

Nonlinear grassland dynamics along a CO₂ gradient

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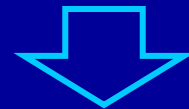
³Nicholas School of the Environment and Earth Sciences, Duke University, NC

Outline

1. Introduction and motivation
2. Leaf-scale photosynthesis model
 - Preliminary results
3. Canopy-scale model for plant-atmosphere CO₂ and water exchange
 - Preliminary results
4. Future developments

LYCOG experiment

- The **LY**simeter **CO₂** **G**radient (LYCOG) experiment reproduces a continuous gradient of atmospheric CO₂ from ~200 to ~550 ppm in a grassland ecosystem.
- Unique data sets showing strongly nonlinear grassland responses to elevated CO₂ (e.g., productivity, C/N ratios, respiration).
- Responses at different temporal and spatial scales.

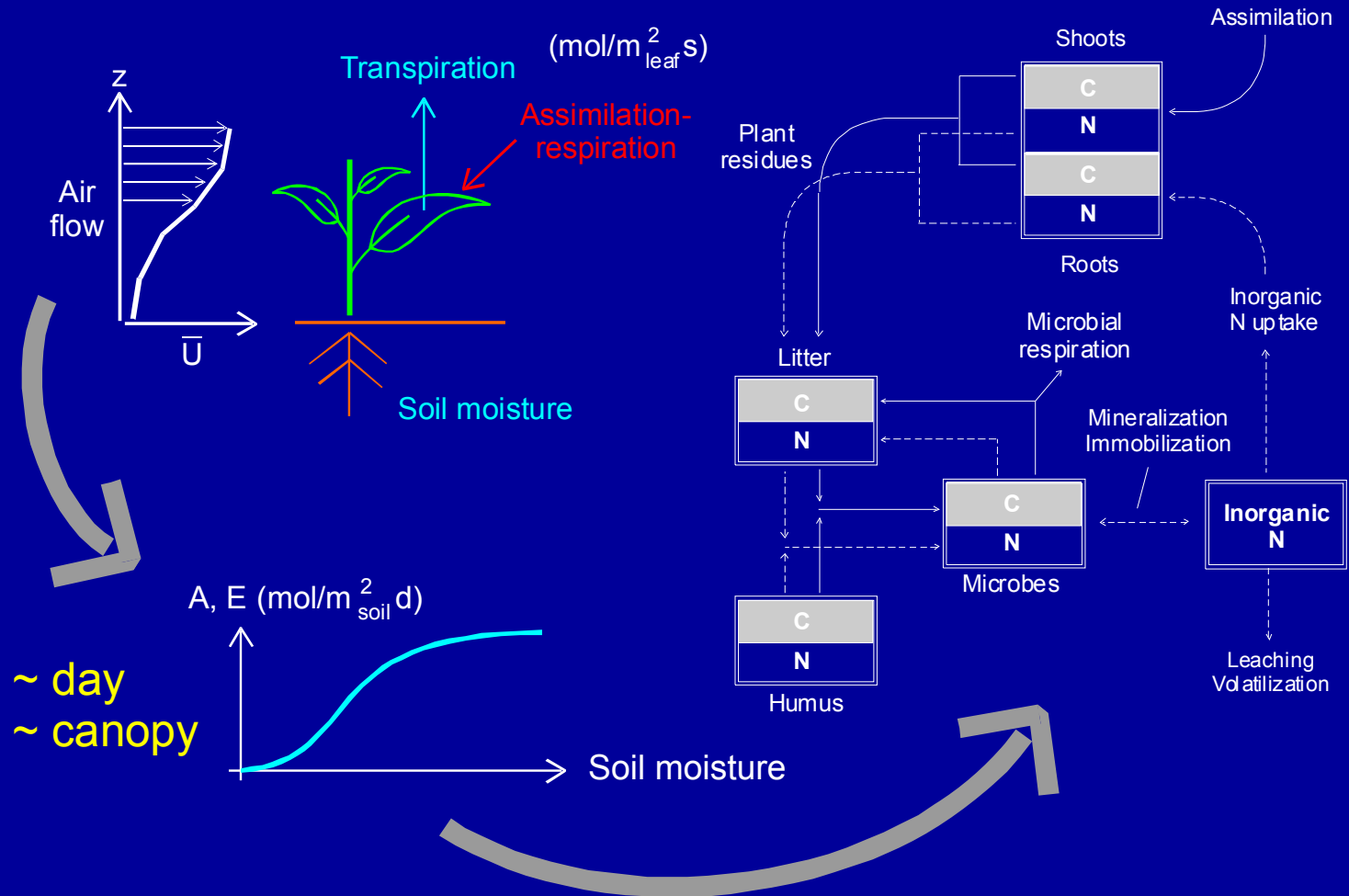


Modeling grassland dynamics under past, current, and future climatic scenarios

Dynamics at different scales

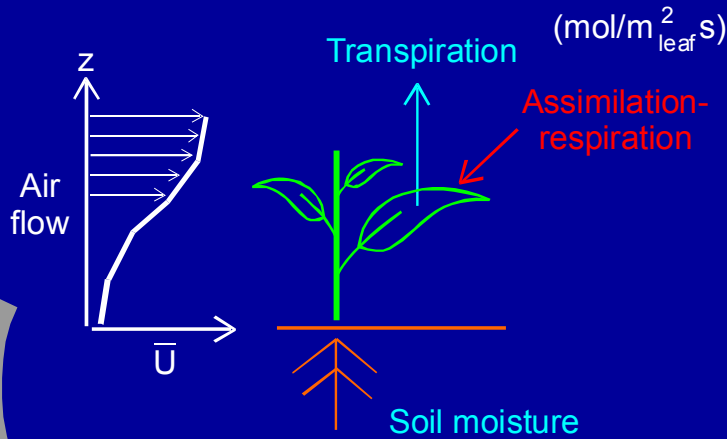
Time scale ~ minutes
 Spatial scale ~ leaf

~ month-year

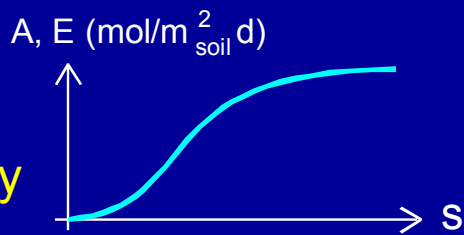


Dynamics at different scales

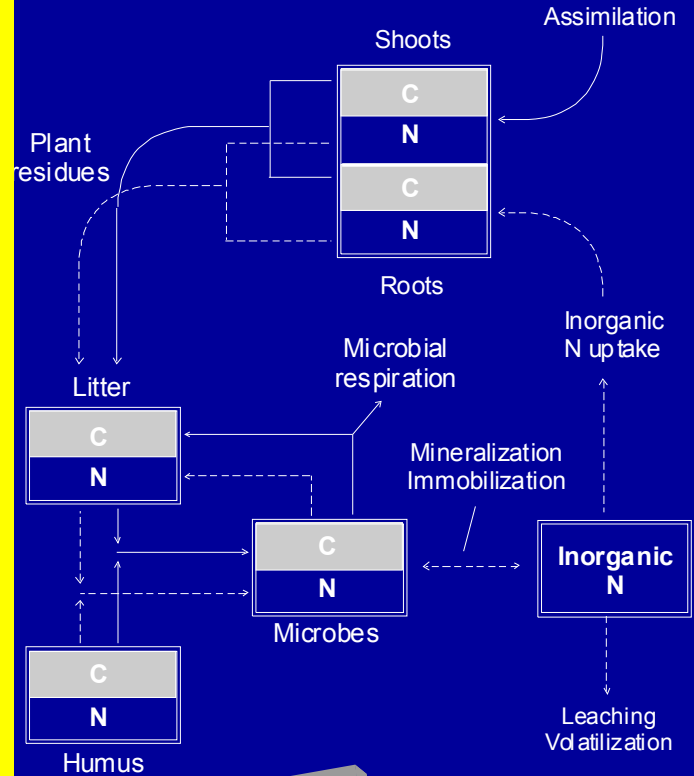
Time scale ~ minutes
 Spatial scale ~ leaf



~ day
 ~ canopy



~ month-year



Modeling goals and applications

- Focus on grassland dynamics
 1. Highly responsive to environmental variability and climatic changes (elevated CO₂ and temperature; altered rainfall patterns)
 2. Potential for C sequestration (increased productivity under elevated CO₂; soil C storage)
 3. Complex internal dynamics (chaotic?)
- Modular framework to allow analysis of individual sub-models or of the fully-coupled soil-plant-atmosphere model
- Uniform level of complexity across scales

Hierarchical model framework

- Coupling of fluid mechanics to plant, soil, and ecosystem biogeochemistry and stoichiometry
- A comprehensive model to describe
 1. Short-term environmental variability ~ minutes (e.g., radiation, turbulent mixing)
 2. Medium-term dynamics ~ days (e.g., soil moisture variability)
 3. Seasonal scale growth patterns and nutrient cycling [currently under development]

Model description and preliminary results

1. Fluid mechanics of the canopy layer
2. Leaf-level photosynthesis

Assimilation and stomatal conductance under different environmental conditions (leaf water status and CO₂)

3. Soil-plant atmosphere continuum
4. Profiles of canopy-atmosphere exchanges

Daily cycles of assimilation and transpiration

3. Whole-canopy fluxes integrated at daily time scale

Effects of soil moisture availability and atmospheric CO₂

Canopy fluid-mechanics

Navier-Stokes equations

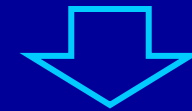


1. Planar-homogeneous system
2. High Reynolds number
3. Stationary flow
4. No subsidence



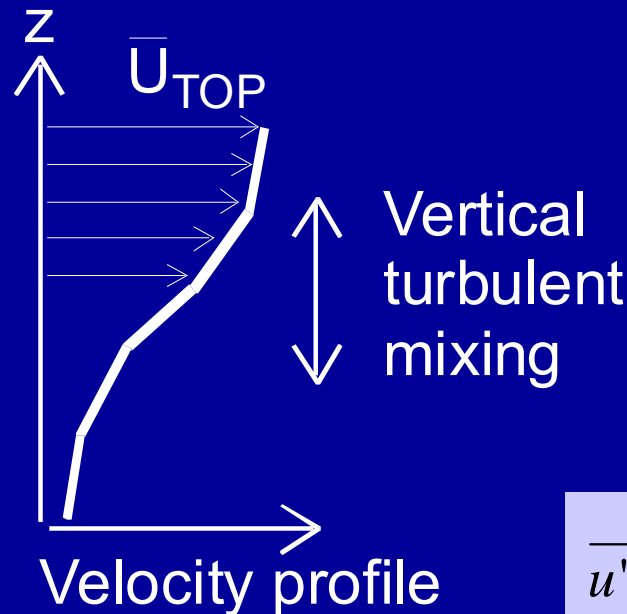
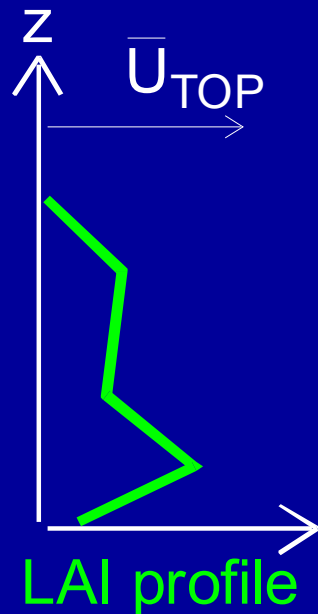
Momentum equation

$$\frac{\partial \overline{u'w'}}{\partial z} = -C_d LAD \overline{u}^2$$



First order closure

$$\overline{u'w'} = -K_T \frac{\partial \overline{u}}{\partial z} \quad K_T = \ell^2 \left| \frac{\partial \overline{u}}{\partial z} \right|$$

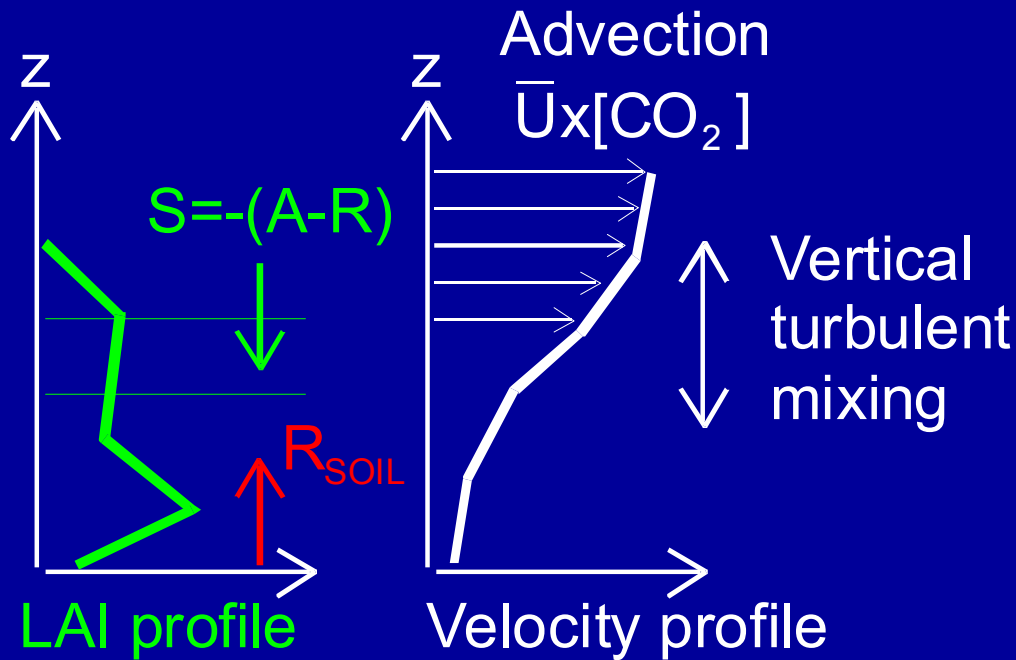


Scalar transport in the canopy

Mass and energy balance equations for scalars



1. CO₂ concentration
2. Water vapor
3. Temperature



Mass balance equation

$$\bar{u} \frac{\partial \bar{c}}{\partial x} = -\frac{\partial \overline{c'w'}}{\partial z} + S$$



First order closure

$$\overline{c'w'} = -K_T \frac{\partial \bar{c}}{\partial z} \quad K_T = \ell^2 \left| \frac{\partial \bar{u}}{\partial z} \right|$$

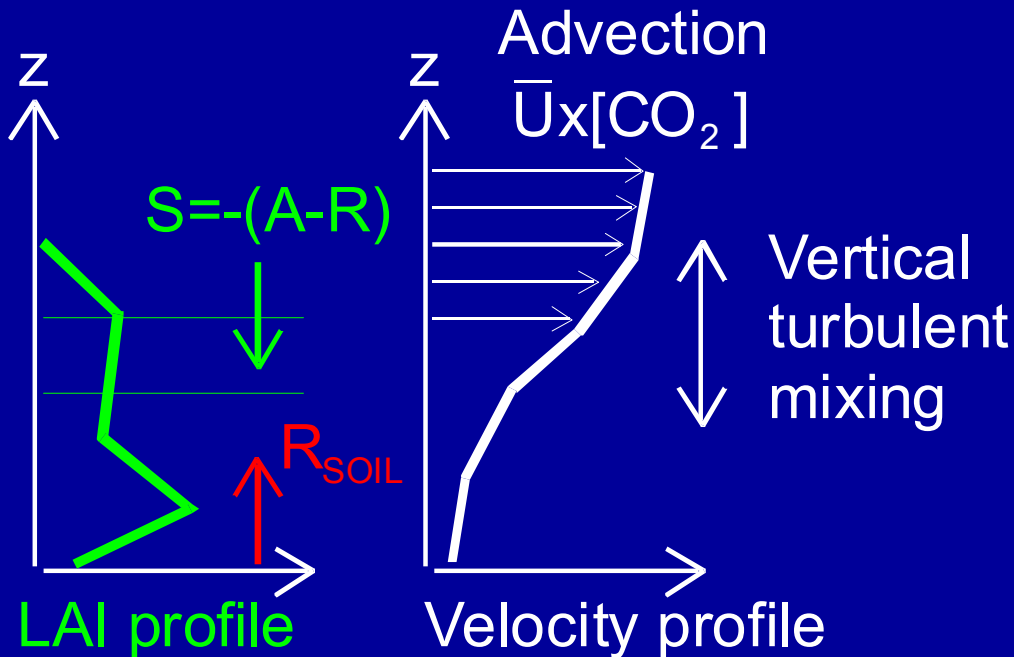
C sources and sinks

Mass balance equation

$$\frac{\partial \bar{c}}{\partial z} = -\frac{\partial \overline{c'w'}}{\partial z} + S$$

– (Assimilation – Respiration)

Ground boundary condition: $+R_{SOIL}$



1. Compute minute time scale A at the leaf level
2. Compute water and heat fluxes along the SPAC
3. Upscale to the daily/whole canopy and up...

Leaf-level photosynthesis – C3

Farquhar assimilation model

$$A_n = \min\{A_J(PAR, c_I), A_C(c_I)\} - R_d$$

$$A_J(PAR, c_I) = J(PAR) \frac{c_I - \Gamma^*}{4c_I - 2\Gamma^*}$$

$$A_C(c_I) = V_{c, \max} \frac{c_I - \Gamma^*}{c_I + K(O_2)}$$

+

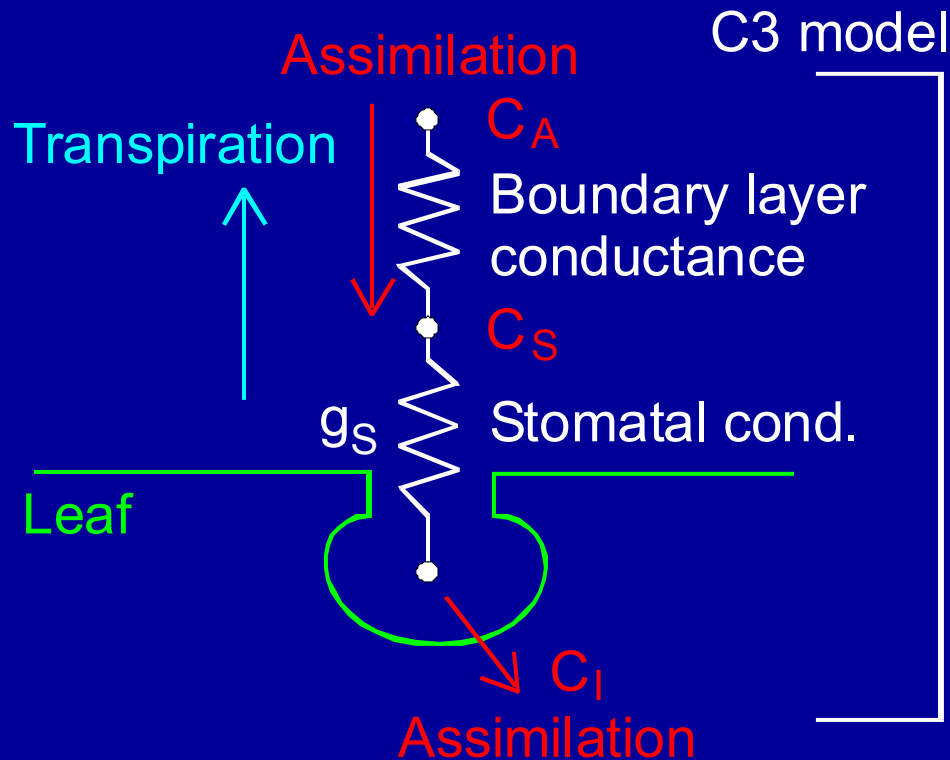
Leuning stomatal model

$$g_s = g_0 + \frac{m A_n}{(c_s - \Gamma^*)(1 + VPD/D_0)}$$

+

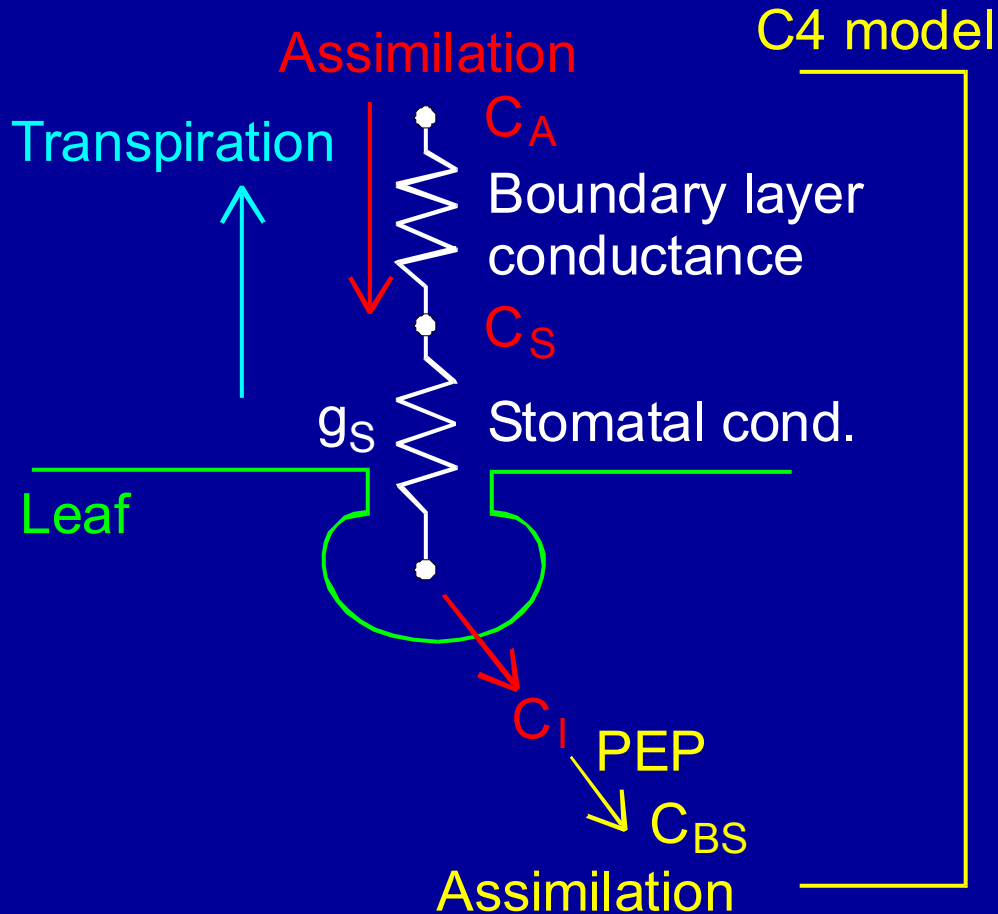
Mass balance equations

$$A_n = g_{BL} (c_A - c_s) = g_s (c_s - c_I)$$



Solve for C_S , C_I , A_n , g_s ←

Leaf-level photosynthesis – C4



Farquhar assimilation model applied at $C=C_{BS}$

+

Leuning stomatal model

+

Mass balance equations

$$A_n = g_{BL} (c_A - c_S) = g_S (c_S - c_I) = V_P(c_I) - g_{BS} (c_{BS} - c_I) - R_m$$

+

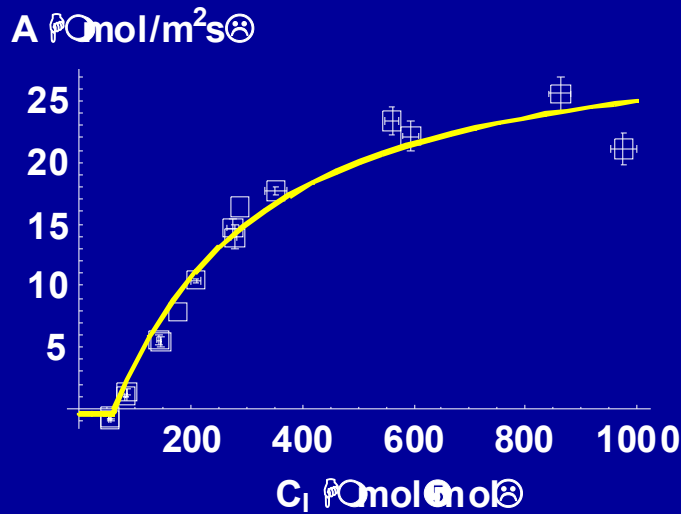
C4 cycle model
von Caemmerer (2000)

$$V_P(c_I) = \min \left\{ V_{P, \max} \frac{c_I}{c_I + K_P}, V_{Pr} \right\}$$

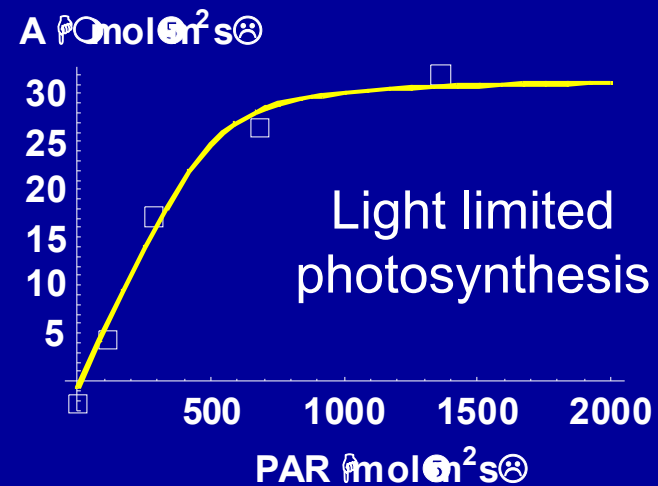
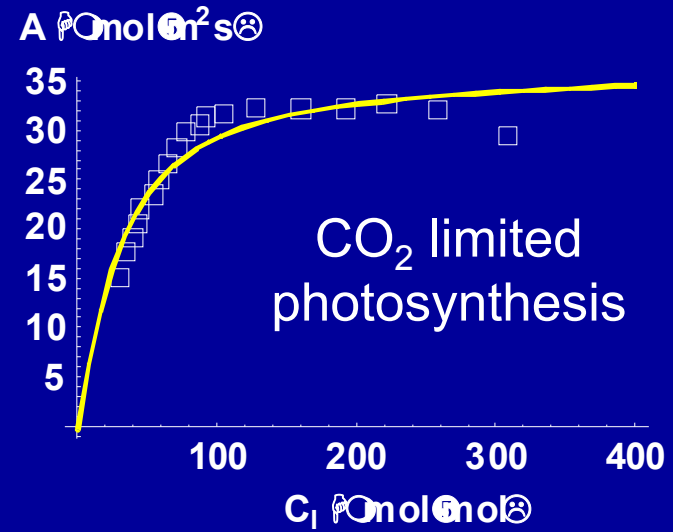
Solve for $C_S, C_I, C_{BS}, A_n, g_s$ ←

Leaf-level photosynthesis - Calibration

C3 - *Solidago canadensis*



C4 - *Sorghastrum nutans*



Observations in the LYCOG experiment (Summer 2006)

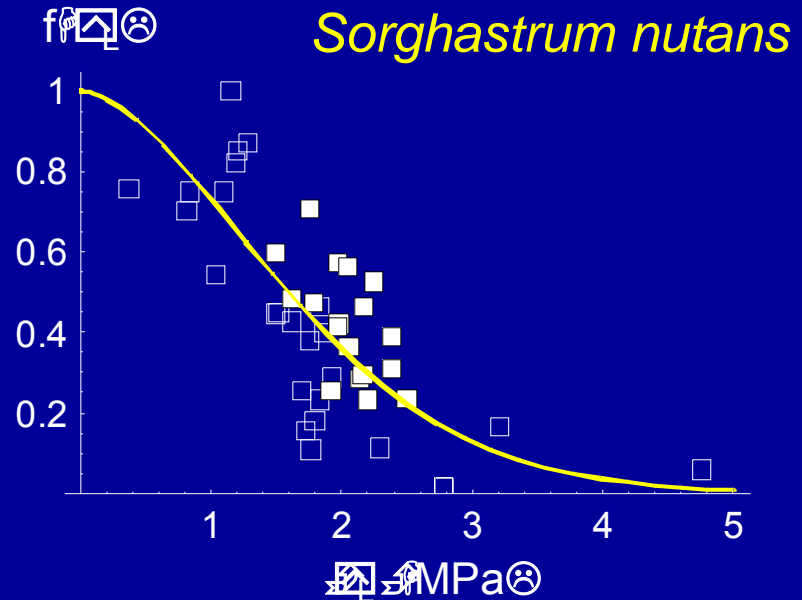
Assimilation model parameters

Data after Polley et al. (1992), J Geophysical Research

Leaf-level water limitation

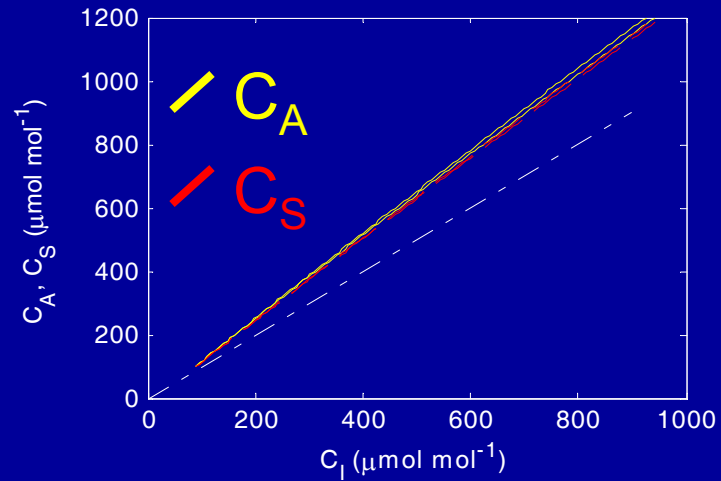
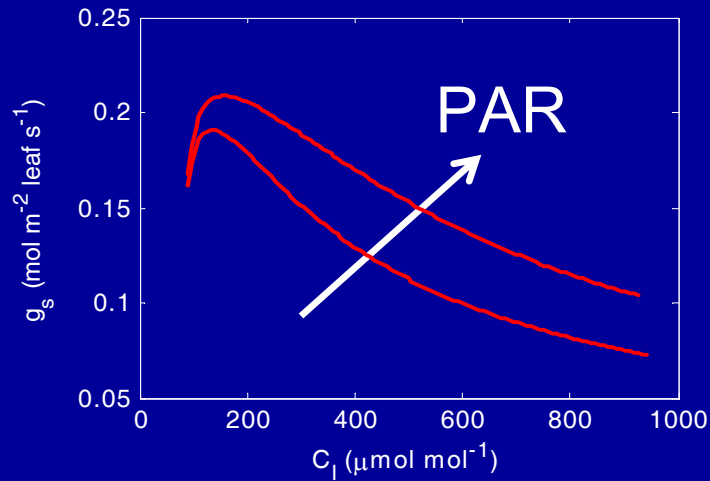
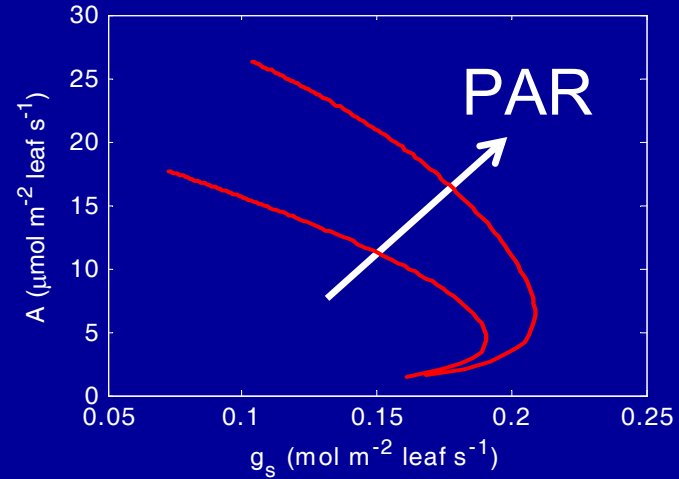
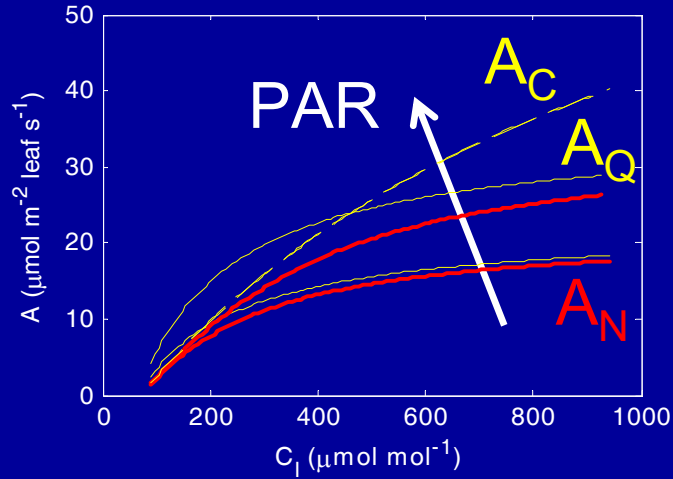
Water limitation to assimilation is modeled by a Weibul-type vulnerability curve
(Daly et al., 2004, J. Hydrom.)

$$f(\psi_L) = \exp\left[-\left(\frac{-\psi_L}{d}\right)^b\right]$$

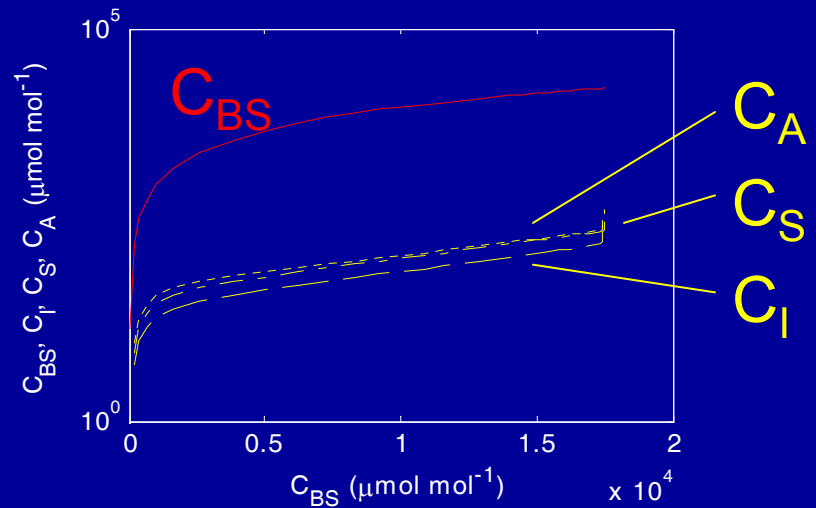
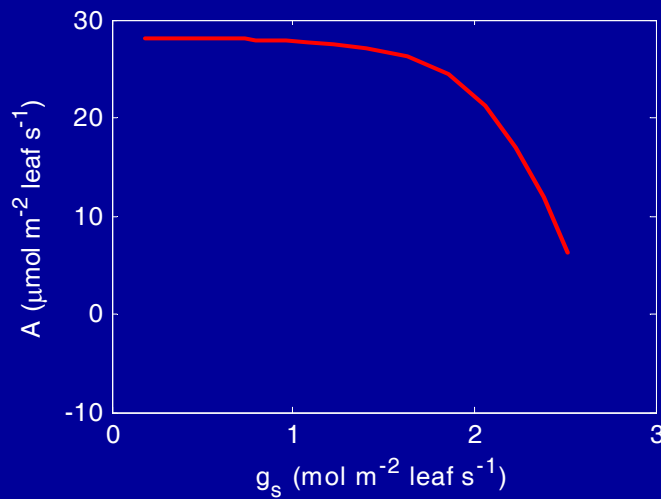
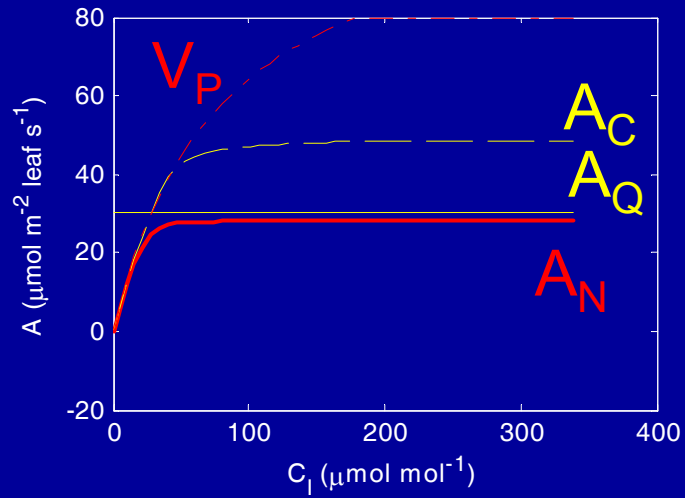
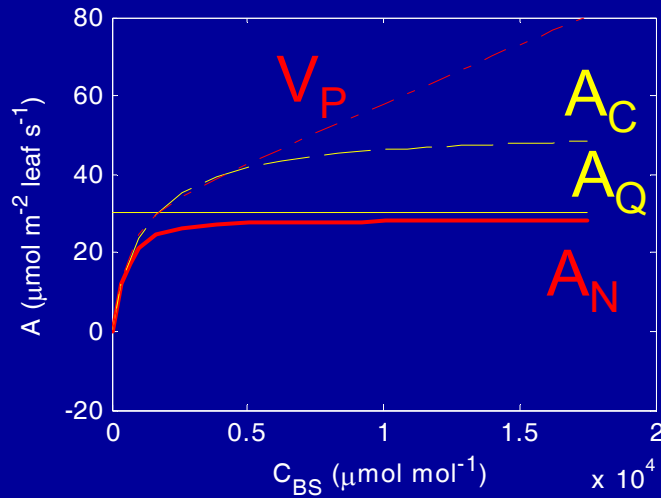


- Data after Polley et al. (1992), J. Geophysical Research
- Observations in the LYCOG experiment (Summer 2006)

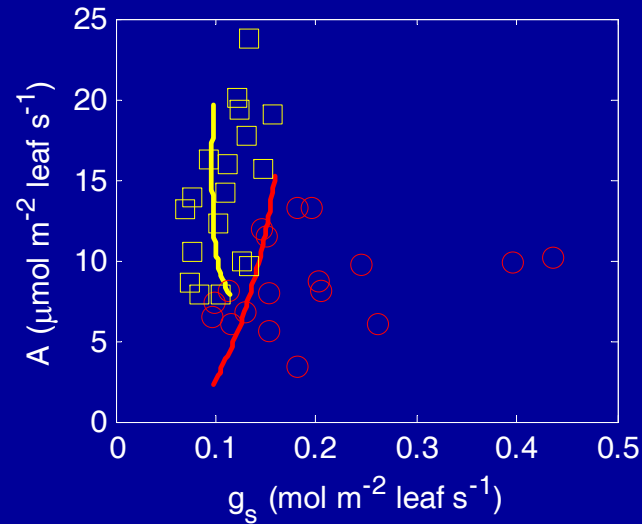
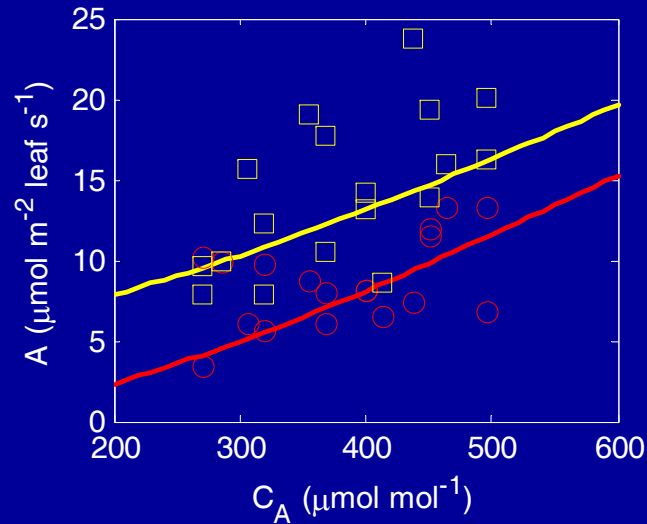
Leaf-level assimilation – C3



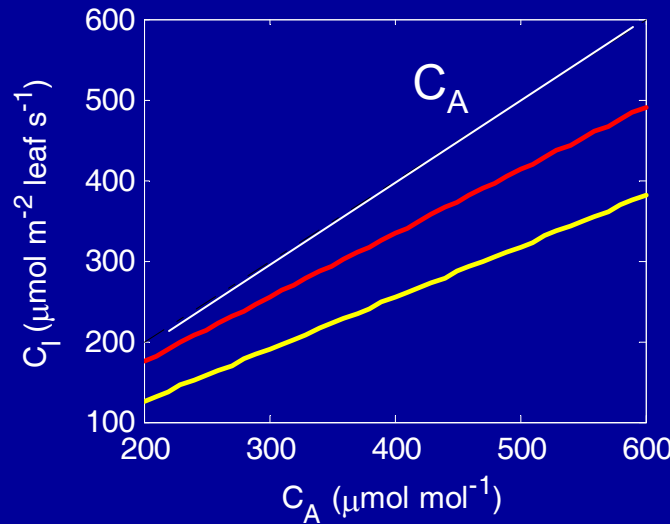
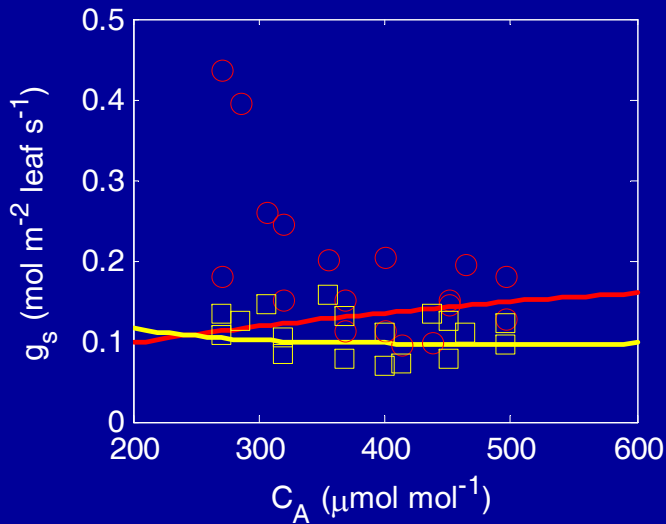
Leaf-level assimilation – C4



Leaf-level assimilation – C3 vs. C4

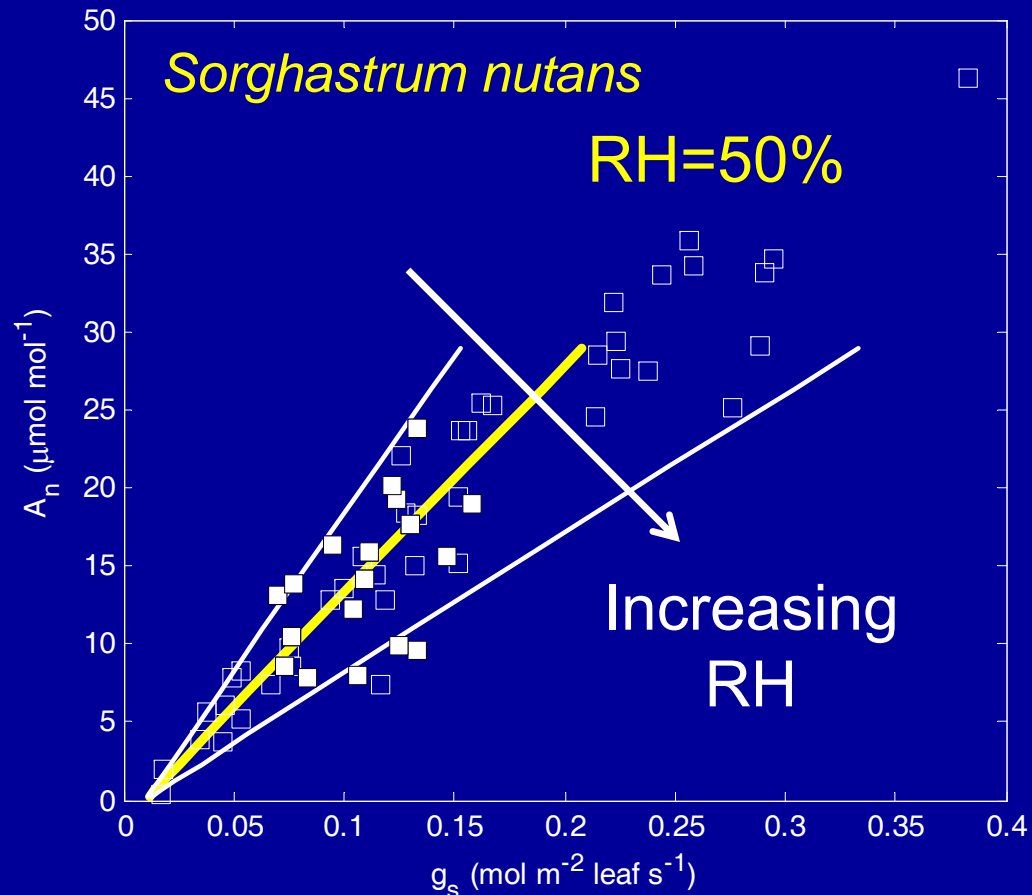


□ / C4
○ / C3



Observations
in the LYCOG
experiment
(Summer
2006)

$A_n - g_s$ relationship while varying Ψ_L

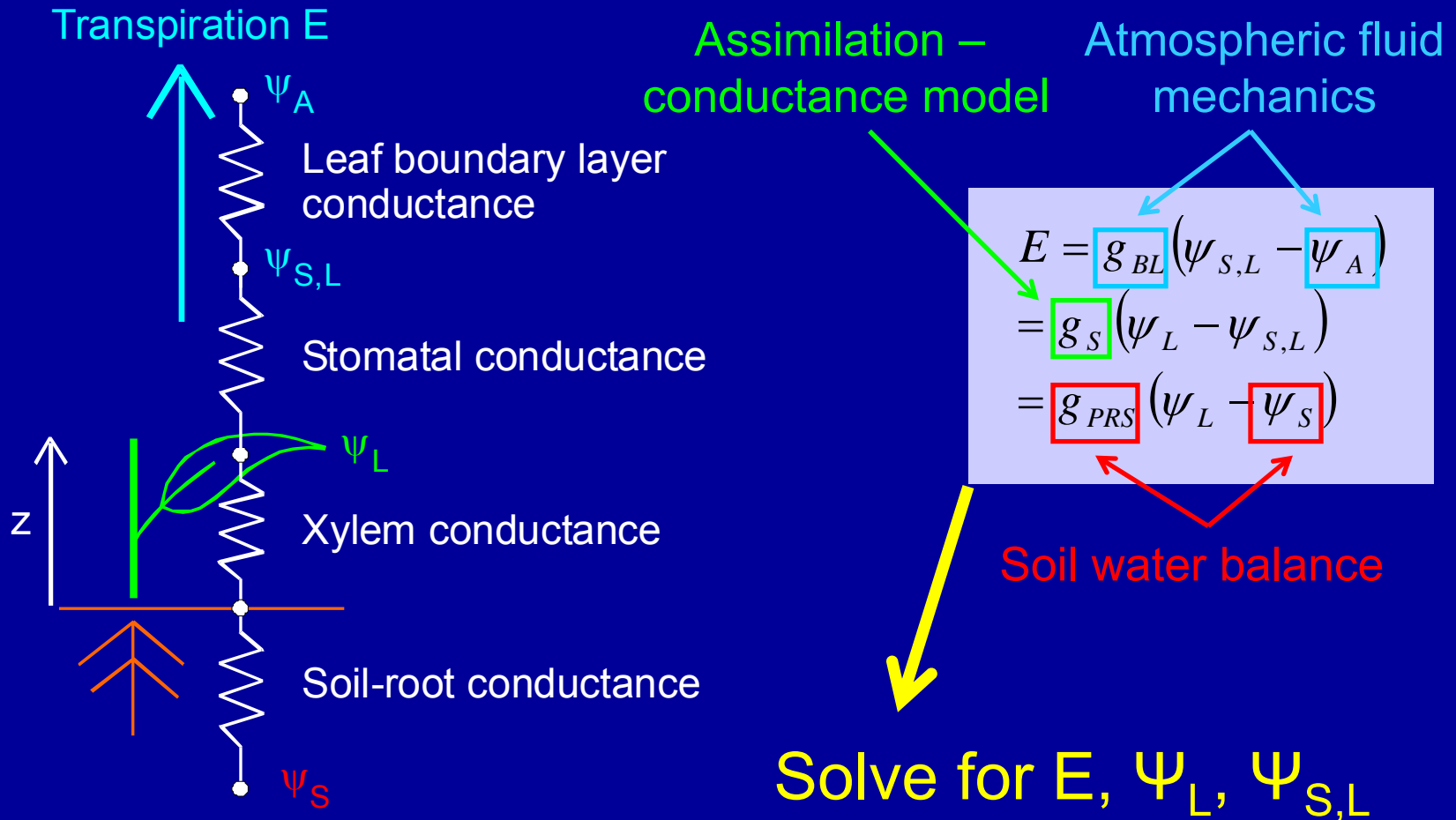


- Data after Polley et al. (1992), J Geophysical Research
- Observations in the LYCOG experiment (Summer 2006)

Soil-plant-atmosphere continuum

Water mass balance equations

Transpiration gradient by water potential fluxes



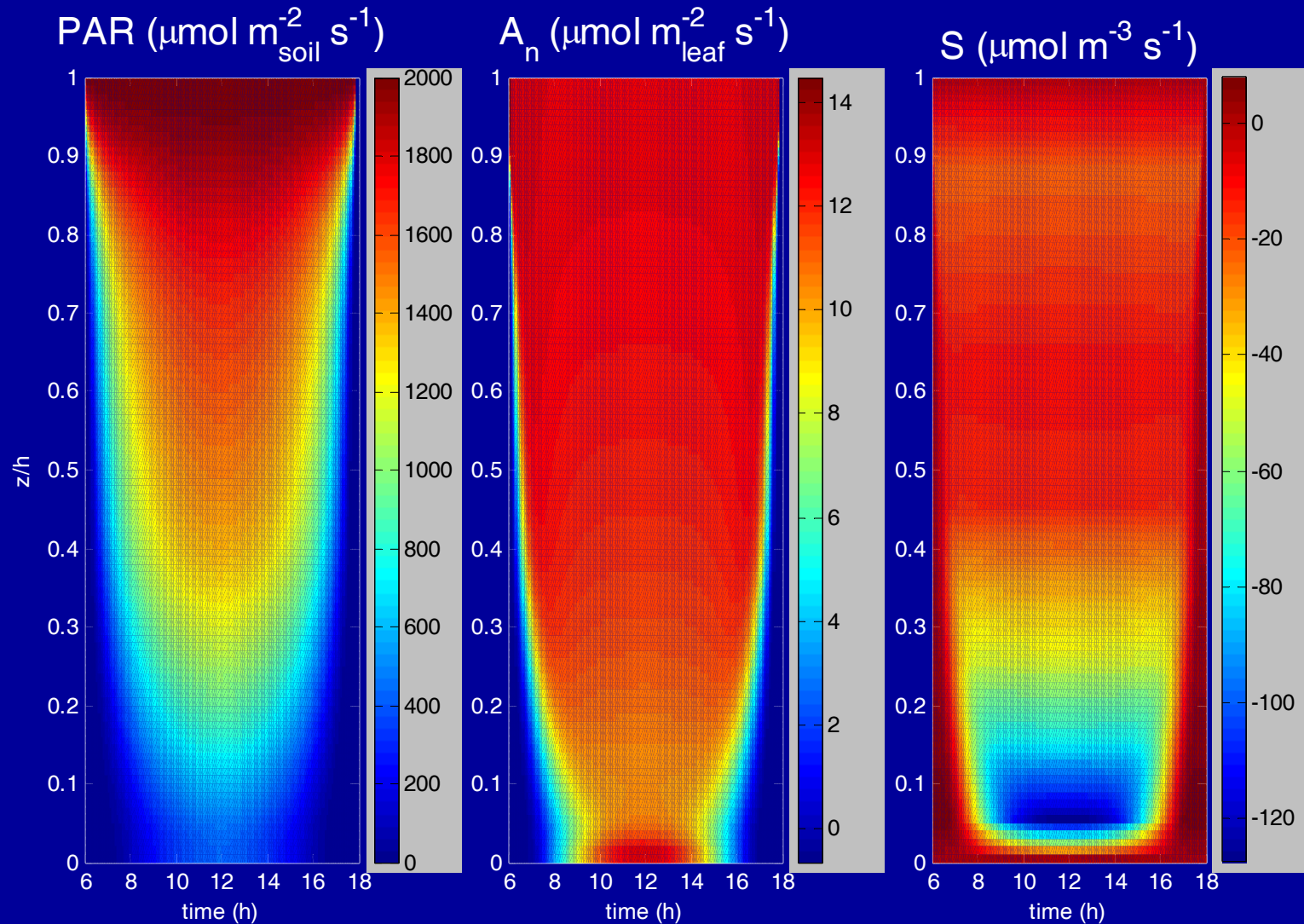
Leaf-level plant-atmosphere CO₂ and water exchanges

- Profiles of horizontal velocity and turbulent stress
- Solar radiation at different levels in the canopy
- Assimilation and respiration models provide sources and sinks
- Solution of mass balance equations for atmospheric scalars
- Computation of water fluxes given conductances and soil boundary conditions

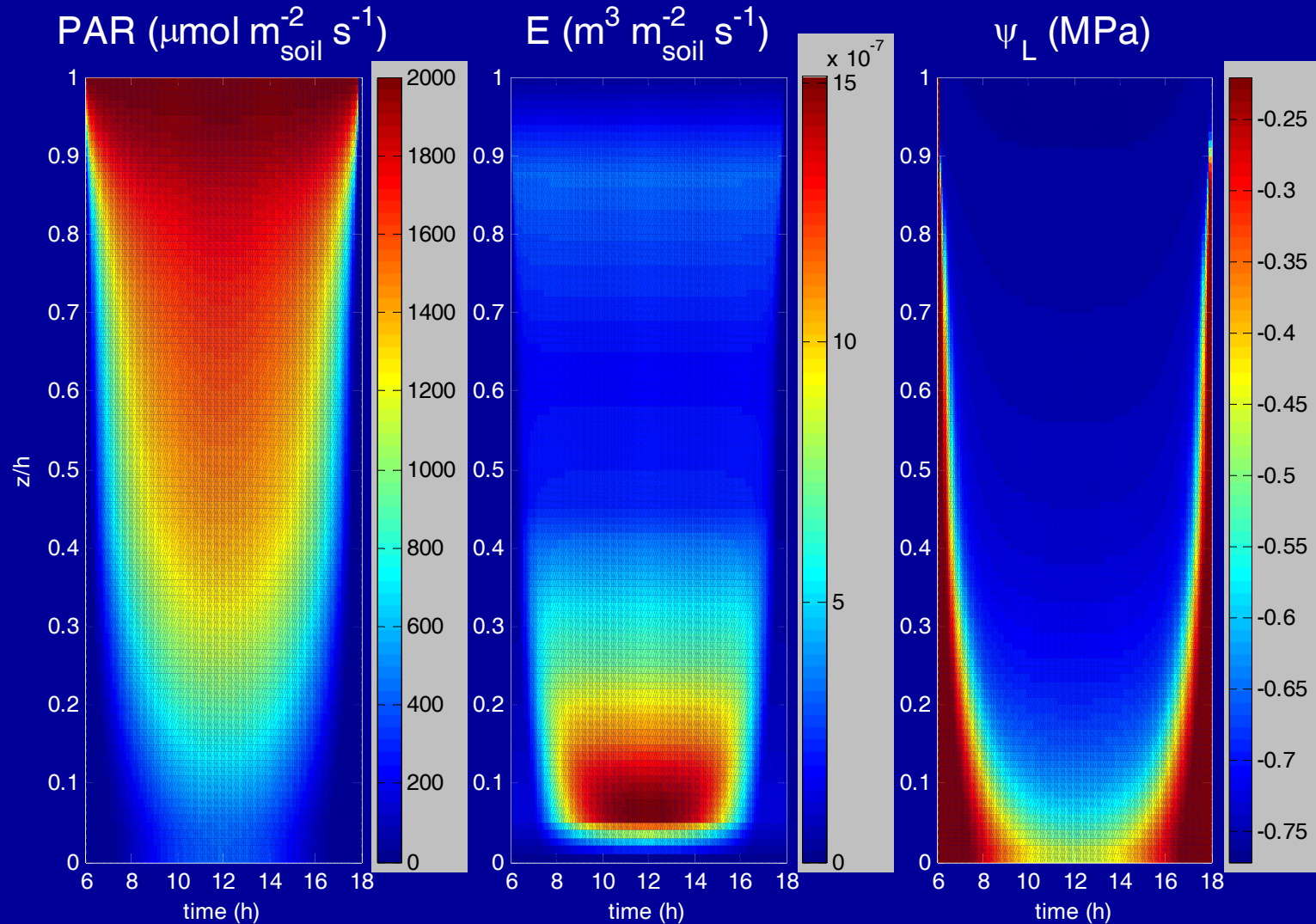


Daily cycles of **plant-atmosphere CO₂ and water exchanges**

Daily cycle of leaf-level plant-atmosphere CO₂ and water exchanges



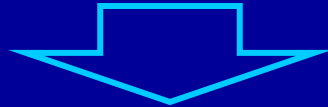
Daily cycle of leaf-level plant-atmosphere CO₂ and water exchanges



From the leaf to the canopy level

1. Spatial up-scaling using LAD observations and a radiation diffusion model within the canopy
2. Temporal up-scaling by integration

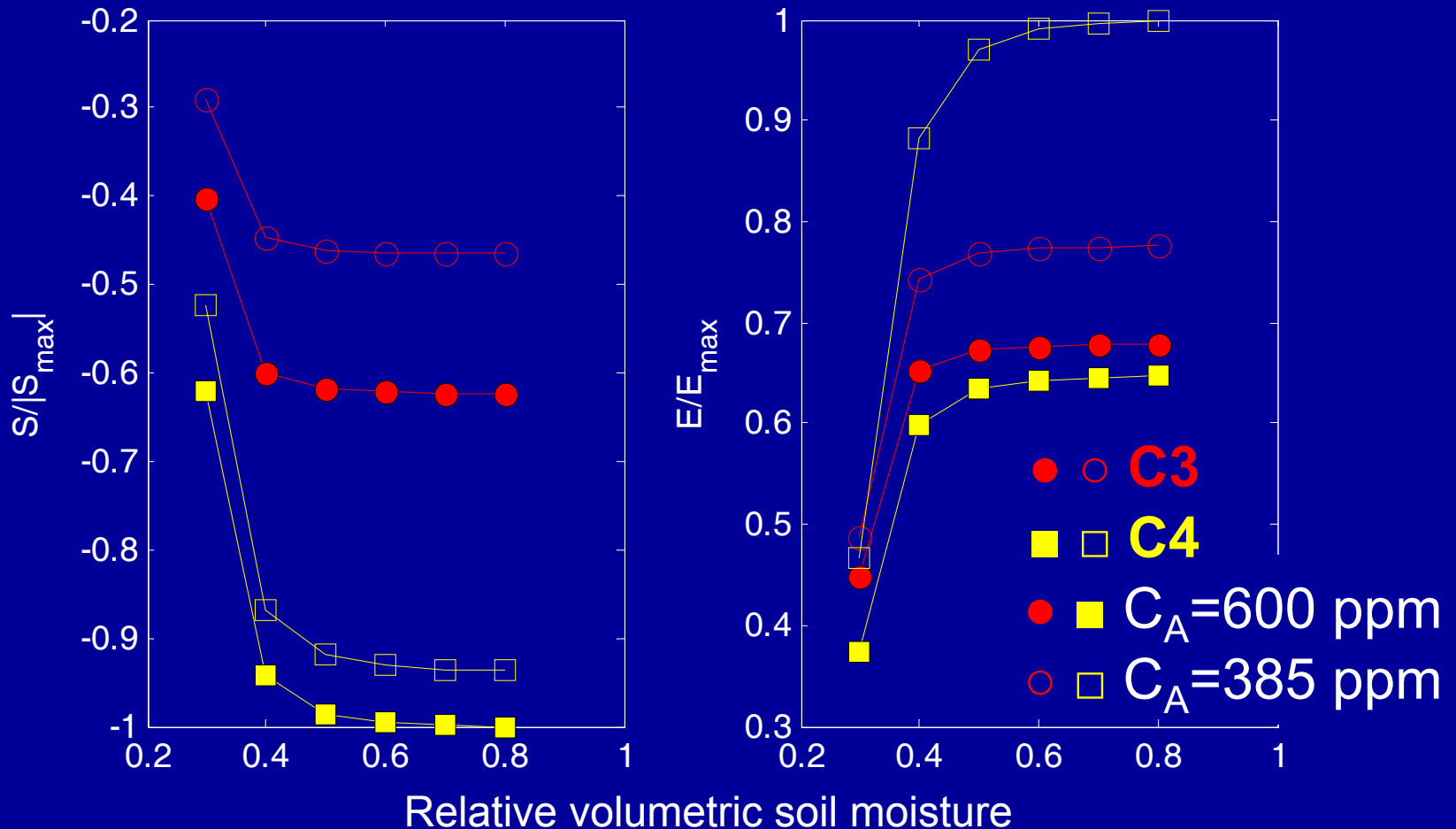
$$\Phi = \int_t \int_z \varphi(z, t) LAD(z) dz dt$$



**Fluxes at the leaf-level are converted to
whole-canopy scale daily values**

Daily plant-atmosphere exchange

Whole-canopy, daily time-scale CO_2 and water sources as a function of soil moisture s and atmospheric CO_2



Future developments

1. Detailed modelling of the LYCOG experiment
2. Development and testing of the plant allocation scheme (e.g., balanced growth..)
3. Analysis of climate change scenarios and comparison with data from rainfall manipulation and warming experiments (e.g., Konza prairie) and elevated CO₂ experiments (LYCOG)

Acknowledgements

This work was supported by the Forest-Atmosphere Carbon Transfer and Storage (FACT-1), funded by the U.S. Department of Energy.