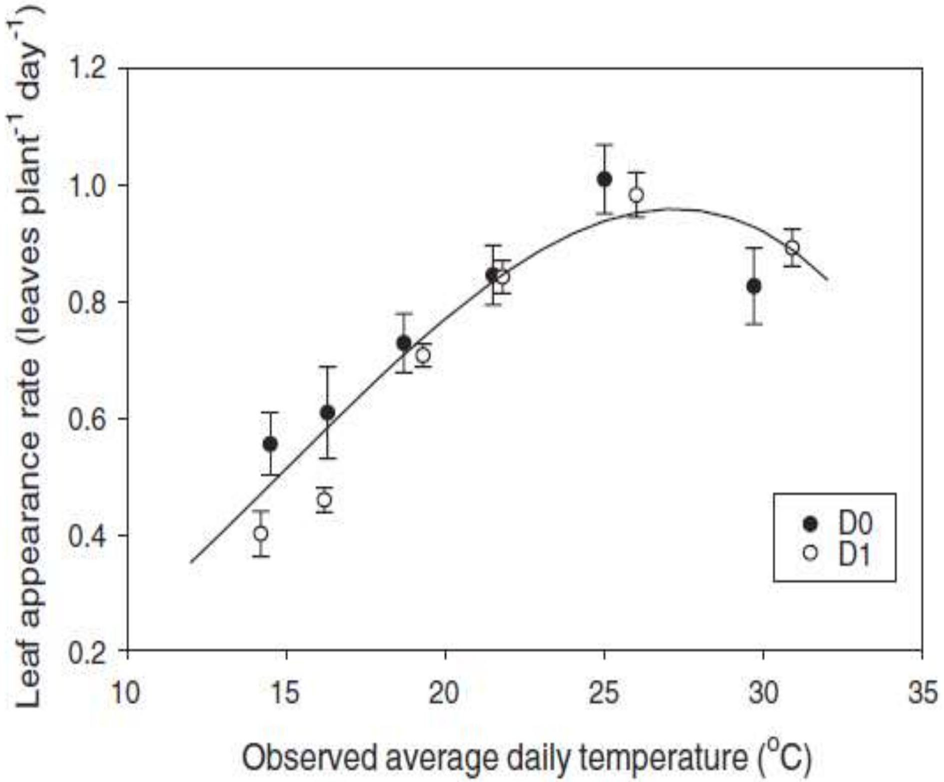


Fig. 1. Leaf appearance rates with standard errors vs. observed average daily temperature for experiments D0 and D1. The nonlinear temperature response model based on the modified β distribution parameters (Table 3) is shown as the solid line.

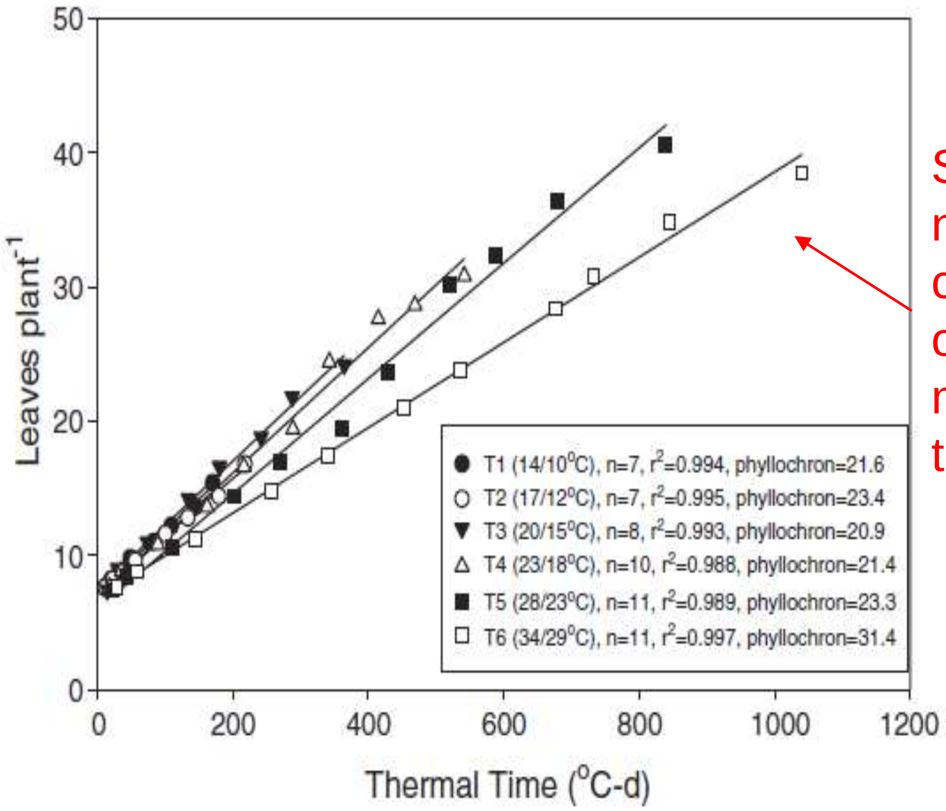
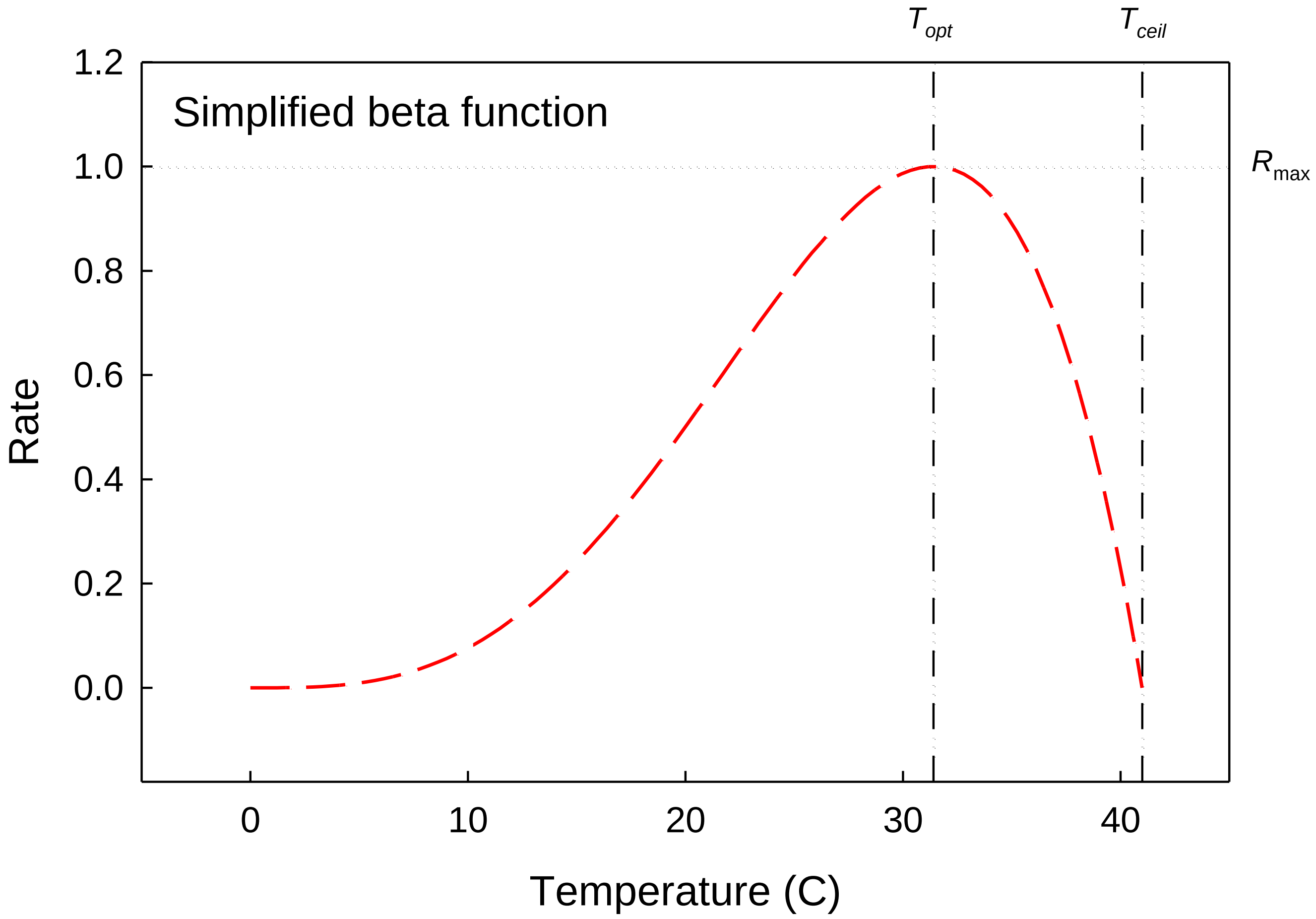


Fig. 3. Leaf appearance data separated for each temperature treatment (T1 through T6) in experiment D1. Data points are the averaged value of five observations at each measurement date (error bars not shown for clarity).

Slopes are not consistent over varying mean temperatures



Beta distribution models mimic the response well only with biologically meaningful parameters

Non-Linear Temperature Response

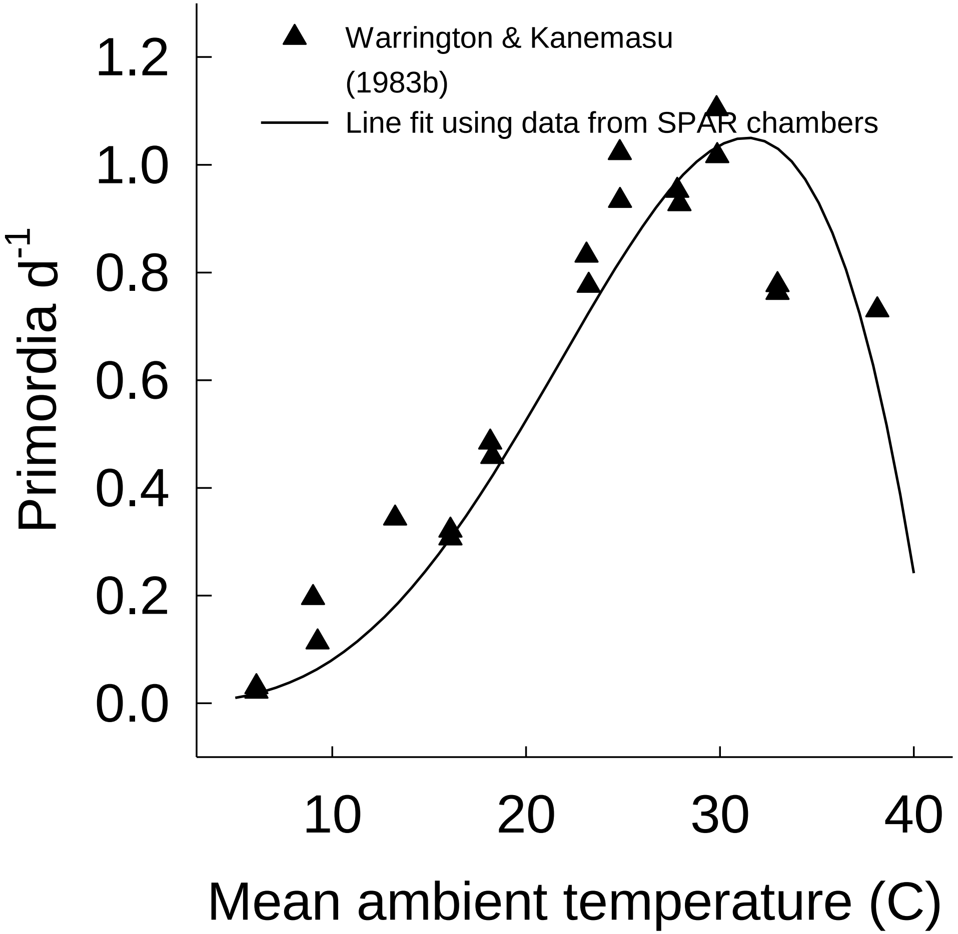
Modified beta-distribution function (Yan and Hunt, 1999)

$$\boxed{r = R_{\max}\left(\frac{T_{ceil} - T}{T_{ceil} - T_{opt}}\right)\left(\frac{T}{T_{opt}}\right)^{\frac{T_{opt}}{T_{ceil} - T_{opt}}}}$$

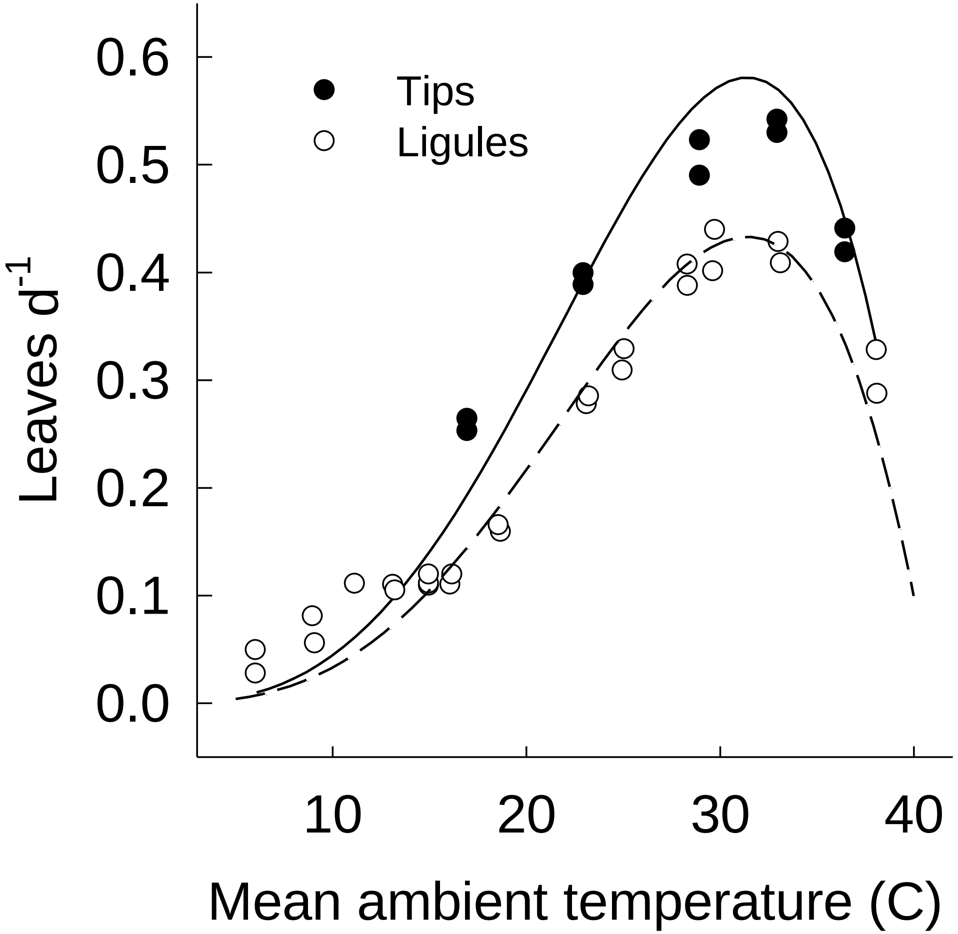
- r – leaf appearance rate, [leaves plant^{-1} day^{-1}]
- R_{max} – maximum r, [leaves plant^{-1} day^{-1}]
- T_{ceil} – ceiling temperature ($r = 0$), [^{o}C]
- T_{opt} – optimal temperature ($r = R_{max}$), [^{o}C]
- Similar T_{opt} (≈31.4) and T_{ceil} (≈41.0) for various growth and developmental events in maize

Temperature dependence of leaf initiation and appearance in corn

(a) Leaf initiation

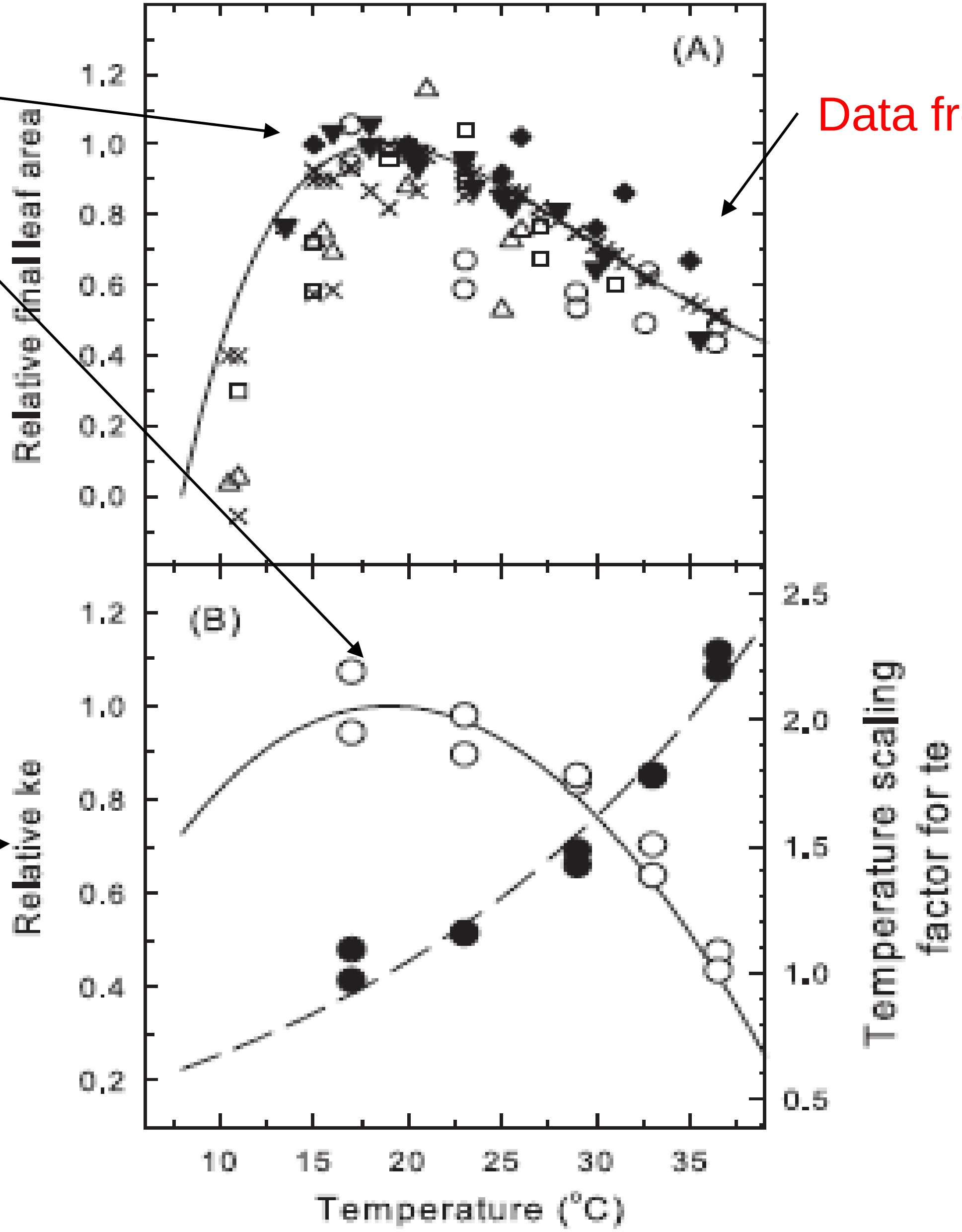


(b) Leaf appearance



Canopy or leaf area in corn as a function of temperature

Shows similar temperature dependence



Data from the literature

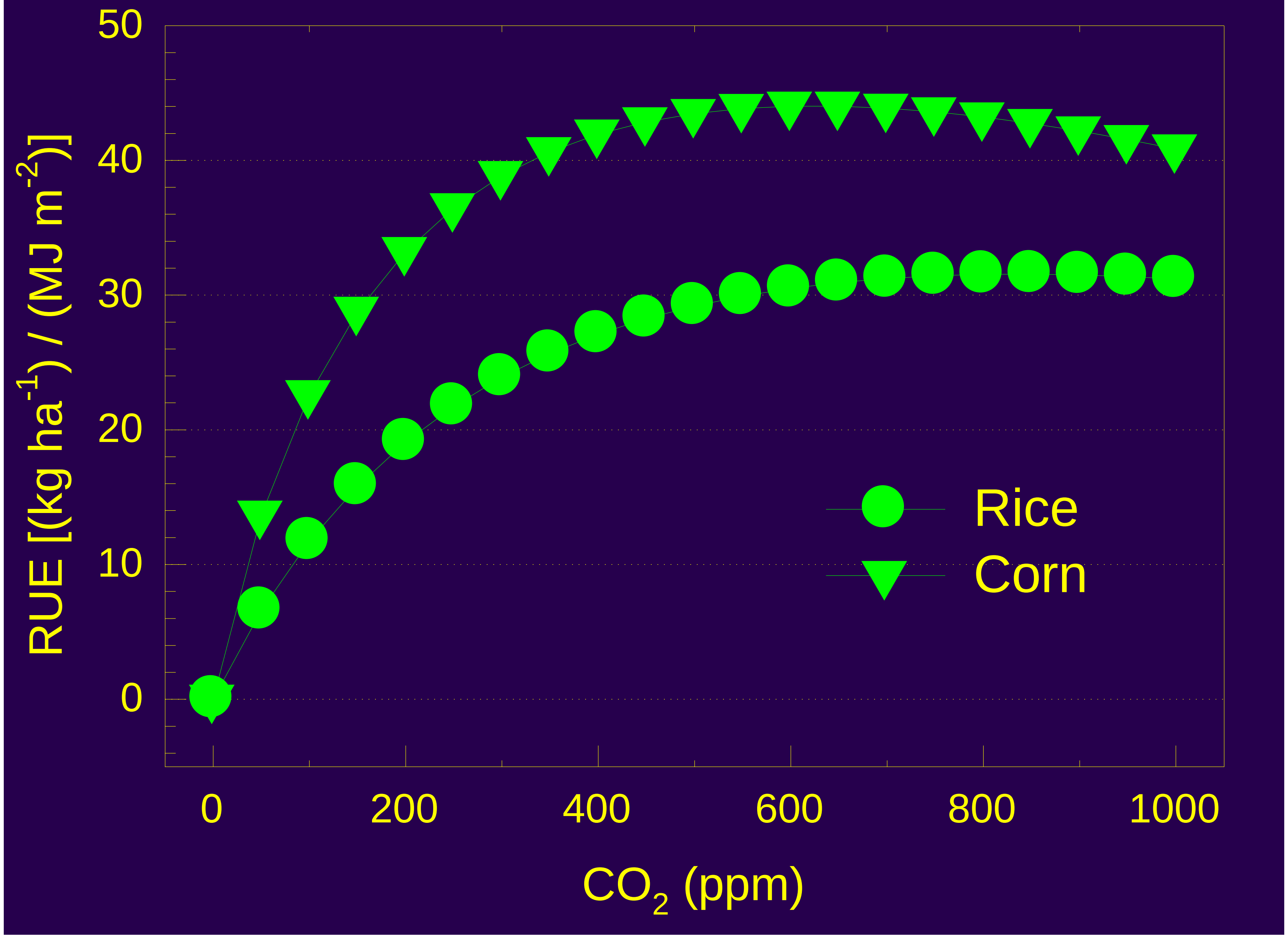
Data from our growth chambers.

K_e is relative leaf growth rate

T_e determines how fast a leaf reaches its maximum size

PHOTOSYNTHESIS

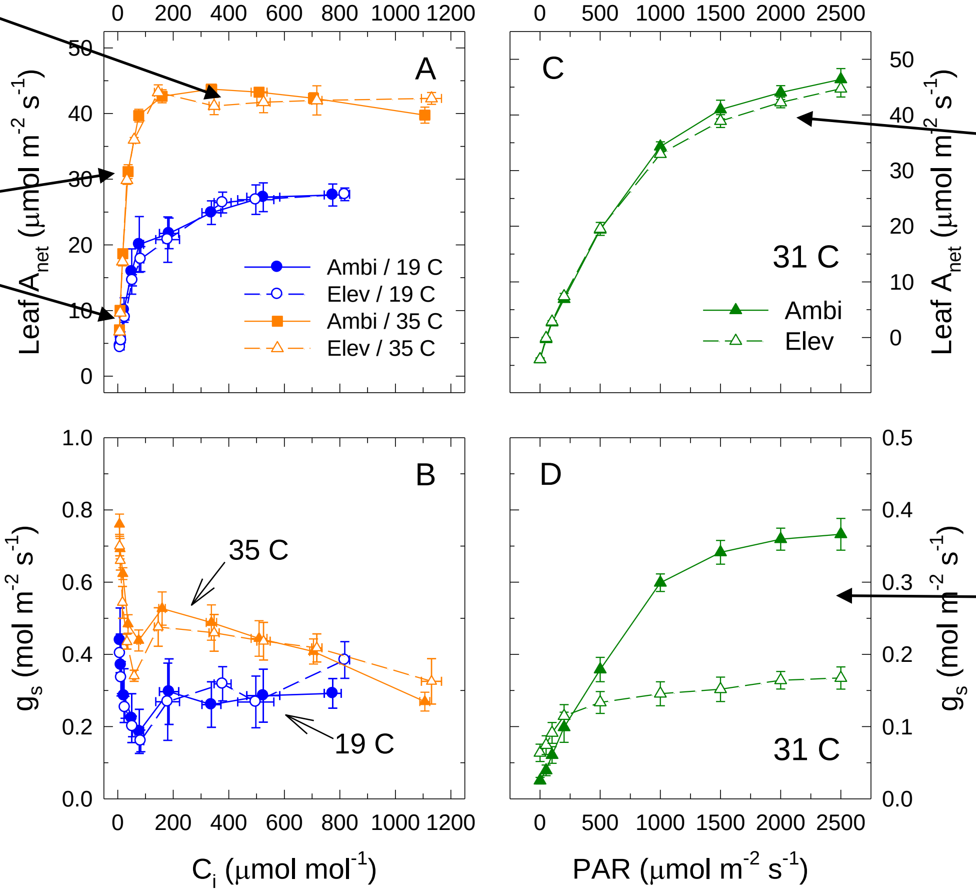
Response to CO_2 in EPIC



Photosynthesis (leaf level) in Maize as a function of CO_2 and temperature

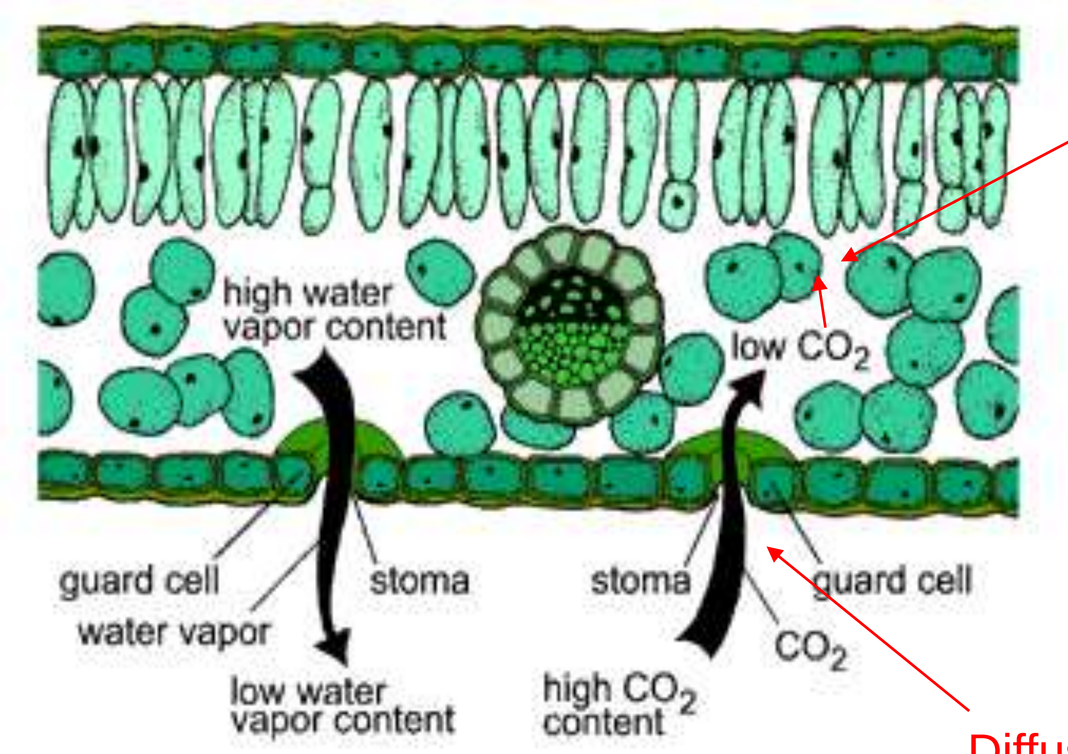
Light limited

Carbon limited



Small difference in net Photosynthesis with increasing CO_2

Large decrease in stomatal conductance and thus transpiration



Enzymatic based reactions to take up CO_2

Diffusion

Photosynthesis can be considered a series of gas exchange processes.

CO_2 diffuses into the leaf interior and water vapor diffuses out.

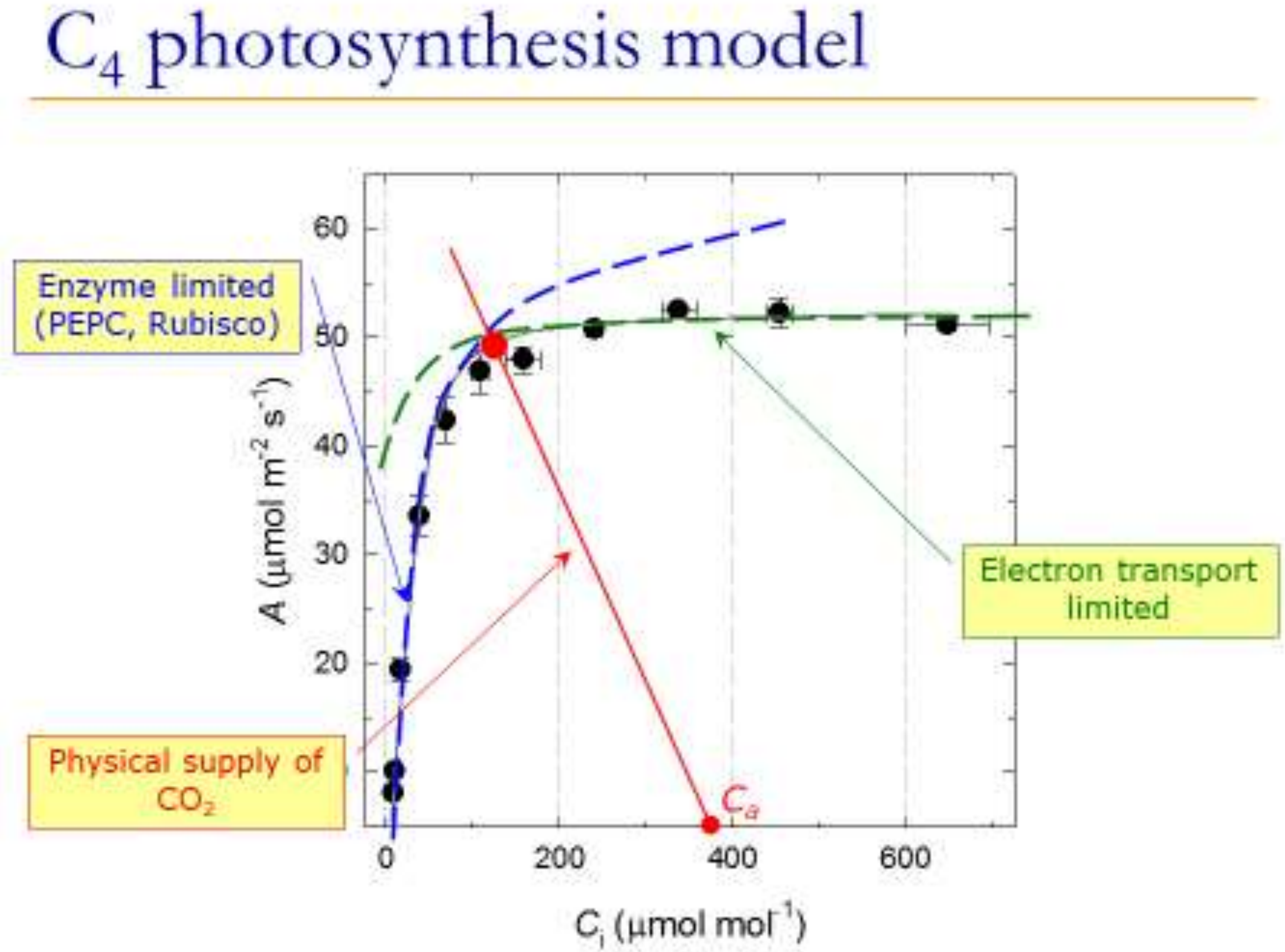
The higher the CO2 concentration, the less the water vapor diffusion. Stomata do not open as widely

http://supercoolandawesome.blogspot.com/2013/05/gas-exchange-in-aquatic-and-terrestrial.html

Photosynthesis

- CO2 supply (source)
  - Diffusion equation
- Biochemical demand (sink)
  - Uses Michaelis-Menton kinetics
  - von Caemmerer (2000)
- Accounts for the CO2 concentrating mechanism and related leakage
  - Function of Ci, leaf temperature and PAR

The sink component



C_4 photosynthesis model

Enzyme limited (PEPC, Rubisco)

Electron transport limited

Physical supply of CO_2

Model for leaf gas-exchange (source component)

- Transpiration and leaf temperature: Penman’s linearized energy budget equation
- Numerically solved for convergence

Calculation of Stomatal Conductance (g_s) and Transpiration (E)

$$g_s = g_0 + g_1 A \frac{h_s}{(C_s / P_a)} f(\psi_l)$$

h_s is relative humidity, C_s is leaf surface CO2 concentration Pa is air pressure, A is net photosynthesis, g_o and g_1 are parameters, f(Ψ) adjusts for water stress

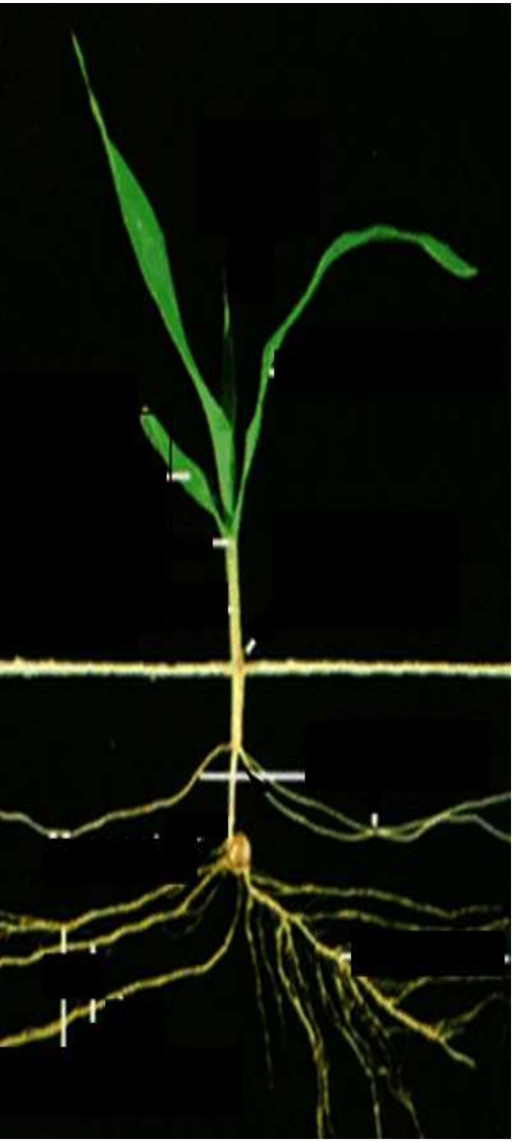
$$E = 2g_v \left(\frac{e_s(T_L) - e_a(T_a)}{P_a} \right)$$

An accurate estimation of leaf temperature is important

g_v is conductance to water vapor (a function of (g_s), e_s is vapor pressure of the leaf surface at leaf temperature (T_L), e_a is vapor pressure of the atmosphere at air temperature (T_a).

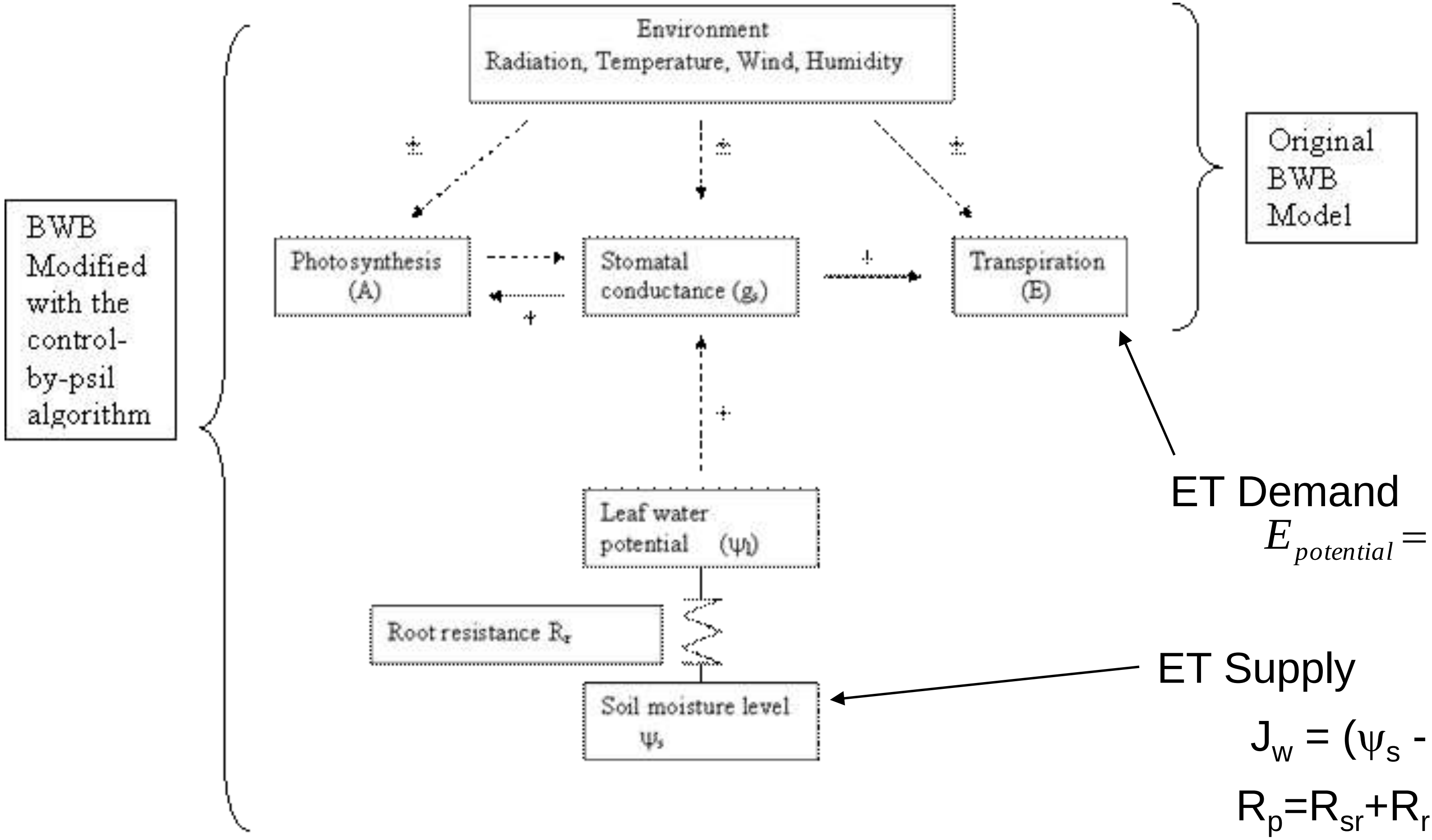
Challenges in modeling gas exchange

- Photosynthesis, transpiration, stomatal conductance, and leaf energy balance are closely linked to each other
- These processes should be coupled to make realistic predictions
  - Coupling enables estimation of unknown variables



$$g_s = g_0 + g_1 A \frac{h_s}{(C_s / P_a)} f(\psi_l)$$

$$f_1(\psi_l) = \frac{1 + \exp\left[s_f \psi_f\right]}{\exp\left[s_f (\psi_f - \psi_l)\right]}$$



ET Demand

$$E_{potential} = 2g_v\left(\frac{e_s(T_L) - e_a}{P_a}\right)$$

ET Supply

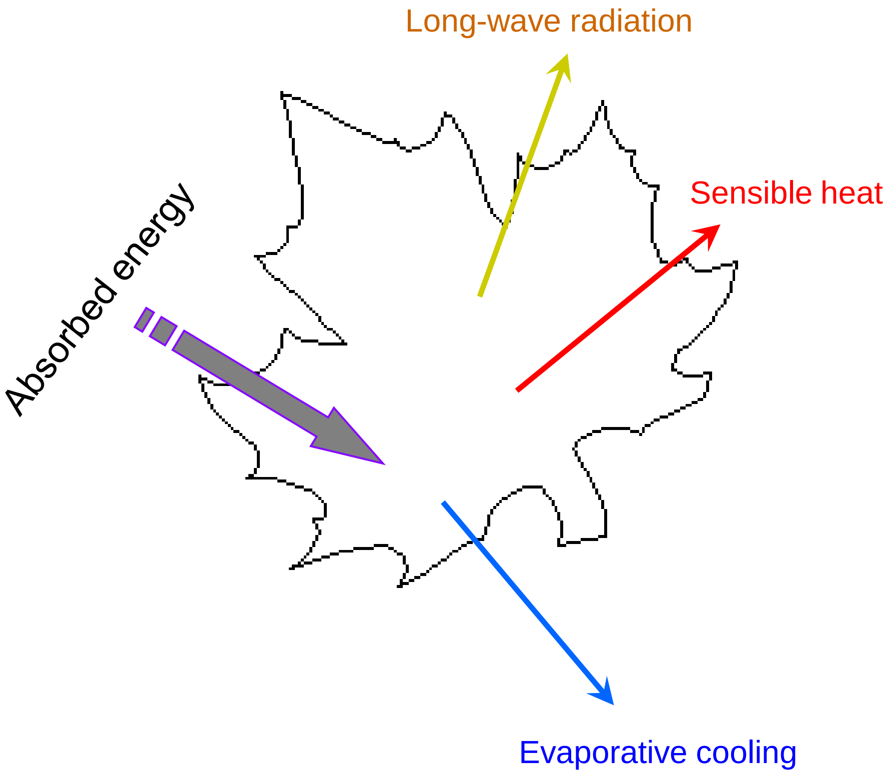
$J_w = (\psi_s - \psi_l)/R_p$

$R_p = R_{sr} + R_r + R_{stem}$

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)



Calculation of Leaf Temperature

$$T_L = T_a + \frac{\gamma^*}{s+\gamma^*}\left[\frac{R_{abs} - \varepsilon \cdot \sigma \cdot T_a^4}{g_{hr} c_p} - \frac{D}{p_a \gamma^*}\right]$$

$$\gamma^* = \frac{\gamma \cdot g_{hr}}{g_v} \qquad g_{hr} = g_h + g_r$$

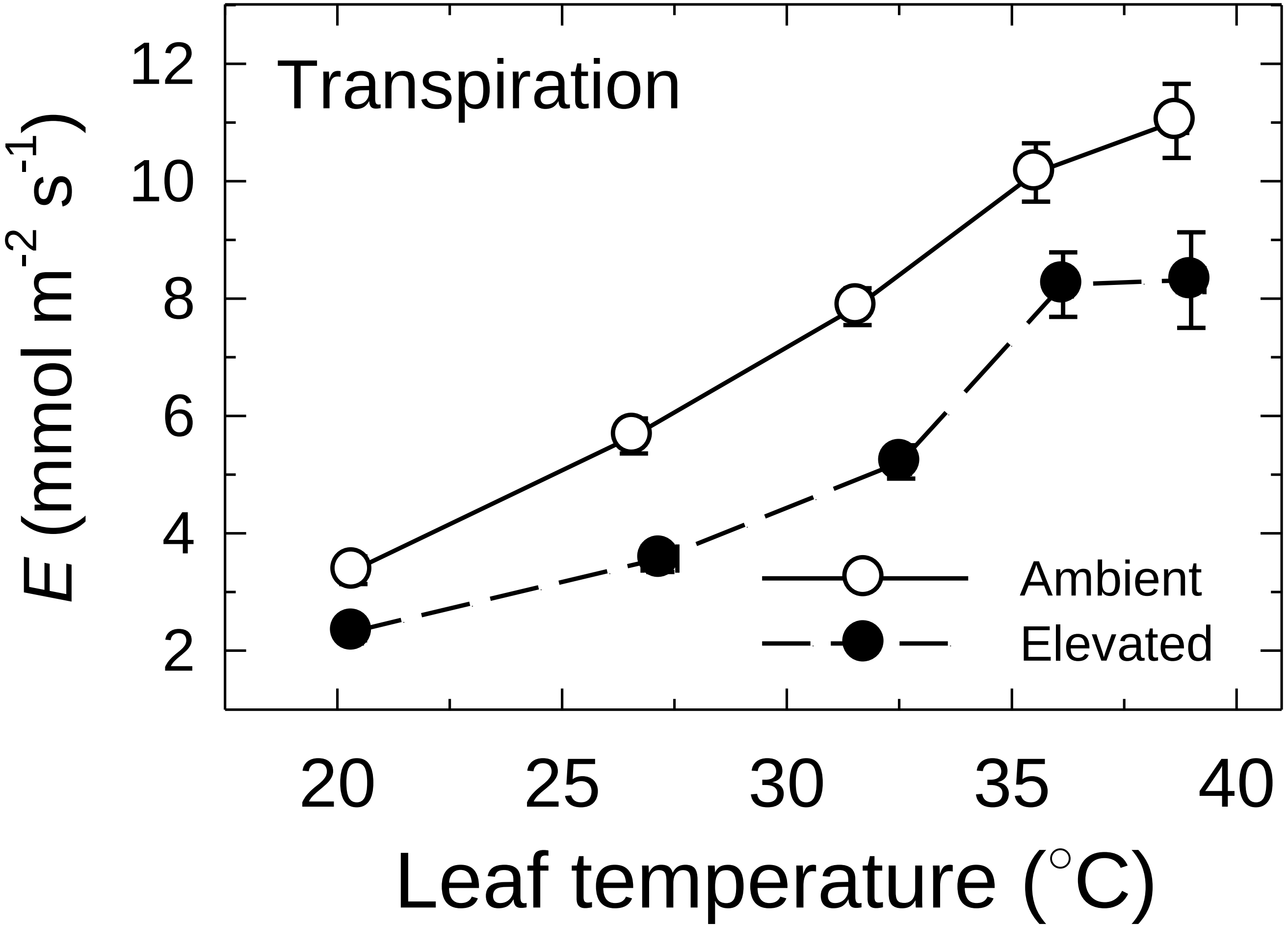
Where T_a is air temperature, R_{abs} is absorbed long-wave and short-wave radiation per surface leaf area, ε is leaf thermal emissivity (set to 0.97), σ is the Stefan-Boltzmann constant (5.67x 10-8 Watts m^{-2} K^{-4}), D is vapor pressure deficit, s is the slope of the slope of the vapor pressure deficit-temperature curve Δ divided by atmospheric pressure. γ is the psychrometric constant (6.66 x 10^{-4}). Total water vapor conductance per surface leaf area, g_v, is calculated from stomatal conductance and heat conductance at the boundary layer:

$$g_v = 0.5\frac{g_s \cdot g_{bw}}{g_s + g_{bw}}$$

Note that g_v requires g_s and is needed to calculate leaf temperature. Hence iteration is required

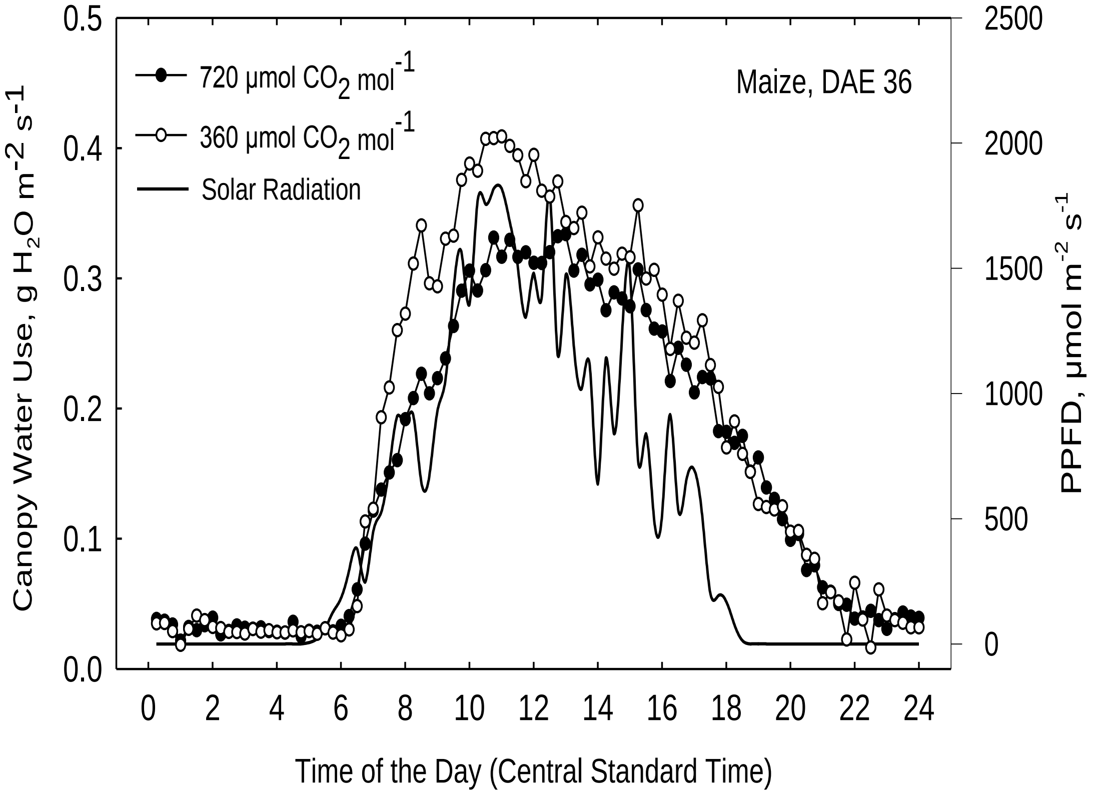
Temperature dependence of transpiration at elevated CO_2

- Consistent decrease in transpiration. Dependence on leaf temperature is similar.



Maize transpiration response – CO_2

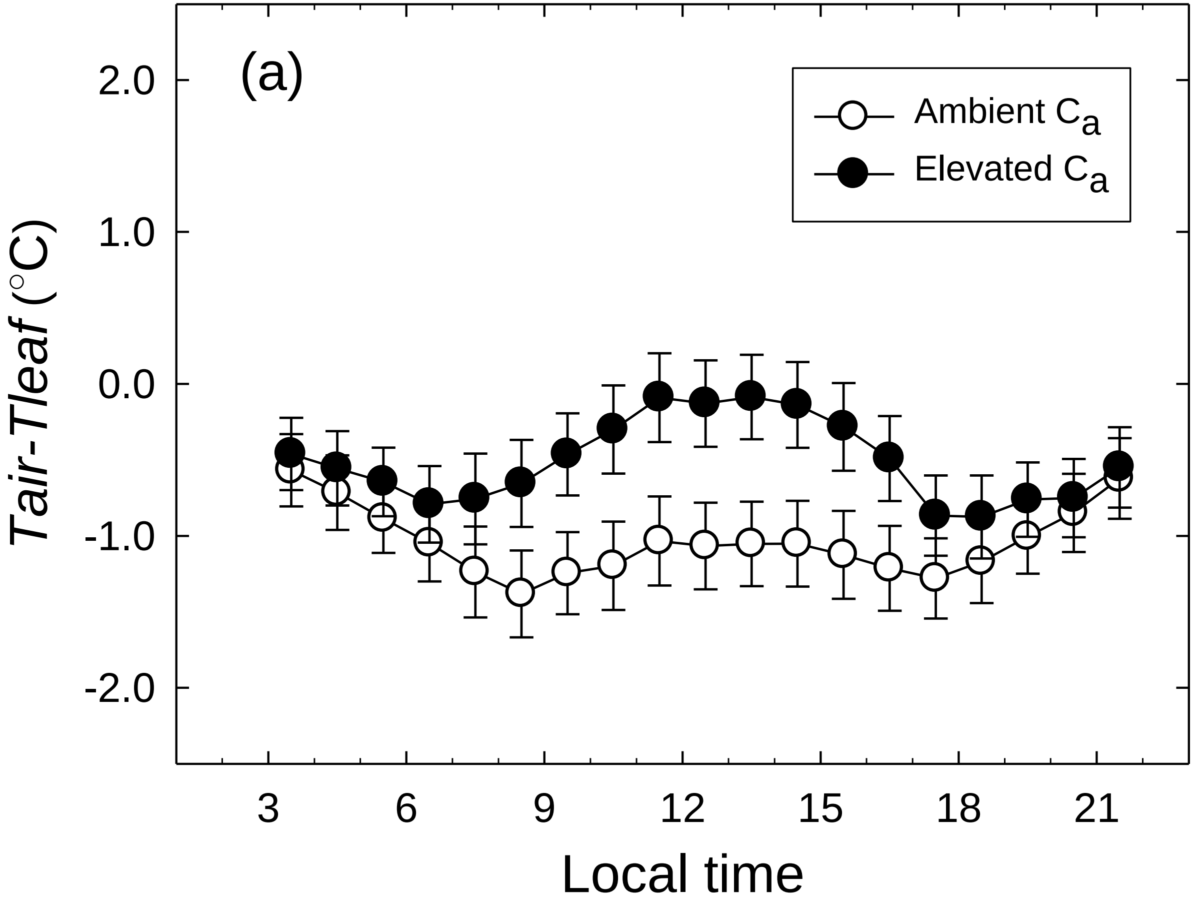
- Canopy Evapotranspiration (Diurnal, DAE 36)



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

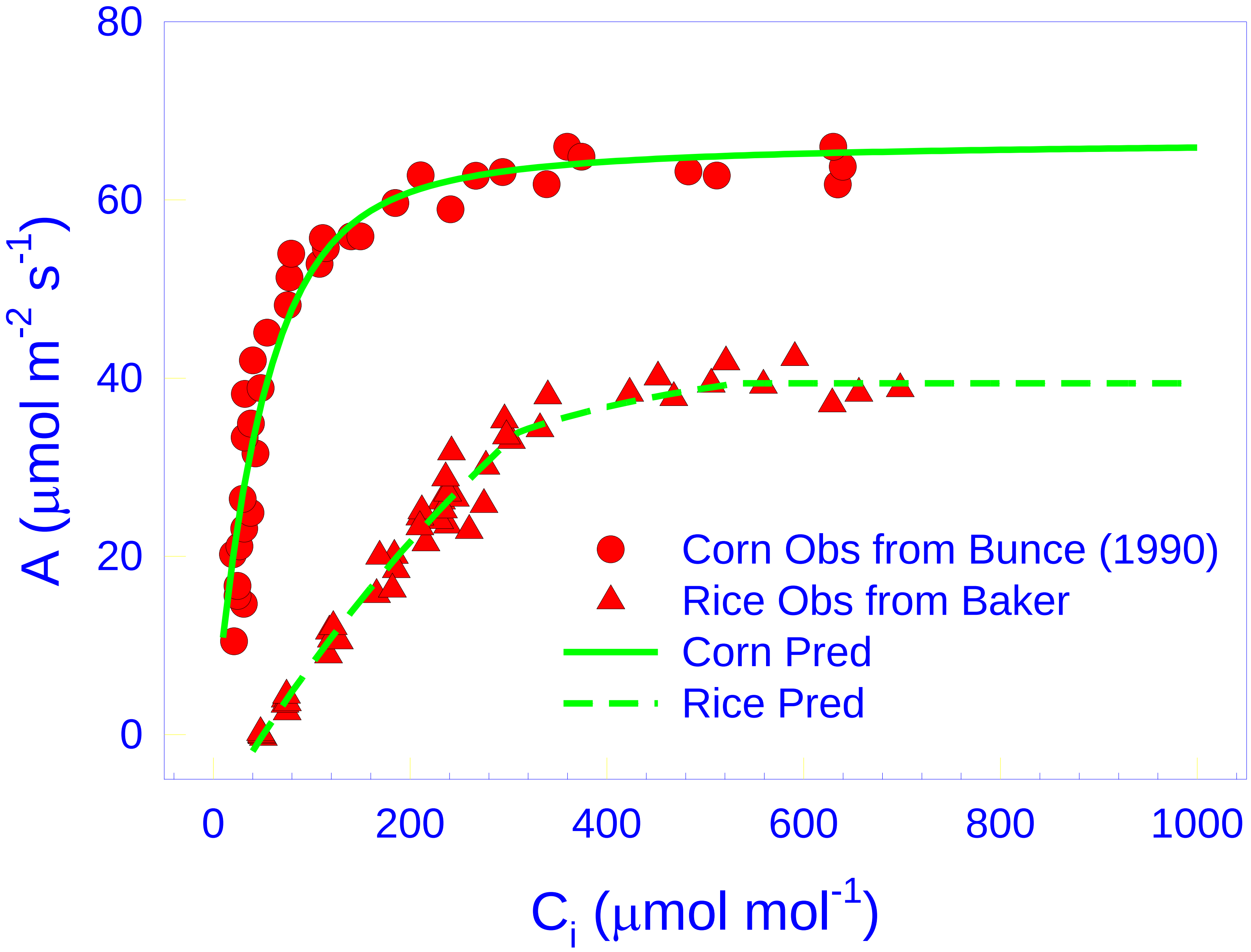
Adapted from: Kim, S.-H., Sicher R.C., Bae H., Gitz, D.C., Baker, J.T., Timlin, D.J. and Reddy. V.R. Canopy photosynthesis, evapotranspiration, leaf nitrogen, and transcription profiles of maize in response to CO2 enrichment. Global Change Biol. 12:588-600. 2006.

Leaf temperature of maize at elevated CO_2

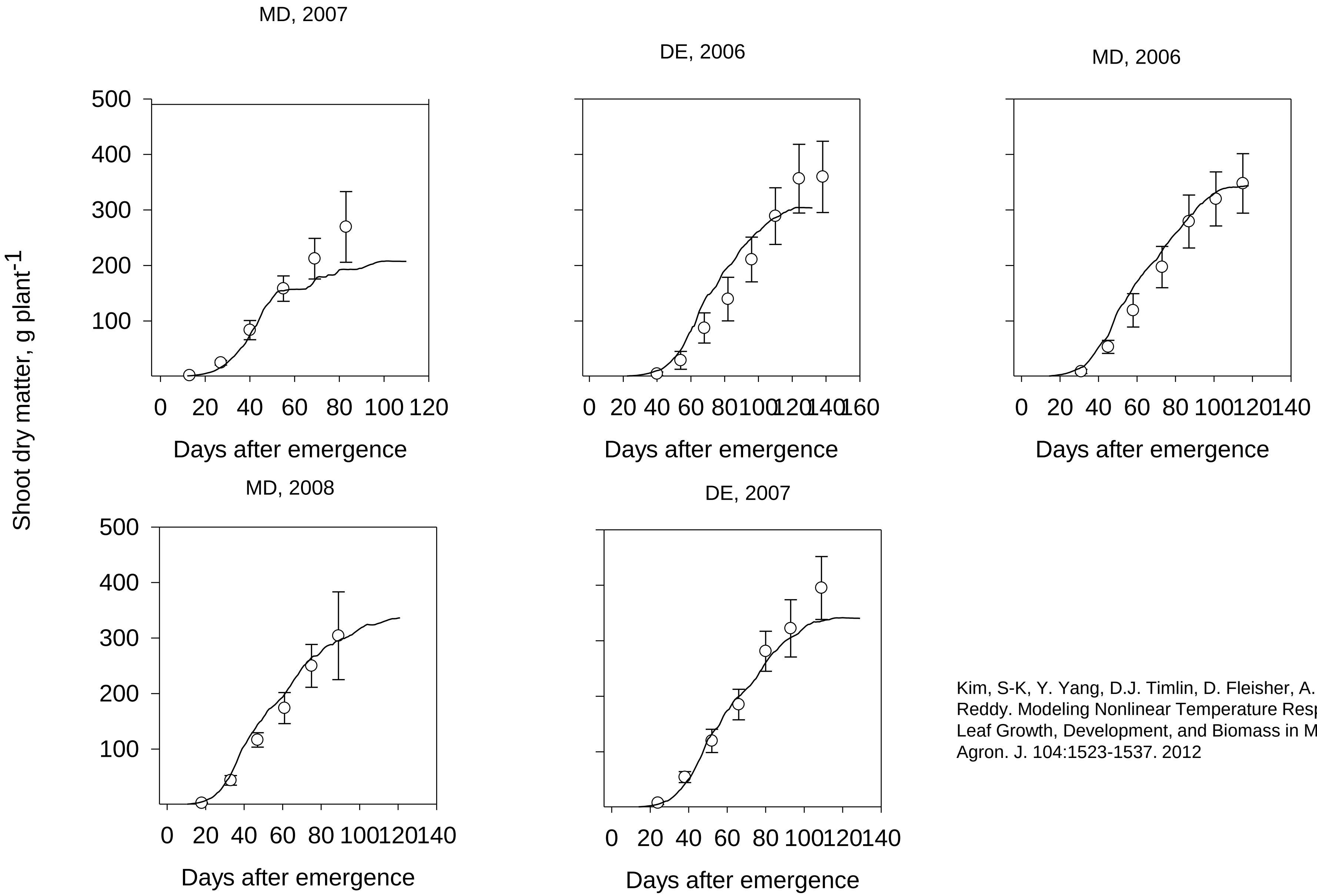


- Increased leaf temperature

Leaf A-C_i response of corn and rice



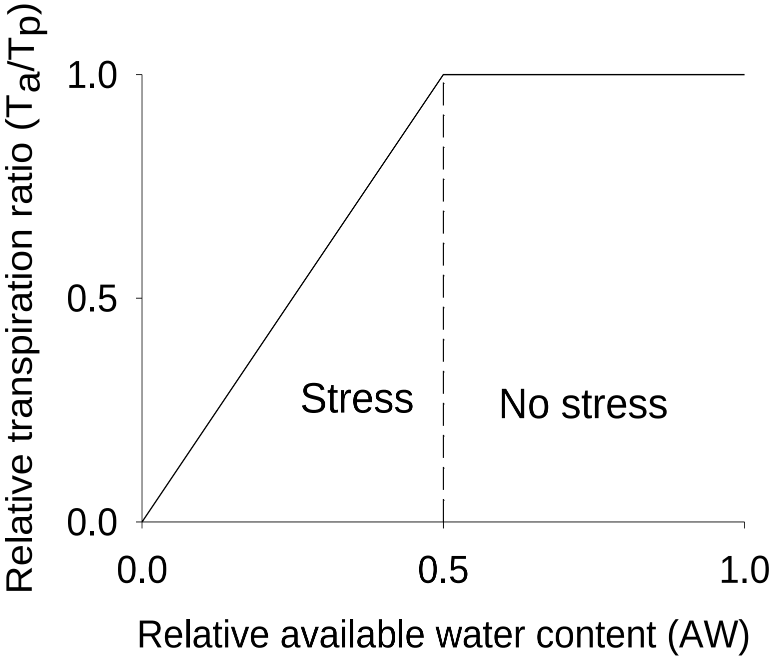
Biomass Calculated by MAIZSIM from Farms on the Eastern Shore of MD



Kim, S-K, Y. Yang, D.J. Timlin, D. Fleisher, A. Dathe, V.R. Reddy. Modeling Nonlinear Temperature Responses of Leaf Growth, Development, and Biomass in MAIZSIM. Agron. J. 104:1523-1537. 2012

WATER STRESS

Simple Method to Model Water Stress



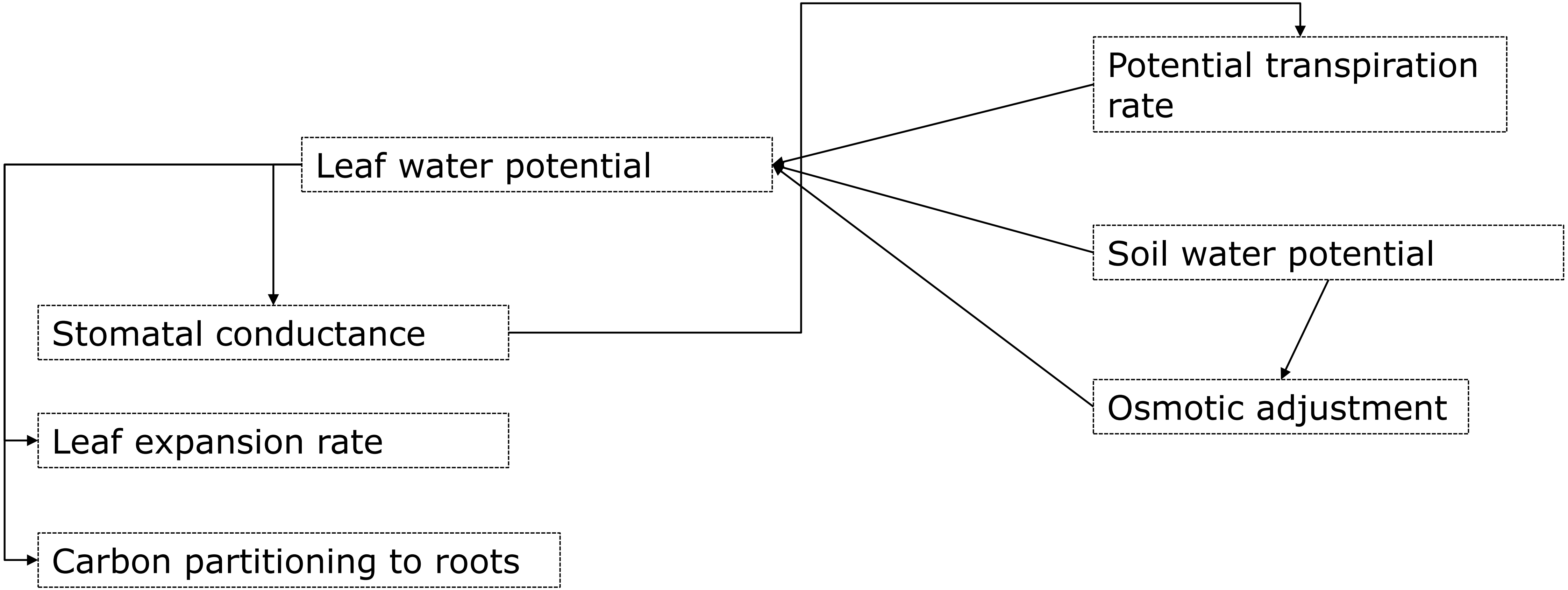
$$A_W = \frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}}$$

Limitations of Current Modeling Approaches

- These are empirical approaches that mimic the impact of water stress on growth and yield not the mechanism.
- Energy balance is not always modeled
- No stomatal response (effects on carbon assimilation) to increased CO_2 or temperature
- Assumes stomata control transpiration and photosynthesis (and growth) proportionally

Response of Plants to Water Availability

- Stomatal closure decreases water loss more than it decreases carbon assimilation
- Linking water loss and photosynthesis as a linear relationship to model water stress will result in underprediction of yields.



Potential transpiration rate

Leaf water potential

Soil water potential

Stomatal conductance

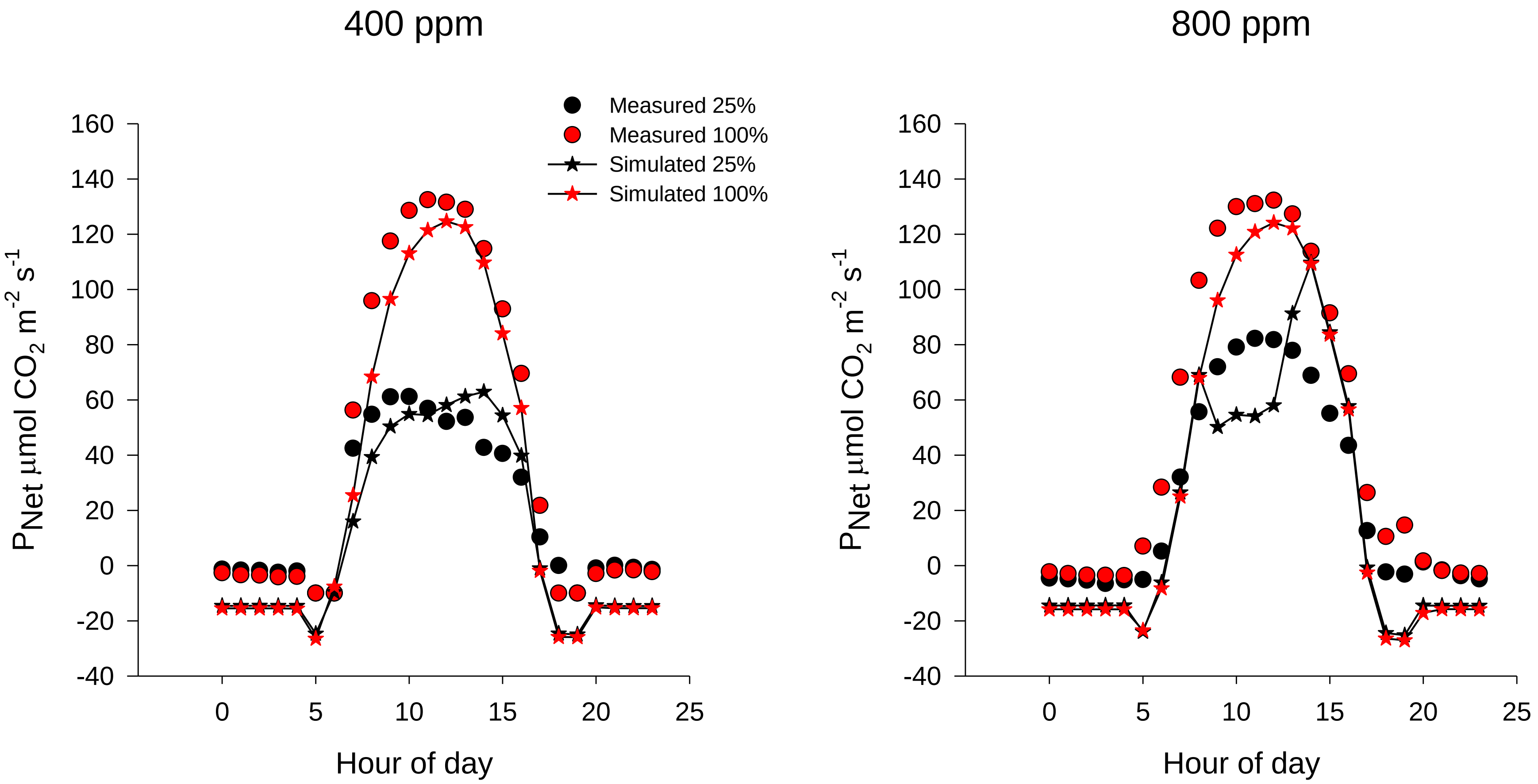
Osmotic adjustment

Leaf expansion rate

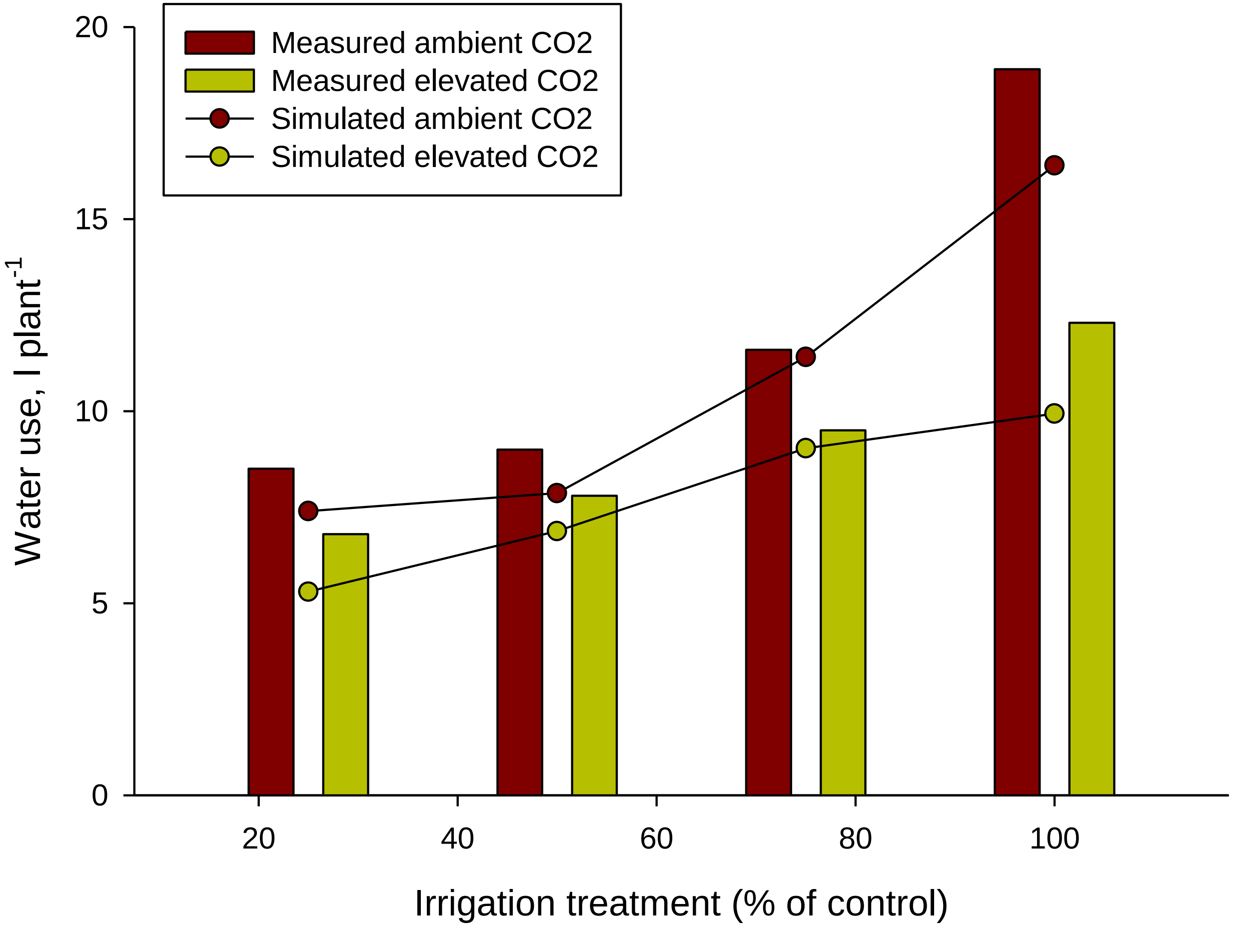
Carbon partitioning to roots

Leaf water potential is a basis for water stress calculations.

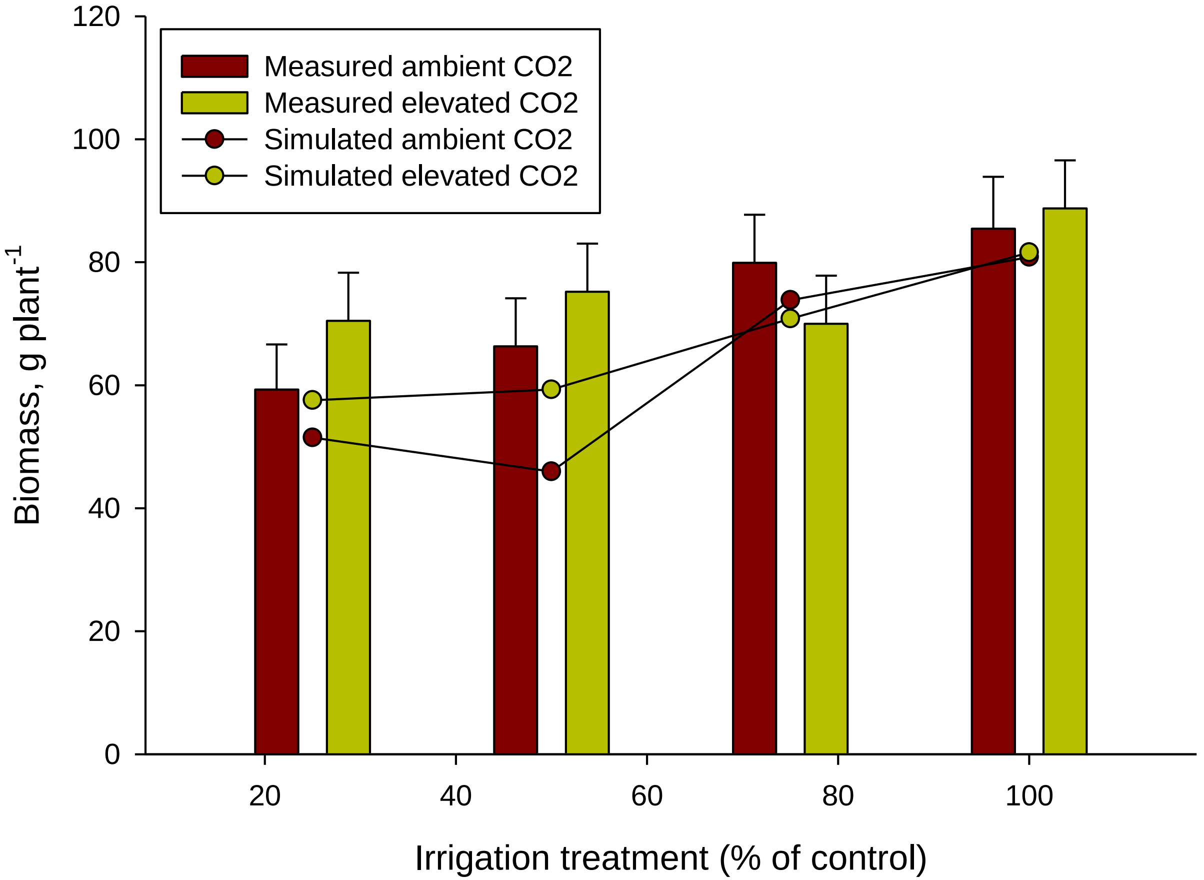
Simulating carbon assimilation rates and transpiration in growth chambers



Water Use, Observed and from Simulations with SPAR Environment Data



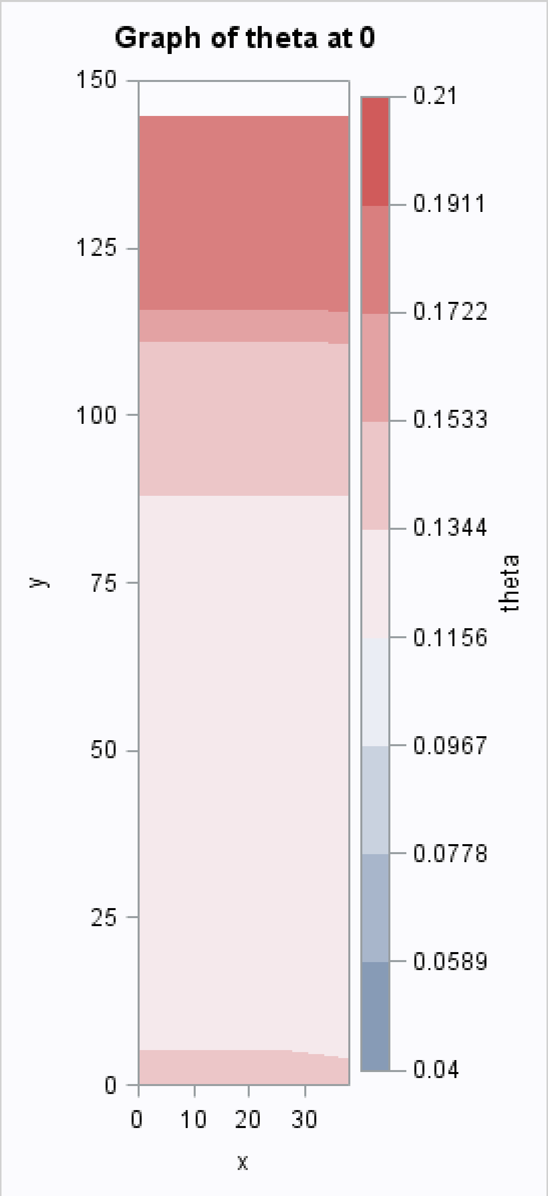
Biomass



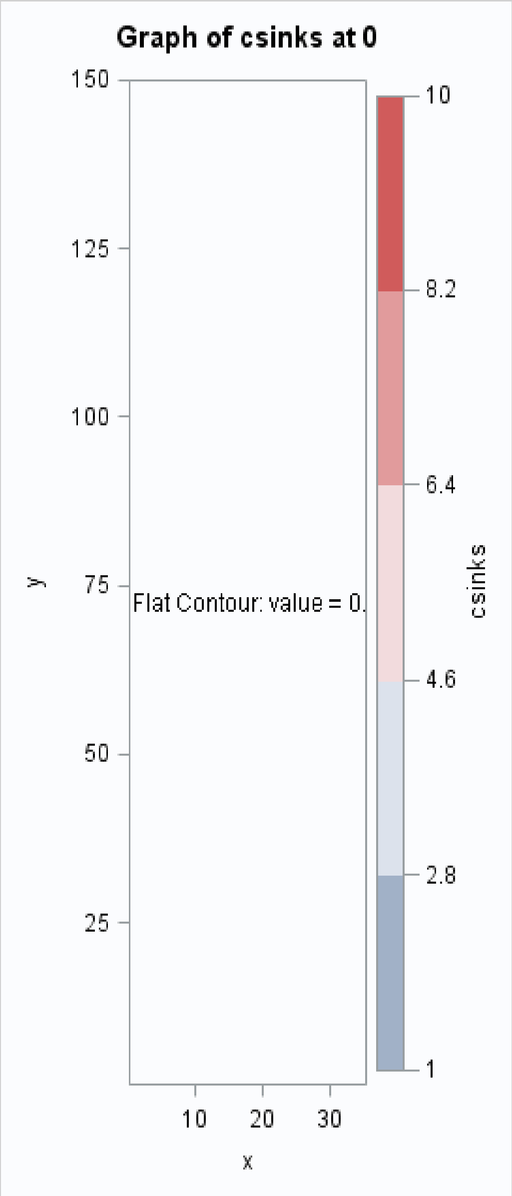
Measured ambient CO2
Measured elevated CO2
Simulated ambient CO2
Simulated elevated CO2
Biomass, g plant^{-1}
0
20
40
60
80
100
120
20
40
60
80
100
Irrigation treatment (% of control)

TESTING AND SOME APPLICATIONS

Water content

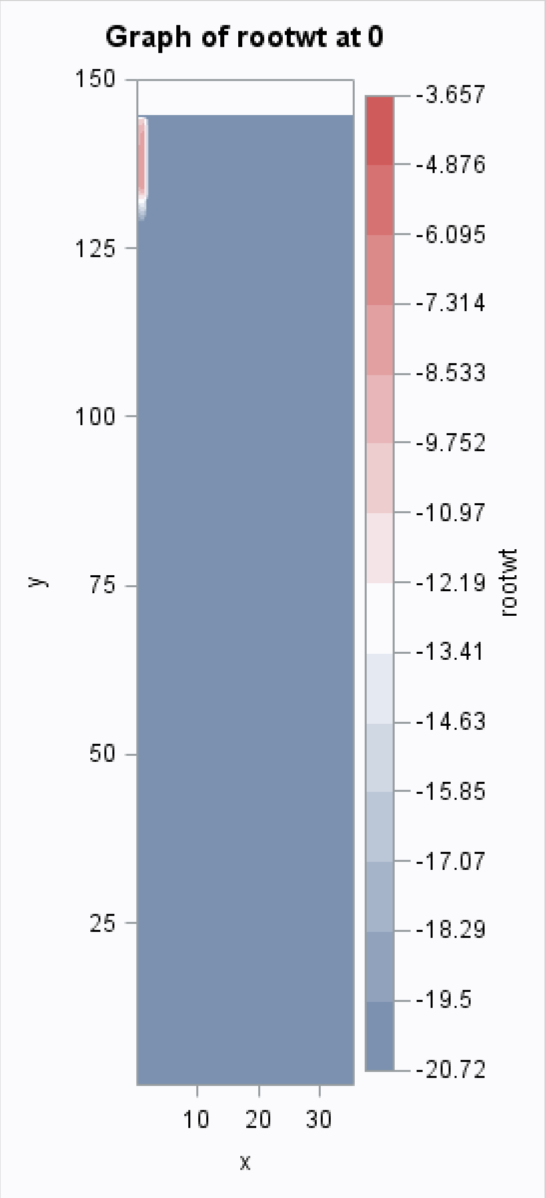


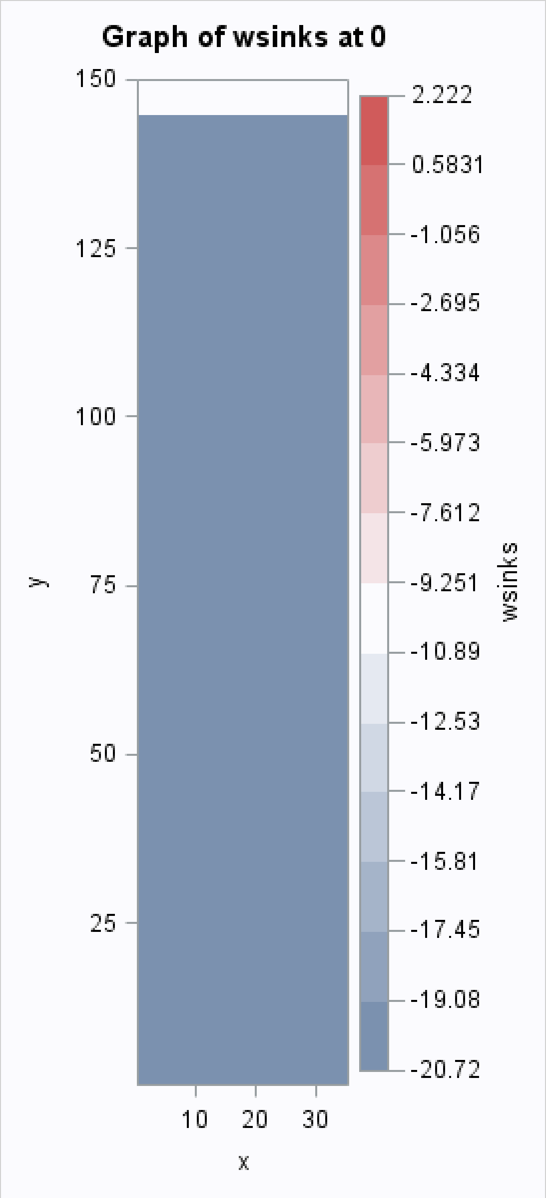
Nitrogen uptake



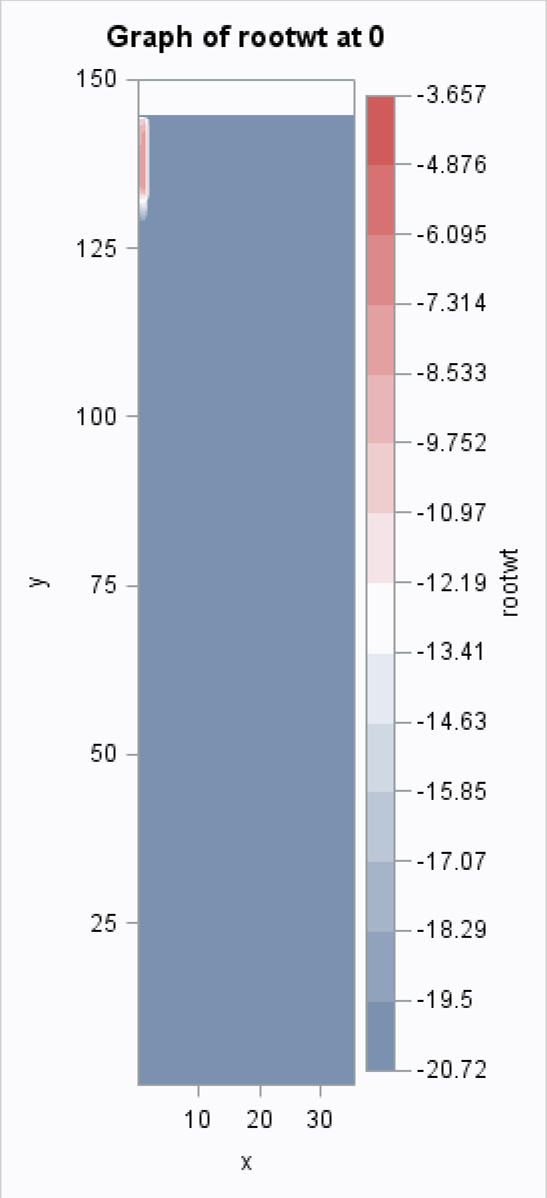
Root growth

Water uptake

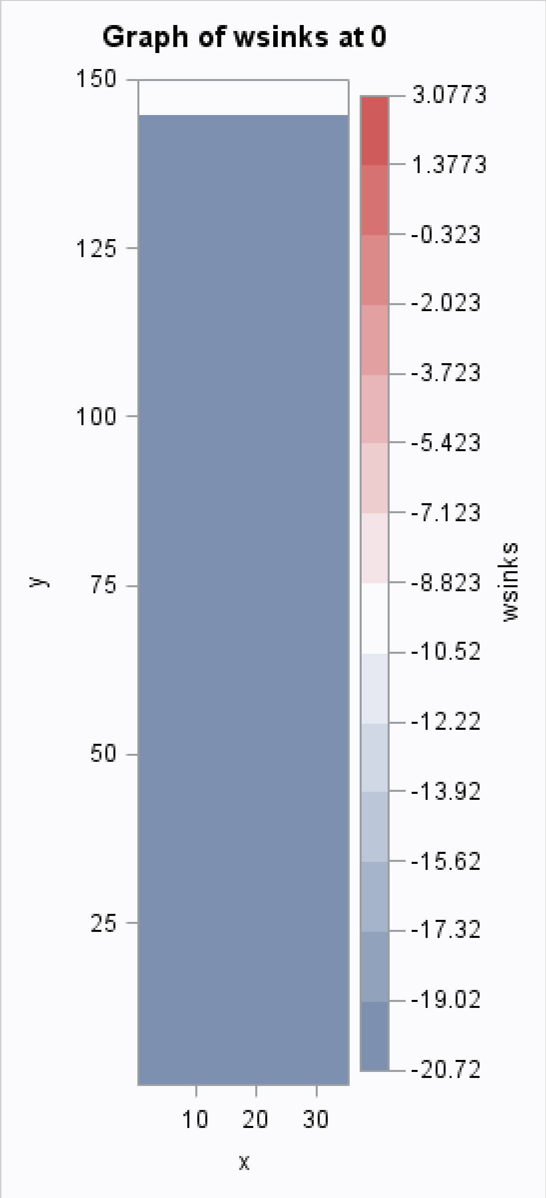




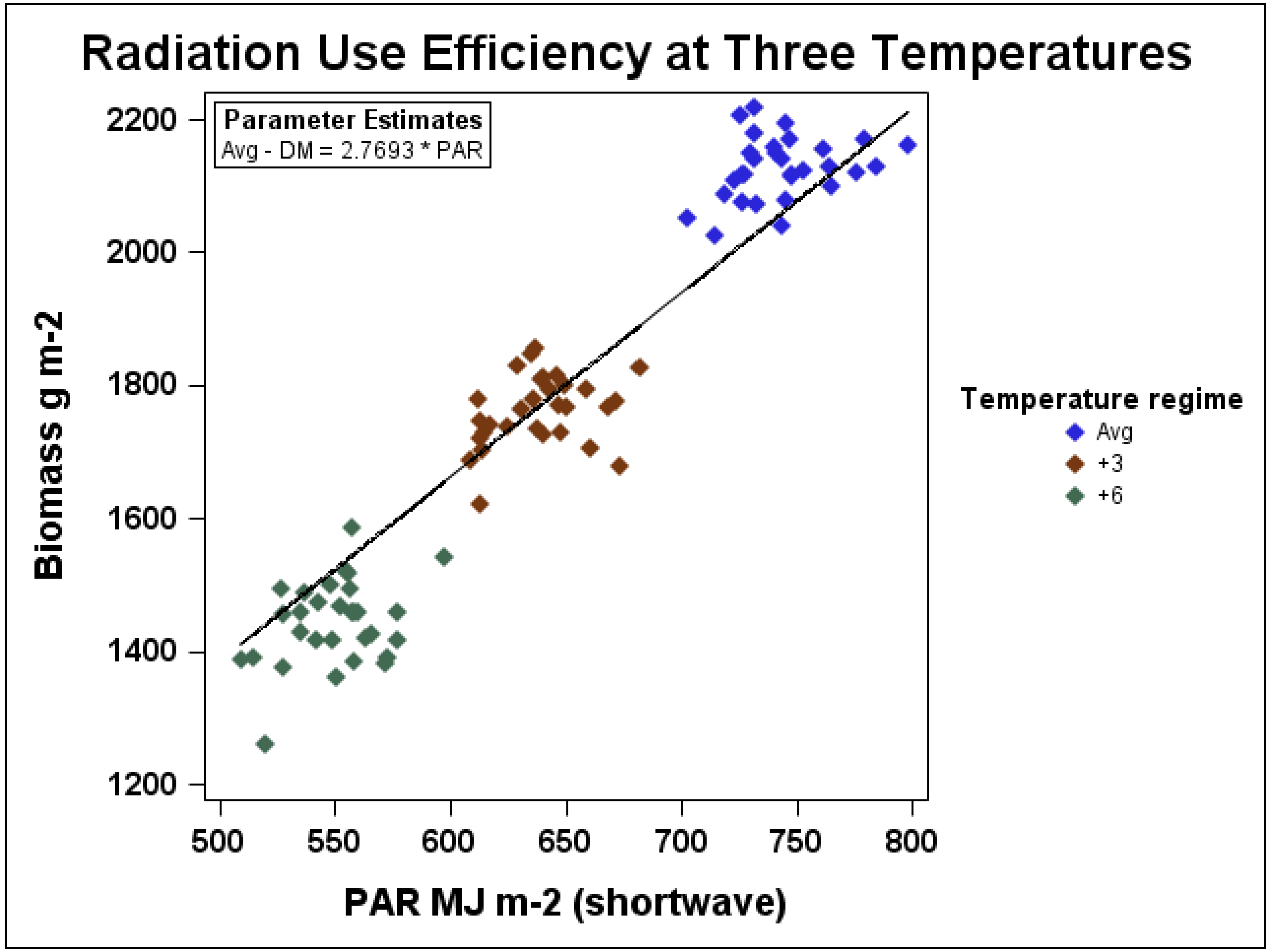
Root growth



Water uptake

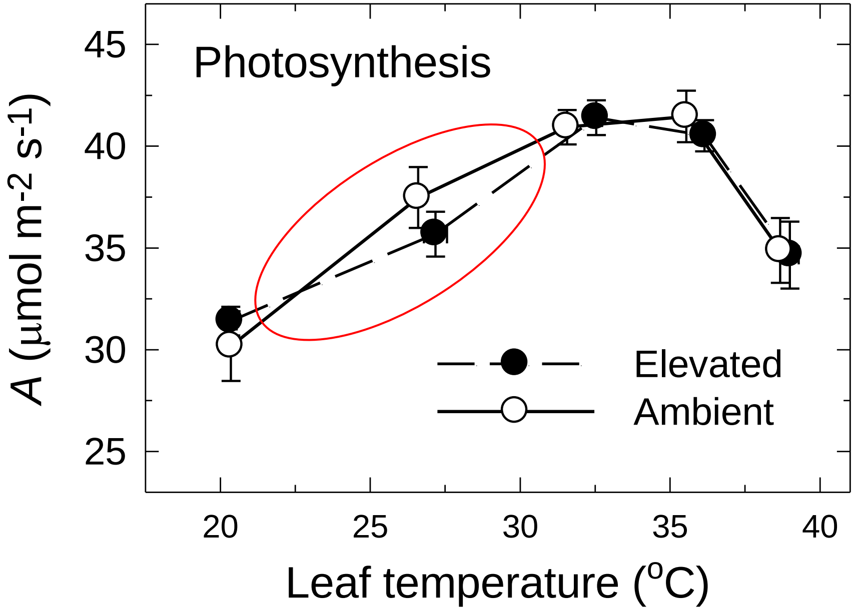


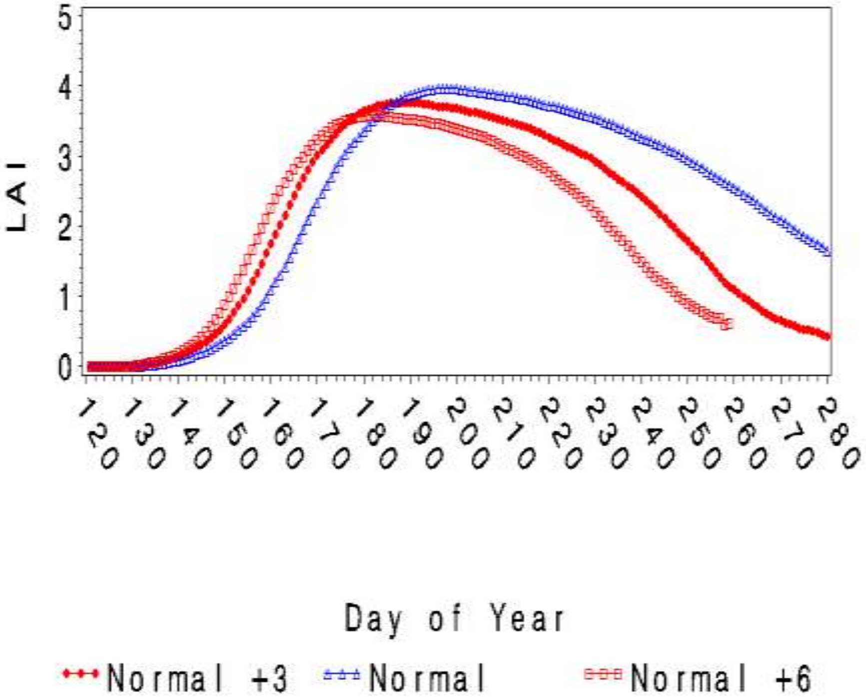
Radiation use efficiency from simulations for three temperature scenarios



What is the reason for the temperature effect?

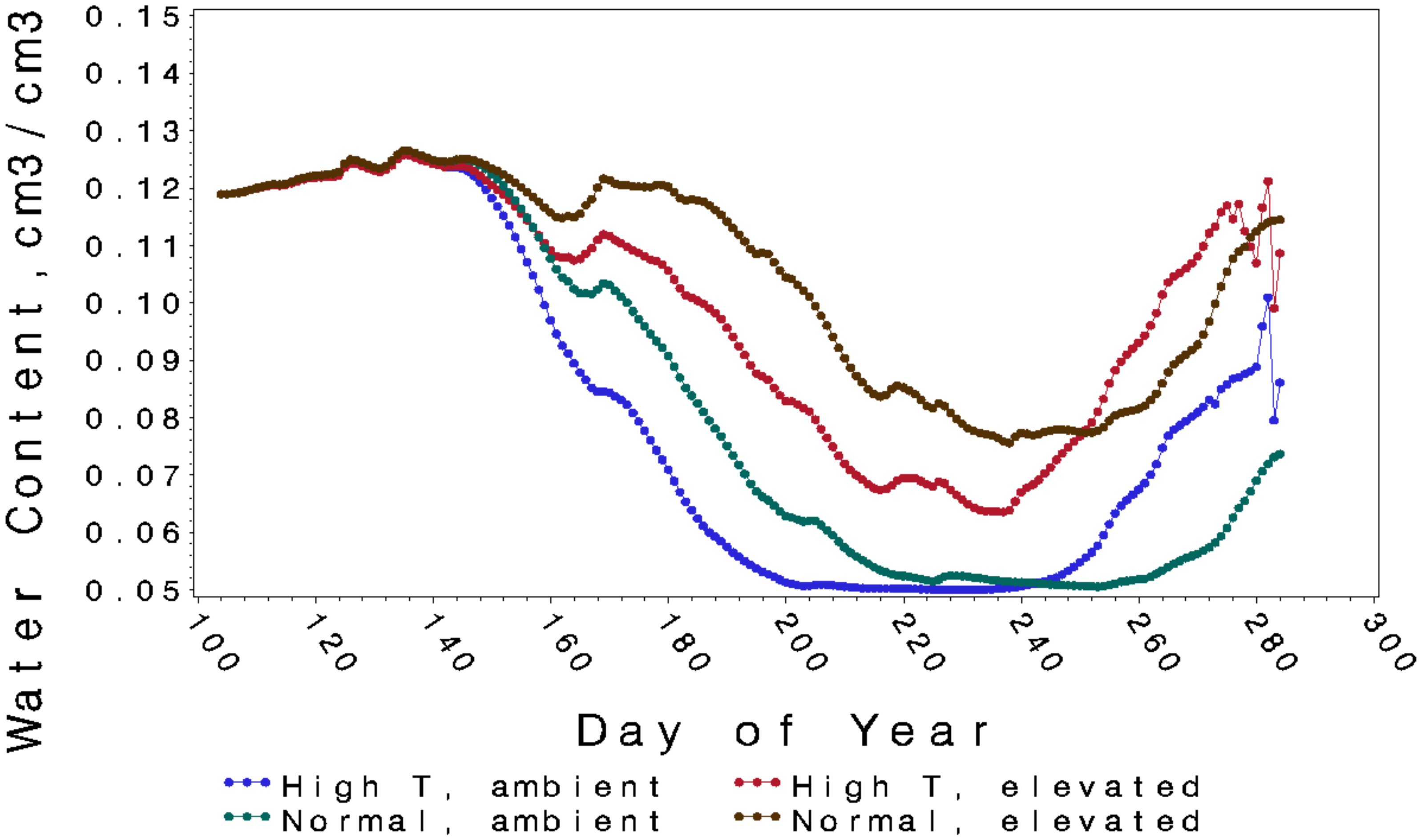
Temperature Regime		
Avg	+3	+6
22.0	25.0	27.5





High temperatures -> rapid growth and smaller leaves-> rapid senescence.

Mean Water Content at 60 cm Depth

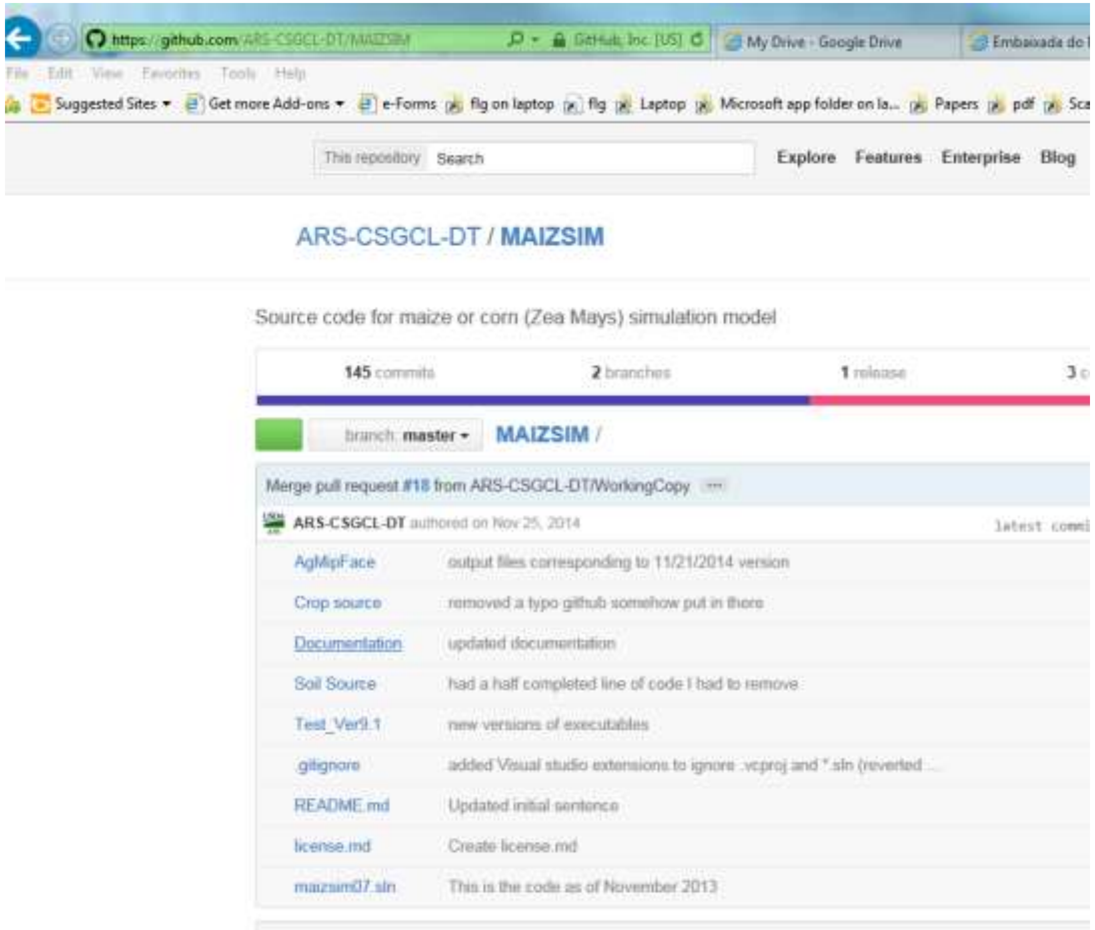


Closing notes

- Complex models are possible.
  - Our experience indicates that although they require more parameters, many of the parameters have physical meaning and can be fit independent of the environment.
- Growth chambers are useful to provide finally controlled conditions to investigate environmental effects on plant growth and development –
  - Very quantitative
  - Fine time scales
- We have a potato (SPUDSIM) and a maize (MAIZSIM) model. soybean and wheat are under development

Closing notes (cont’d)

- MAIZSIM is open source and available on GitHub. Search using keywords Github and MAIZSIM.



ARS-CSGCL-DT / **MAIZSIM**

Source code for maize or corn (Zea Mays) simulation model

145 commits
2 branches
1 release
3

MAIZSIM /

Merge pull request #18 from ARS-CSGCL-DT/WorkingCopy

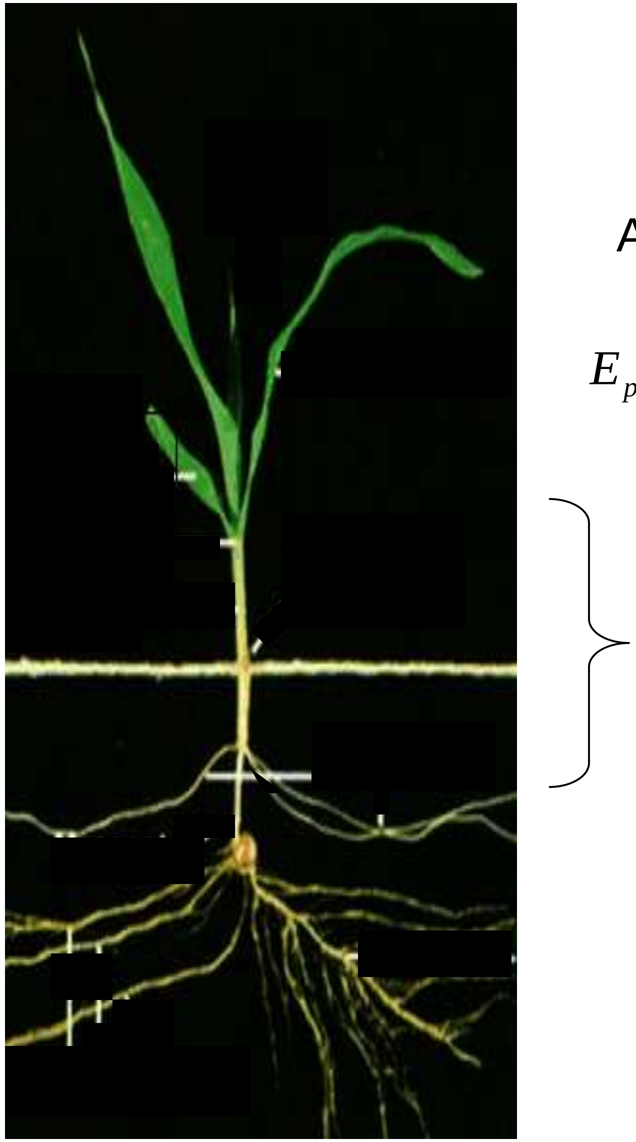
ARS-CSGCL-DT authored on Nov 25, 2014

latest comm

AgMipFace	output files corresponding to 11/21/2014 version
Crop source	removed a typo github somehow put in there
Documentation	updated documentation
Soil Source	had a half completed line of code I had to remove
Test_Ver9.1	new versions of executables
.gitignore	added Visual studio extensions to ignore .vcproj and *.sln (reverted …
README.md	Updated initial sentence
license.md	Create license.md
maizsim07.sln	This is the code as of November 2013

THANK YOU!

The Coupled Model



A, g_s, c_i, T_l

$$E_{potential} = 2g_v\left(\frac{e_s(T_L) - e_a}{P_a}\right)$$

A, g_s, c_i

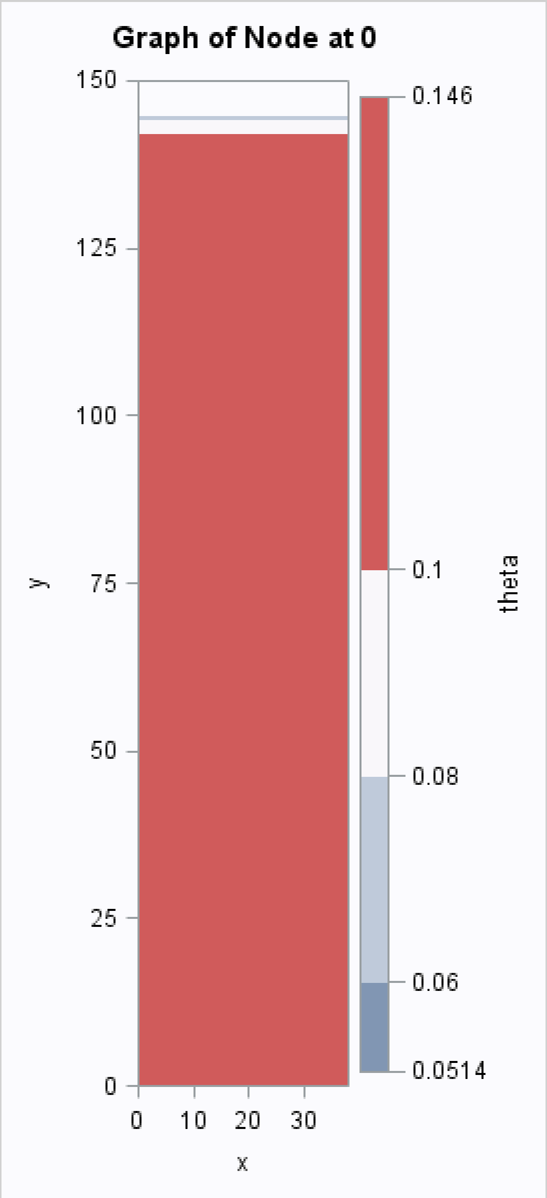
$g_s = f(A, h_s, c_i, \psi_{leaf})$

$A = f(g_s, T_l, R_{abs}, c_i)$

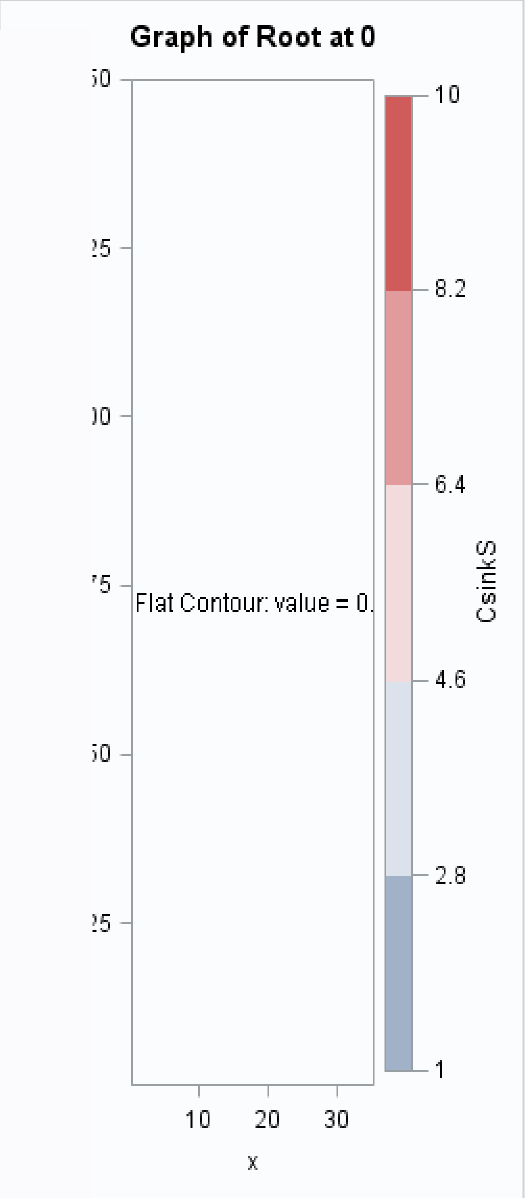
$$T_l = \frac{R_{abs} - \varepsilon_s \sigma T_a^4 - \lambda J_{stem}}{c_p(g_r + g_{Ha})}$$

$J_w = (\psi_s - \psi_l)/R_p$

$R_p = R_{sr} + R_r + R_{stem}$



Graph of Node at 0



Graph of Root at 0

Current Modeling Approaches Can be Improved

- We need a more physiologically based approach that takes into account processes that plants have developed to optimize carbon assimilation and minimize water loss under all conditions of water availability and especially water deficit situations.