Exploring the Response of the Central US Agro-Ecosystem to Climate Change

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Jet Propulsion Laboratory / Caltech
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Carl Bernacchi (Plant Biology, UIUC)

Steve Long (Plant Biology, UIUC)

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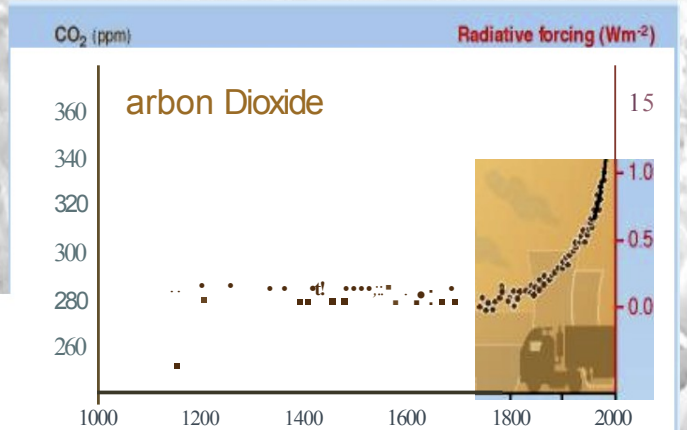
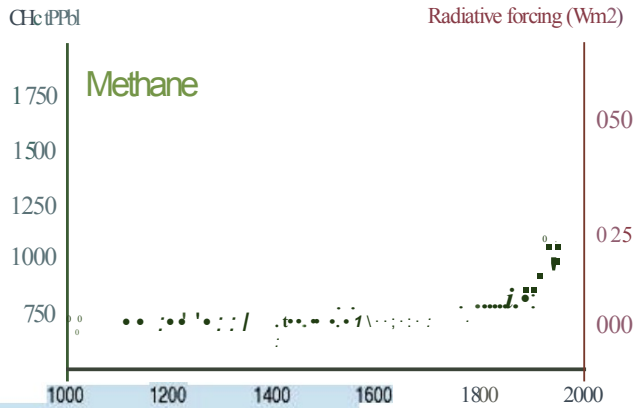
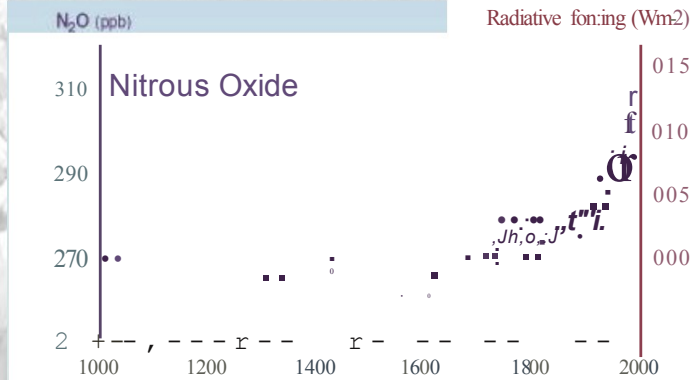
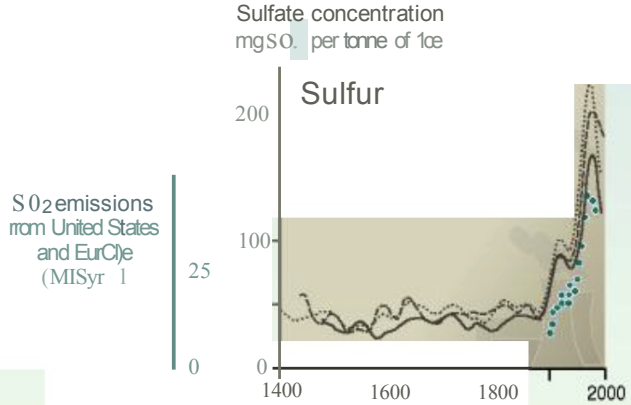
Rapid Changes in Atmospheric Composition



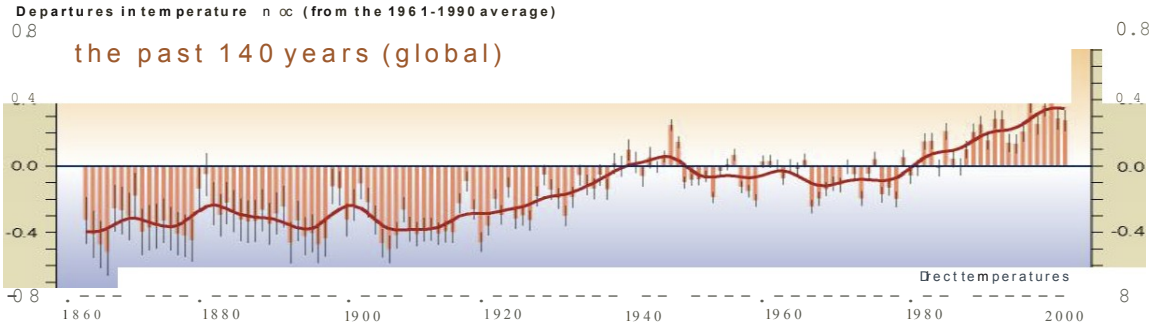




Sulfate aerosols deposited In Greenland Ice



Variations of the Earth's surface temperature for...



Vol 439 6 F@bruary 2006ldae10.1018/nZilniO

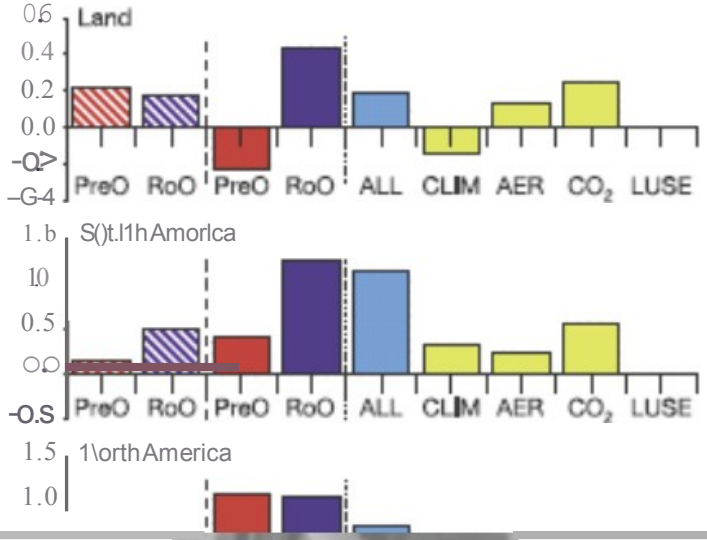
nature

LETTERS

Detection of a direct carbon dioxide effect in continental river runoff records

N. Gedney[1], P. M. Cox[2], R. A. Bett, 0. Bouche, C. Huntingford[4] & P. A. Stott[5]

Continental runoff has increa ed through the twentieth century•..L despite more int ive human water coruumption. Possible reasons for the increa e include: climate change and variability, deforestation, solar dimming\ and direct atmospherk carbon dio:x.ide (COt) effecu on plant transpirations. All of these mecha n i s have the potential to aJ'ect precipitation and/or evaporation and thereby modify runoff. Here we use a mechanistic land surra moder and optimal fingerprinting statistical teduliques[7] to attribute observational runoff changes• into contributioru due to these factors. The model sucassfuDy captuns the dimate- dri n inteNJUtUal runoff variability, but twentie ntury cli mate alone is iruufficientto explain the runoff' trends. Instead we find that the ttnds are consistent with a sul ressl0n to transpiration due to CO2-induced stomatal closure. This result will affect projections of freshwater availability, and also represents the detection of a direct CO_2 effect on the functioning of the terrestrial biosphere.



RESEARCH ARTICLES

Food for Thought Lower-Than Expected Crop Yield Stimulation with Rising $C0_2$ Concentrations

Stepllen P. Lon!J.1.2.1• Ellr.abtUI A..Ainsworth.4..L.1 Andie• D. B. Le.akey,1 .
Jose:t N0sber9ets. C()flald R. on•·u .1

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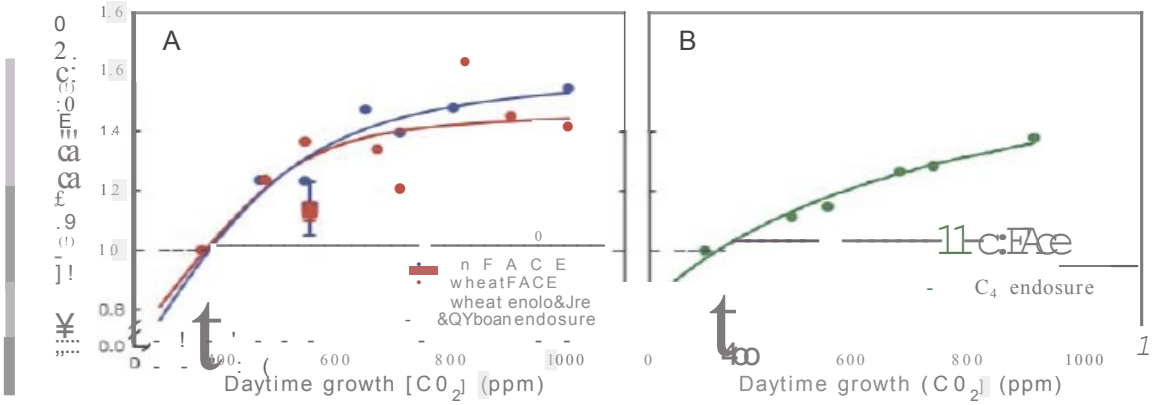


Overview

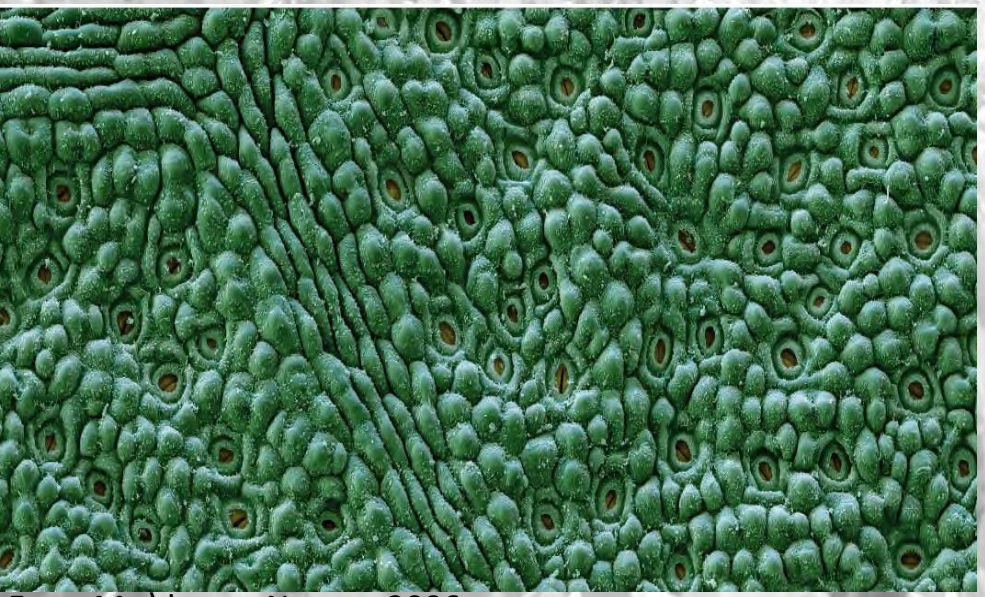
Free Air Carbon Enrichment (FACE) provides us with evidence for potentially dramatic changes in land-atmosphere interactions and surface hydrology

- Results differ with those of enclosure-based studies
- Much evidence of change based on *canopy-top leaf gas exchange obs*

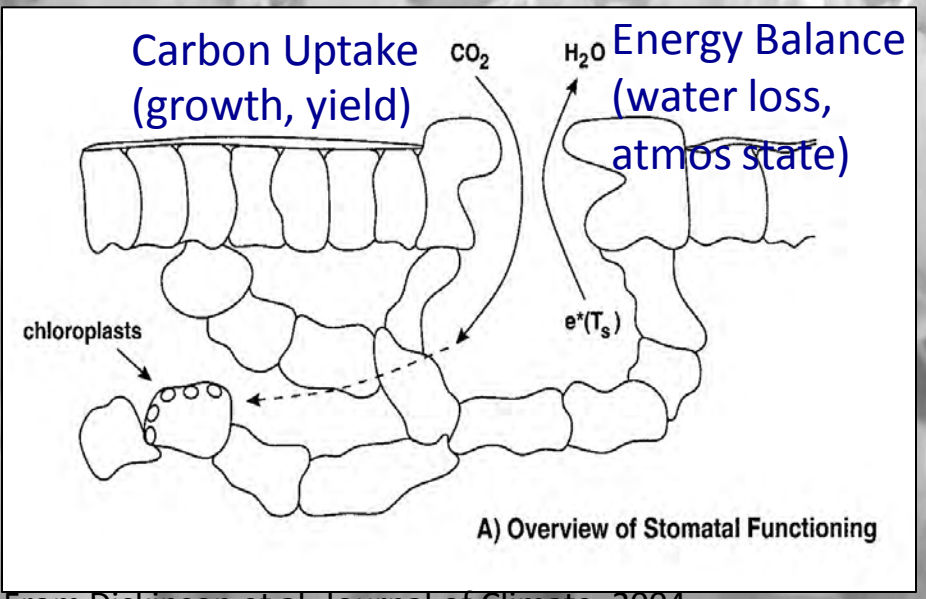
1) Demonstrate a *multi-layer canopy-root-soil system model* capable of accurately predicting canopy-atmosphere exchange of CO_2, water vapor and sensible heat
   - Bondville Ameriflux dataset: eddy-covariance
   - C3 (soy)
   - C4 (maize)

2) Use this model to analyze the impact of observed vegetation acclimation to elevated CO_2 on canopy-scale gas and energy exchange
   - SoyFACE: Canopy-top gas exchange
   - Soy acclimation: ecophysiological, biochemical and structural
   - Maize acclimation: ecophysiological

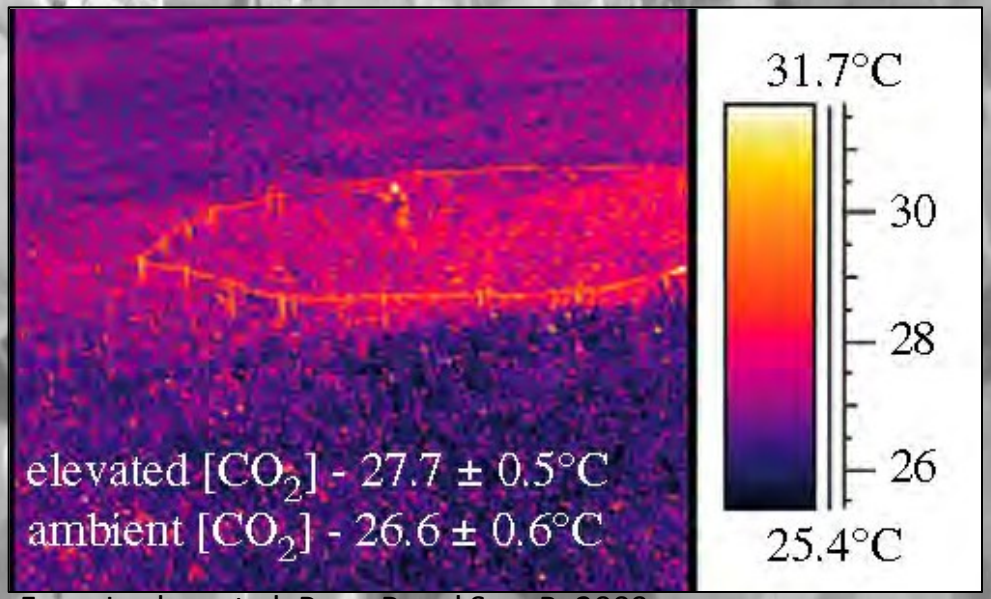
Stomatal Control of Land Surface Response



From Ma\hews, Nature, 2006



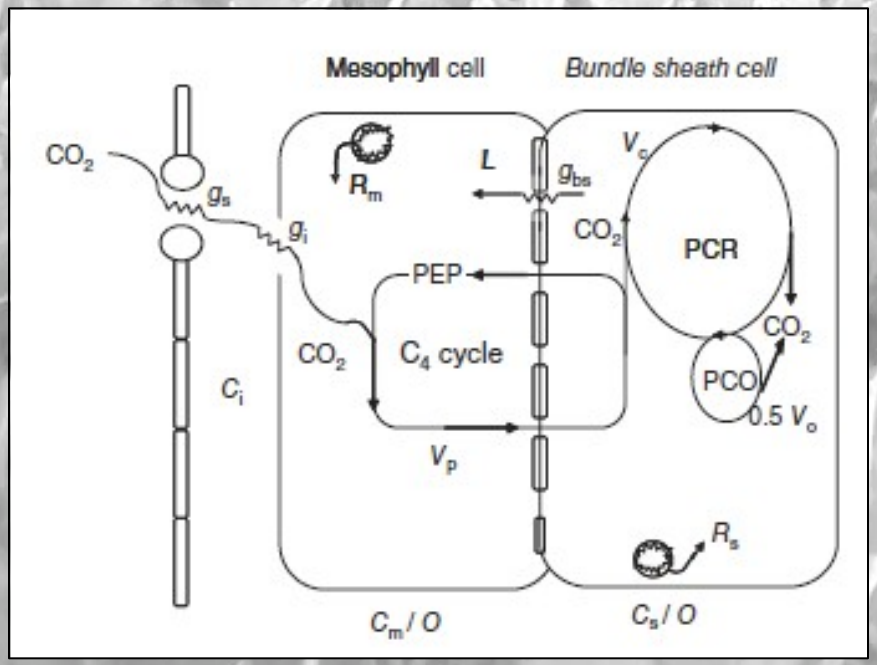
From Dickinson et al, Journal of Climate, 2004



From Leakey et al, Proc. Royal Soc. B, 2009

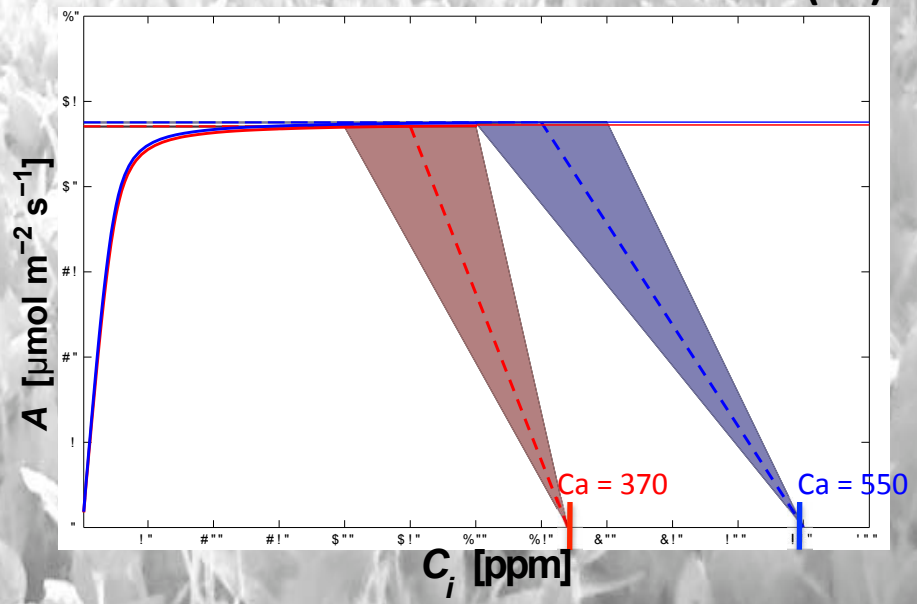
PhotosynthePc SPmulaPon by Elevated CO_2

C4 PhotosynthePc Pathway

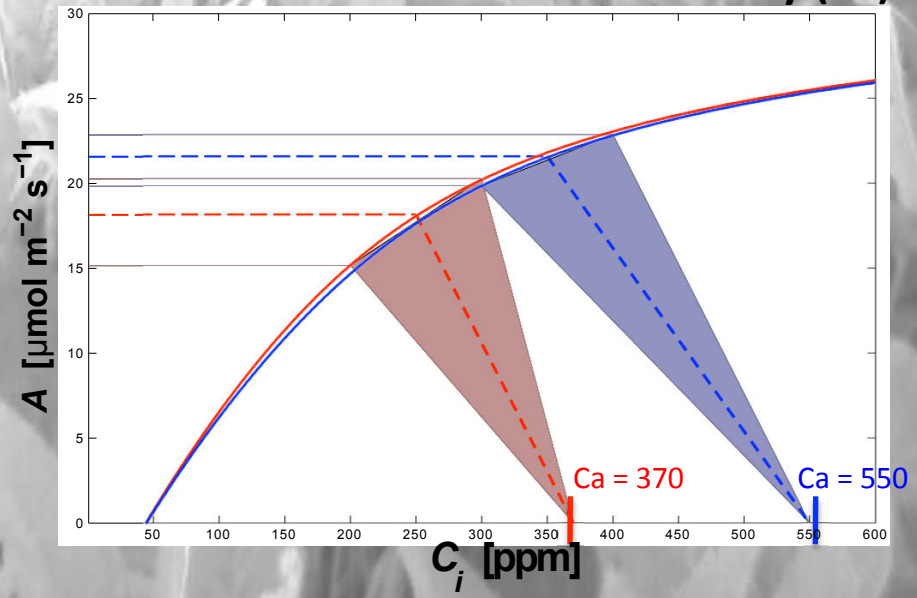


From Massad et al, PCE 2004

Maize (C4)



Soy (C3)



Talk Outline

Modeling Canopy-Atmosphere Exchange

o Canopy-root-soil model framework and canopy scaling o

Focus on canopy biophysics

o Within-canopy variability in radiaPon and met environments o

ValidaPon against Bondville (Illinois, USA) eddy covariance data o

Canopy responses to water stress

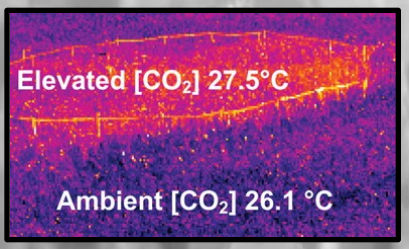
Canopy Responses to Elevated CO_2

o SimulaPon scenarios to examine impacts of observed acclimaPon on canopy-atmosphere gas exchange

oStructural (soybean) o

Biochemical (soybean)

o Ecophysiological (soybean, maize)



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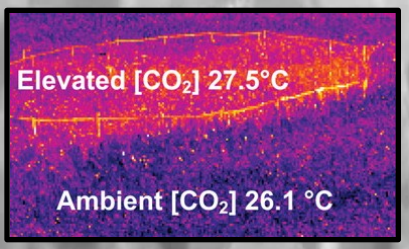
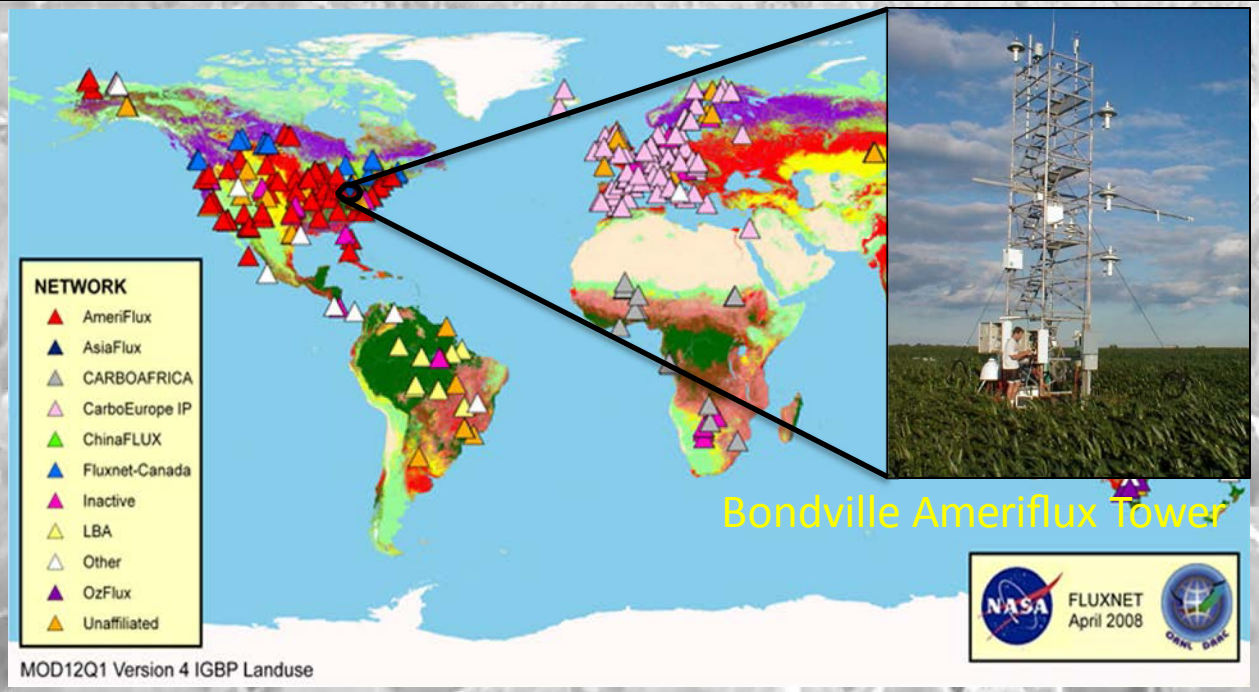


Study Sites



Eddy covariance fluxes

- Net CO_2 (F_c, A_n)
- Latent energy (LE)
- Sensible heat (H)
- ~6200 (maize) and 7500 (soybean) data points

Ambient meteorological condiPons:

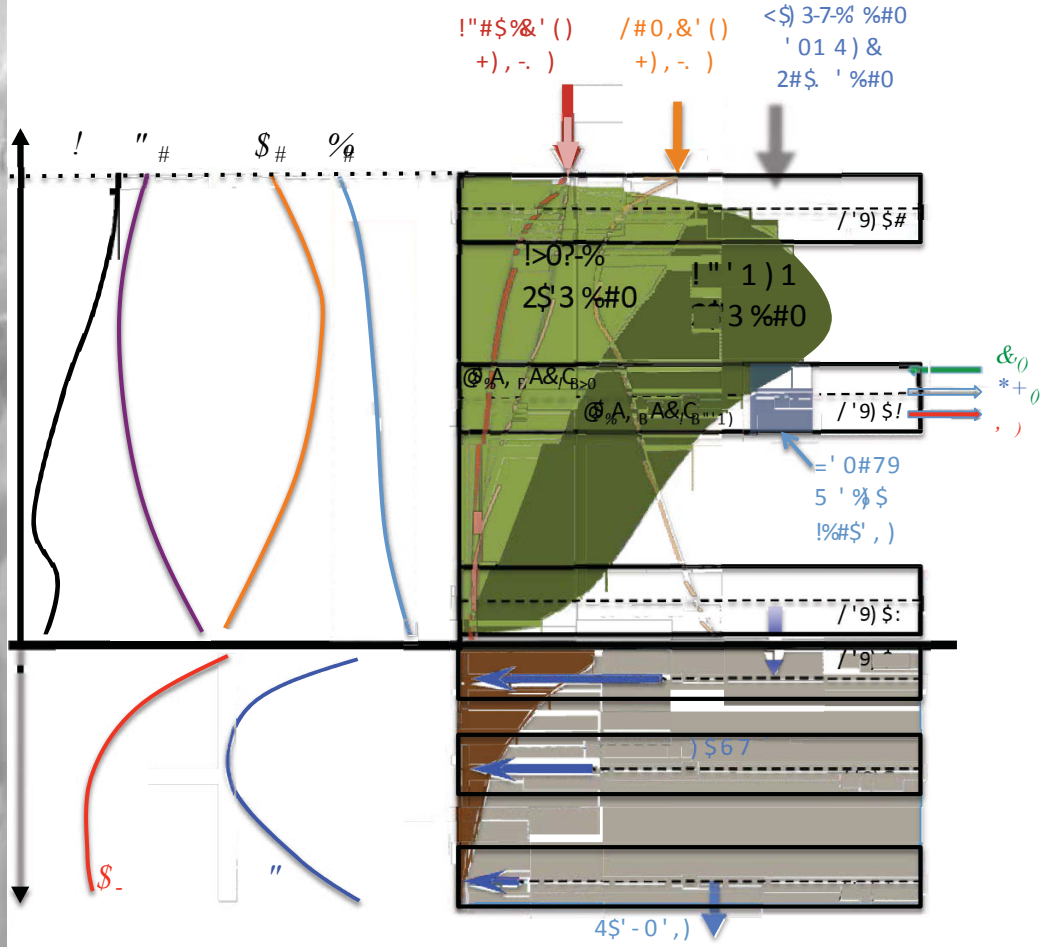
- PAR, NIR, LW
- U, T_a, e_a

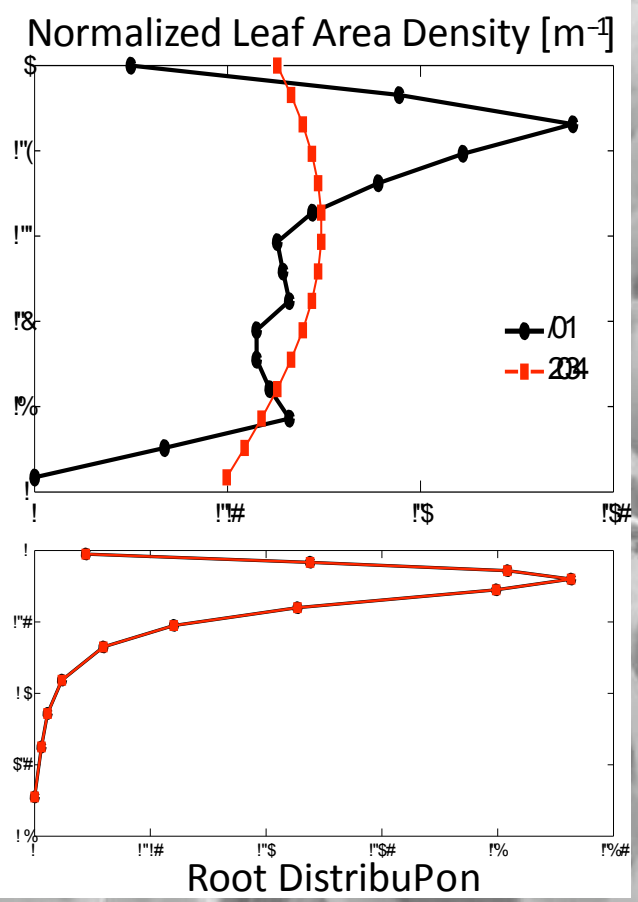
Free Air Carbon Enrichment (FACE)

•vegetaPon fumigated with 550 ppm CO_2= esPmated 2050 concentraPon

•ObservaPons include a variety of *leaf-level* biochemical and ecophysiological variables, and energy balance components

MLCan Overview

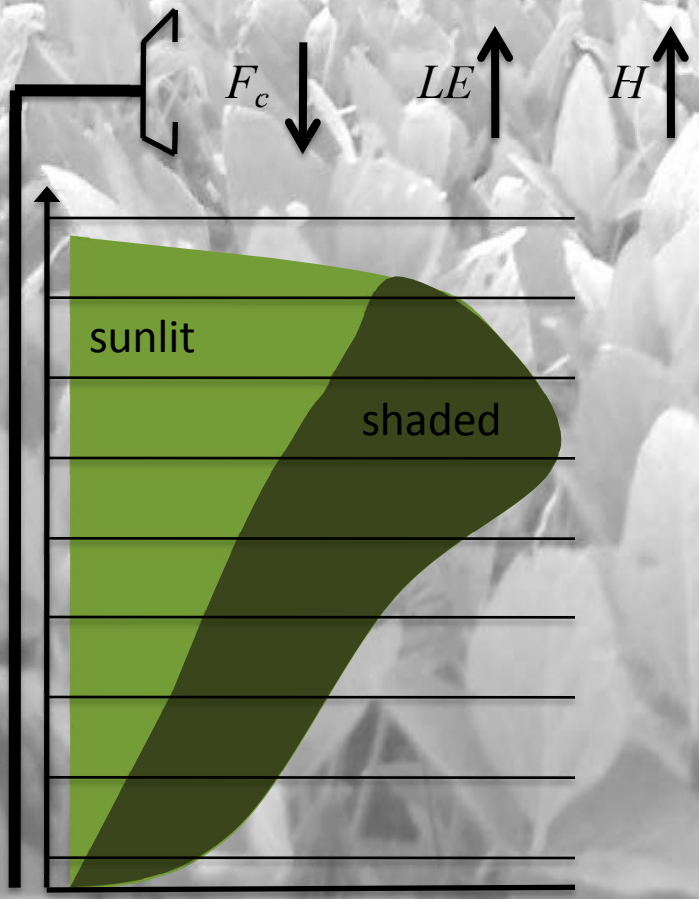




Canopy Scaling

Model *valida- o n d a t a*:

F_c, LE, H → Eddy covariance: verPcal integral of sources/sinks



$$F_c = \int_0^h \left(S_{c,sun}(z) + S_{c,shade}(z)\right) dz$$

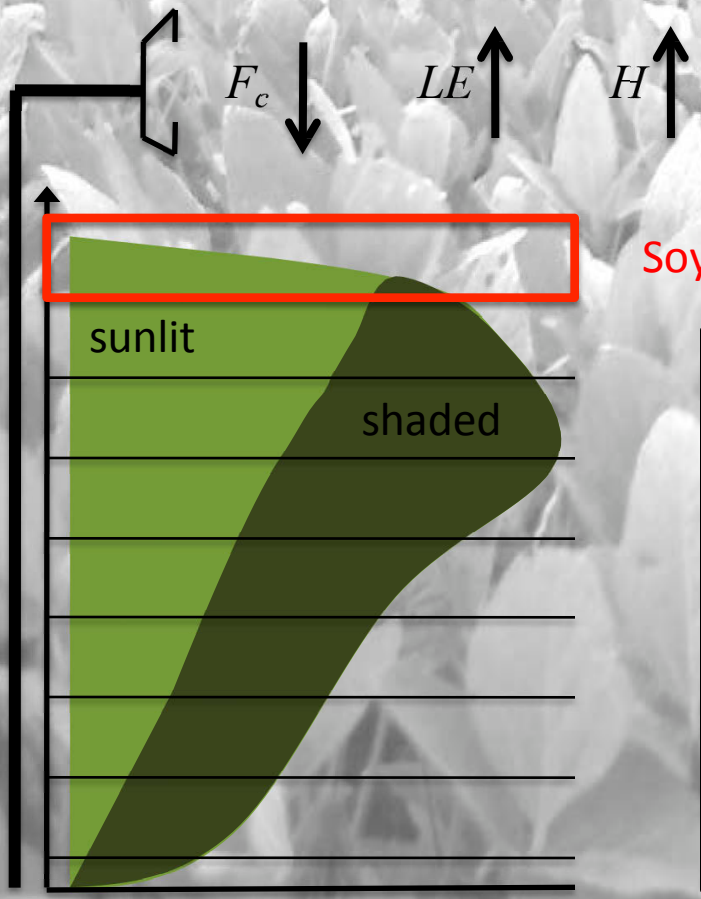
$$LE = \int_0^h \left(S_{v,sun}(z) + S_{v,shade}(z) + S_{v,wet}(z)\right) dz$$

$$H = \int_0^h \left(S_{h,sun}(z) + S_{h,shade}(z)\right) dz$$

Canopy Scaling

Model *valida- o n d a t a*:

F_c, LE, H → Eddy covariance: verPcal integral of sources/sinks



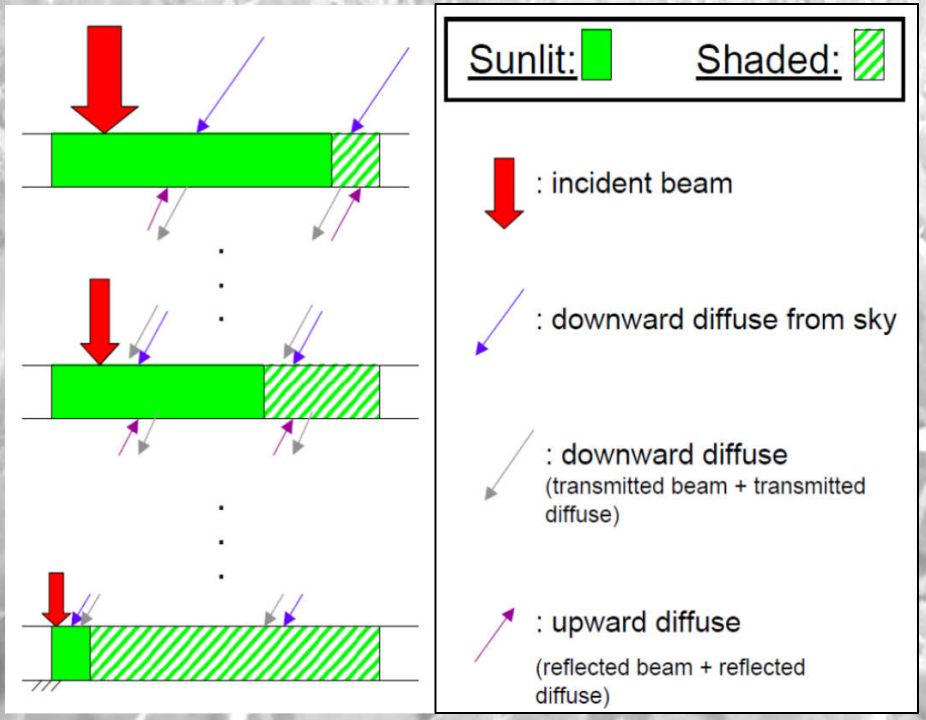
SoyFACE ObservaPons (leaf scale)

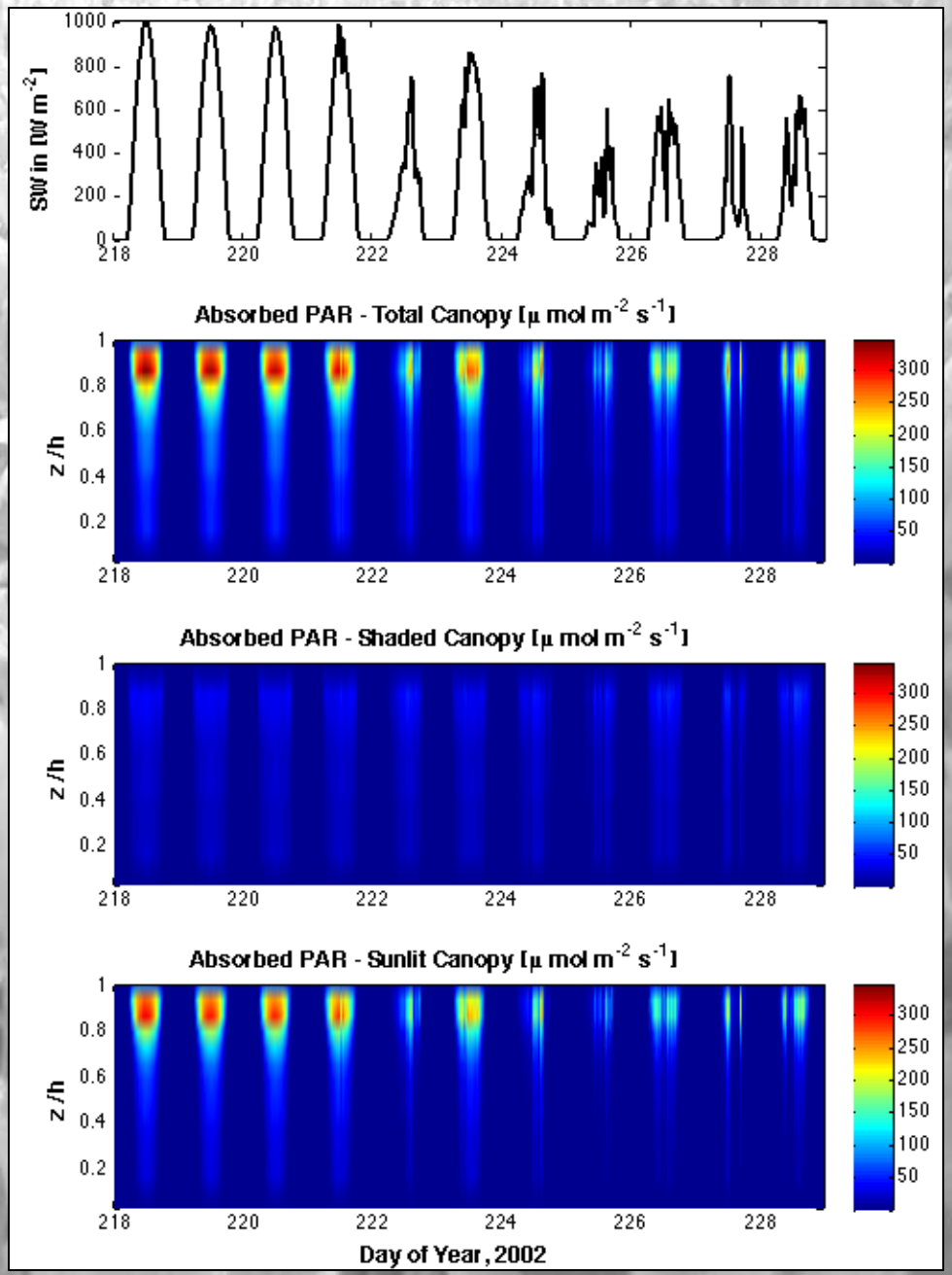
$$F_c = \int_0^h \left(S_{c,sun}(z) + S_{c,shade}(z)\right)dz$$

$$LE = \int_0^h \left(S_{v,sun}(z) + S_{v,shade}(z) + S_{v,wet}(z)\right)dz$$

$$H = \int_0^h \left(S_{h,sun}(z) + S_{h,shade}(z)\right)dz$$

Shortwave (PAR & NIR) RadiaPon Regime





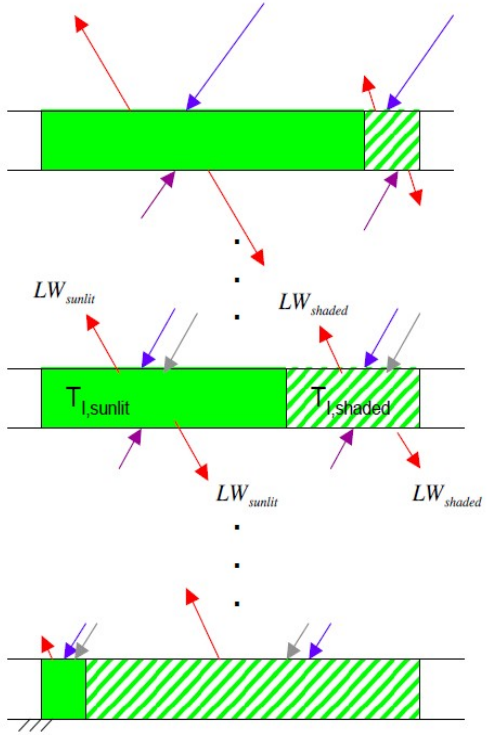
ExponenPal exPncPon of radiaPon with cumulaPve LAI (ξ):

$$\tau = \exp[-K_b \cdot \Omega \cdot \xi]$$

ExPncPon coefficient:

$$K_b = \frac{\sqrt{x^2 + \tan^2 \phi}}{x + 1.774(x + 1.182)^{-0.733}}$$

Longwave RadiaPon Regime



Incident Radiation Components:

: downward sky longwave

: scattered downward

(reflected downward + transmitted downward + downward emission)

: scattered upward

(reflected upward + transmitted upward + upward emission)

Canopy Emission Components:

: layer emission

$$LW_{sunlit} = \varepsilon_l \sigma T_{l,sunlit}^4 \cdot LAI_{sunlit}$$

$$LW_{shaded} = \varepsilon_l \sigma T_{l,shaded}^4 \cdot LAI_{shaded}$$

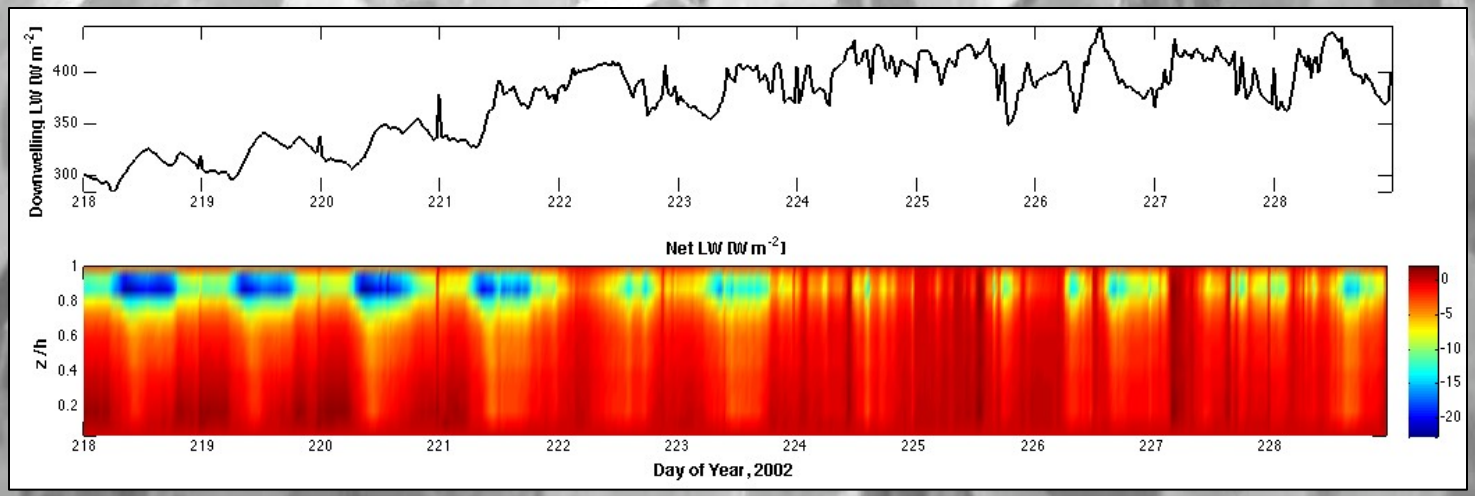
Longwave emission at each layer:

$$R_{lw} = \epsilon_a \sigma T_{ak}^4$$

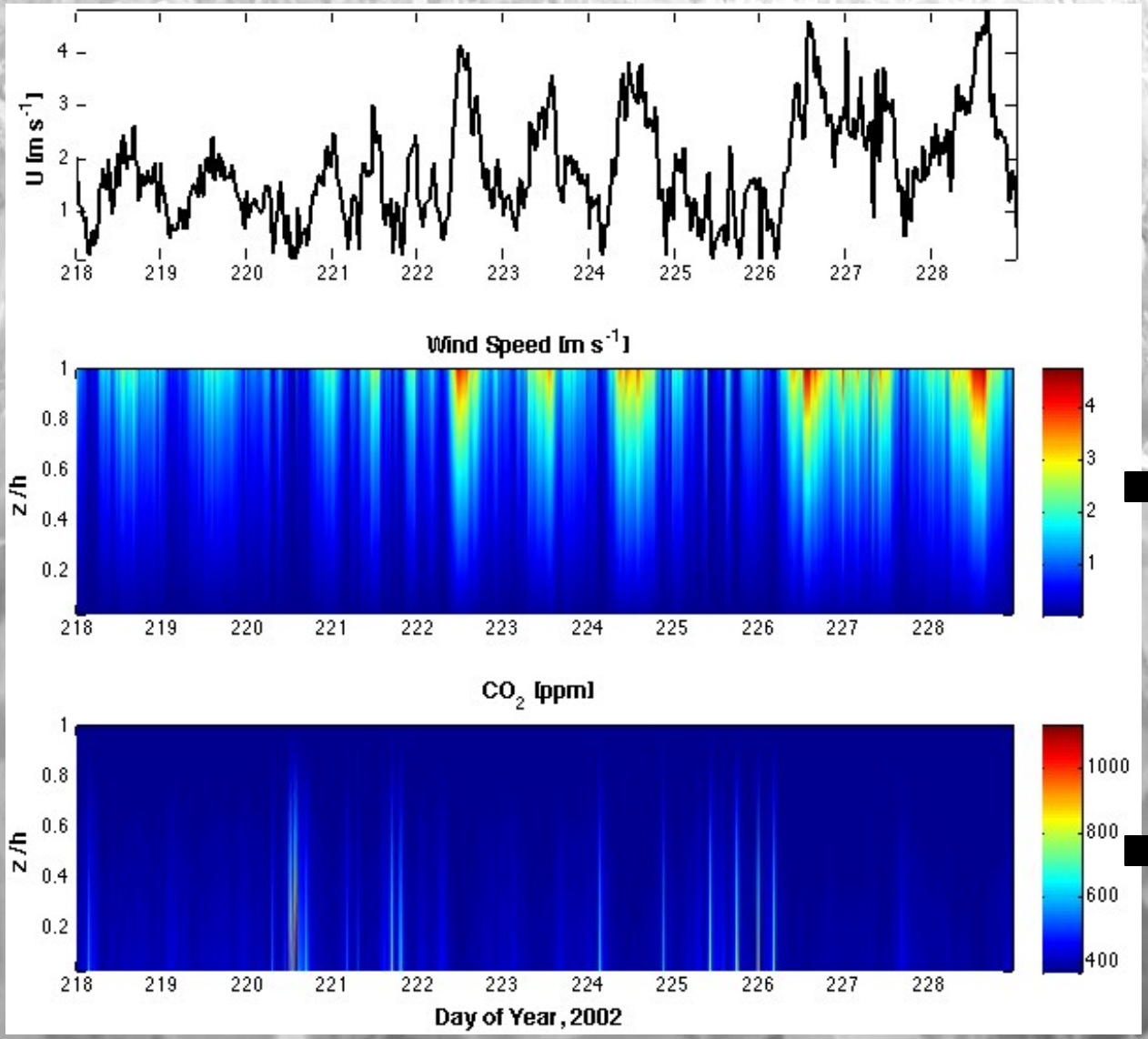
$$\epsilon_a = 1.72 \left(\frac{e_a}{T_{ak}} \right)^{1/7}$$

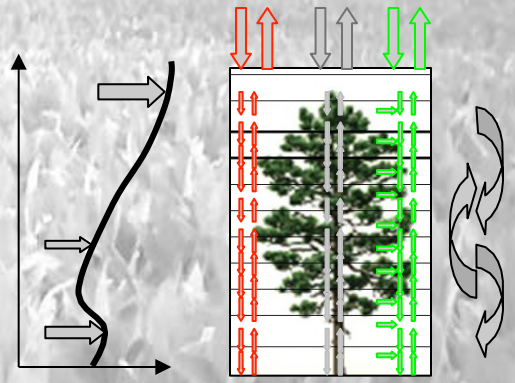
Downward LW

(Absorbed – Emi\ed) LW Through Canopy



Canopy Micro-Environment





Wind speed profiles through canopy over 12 days

CO_2 concentraPon profiles through canopy over same period

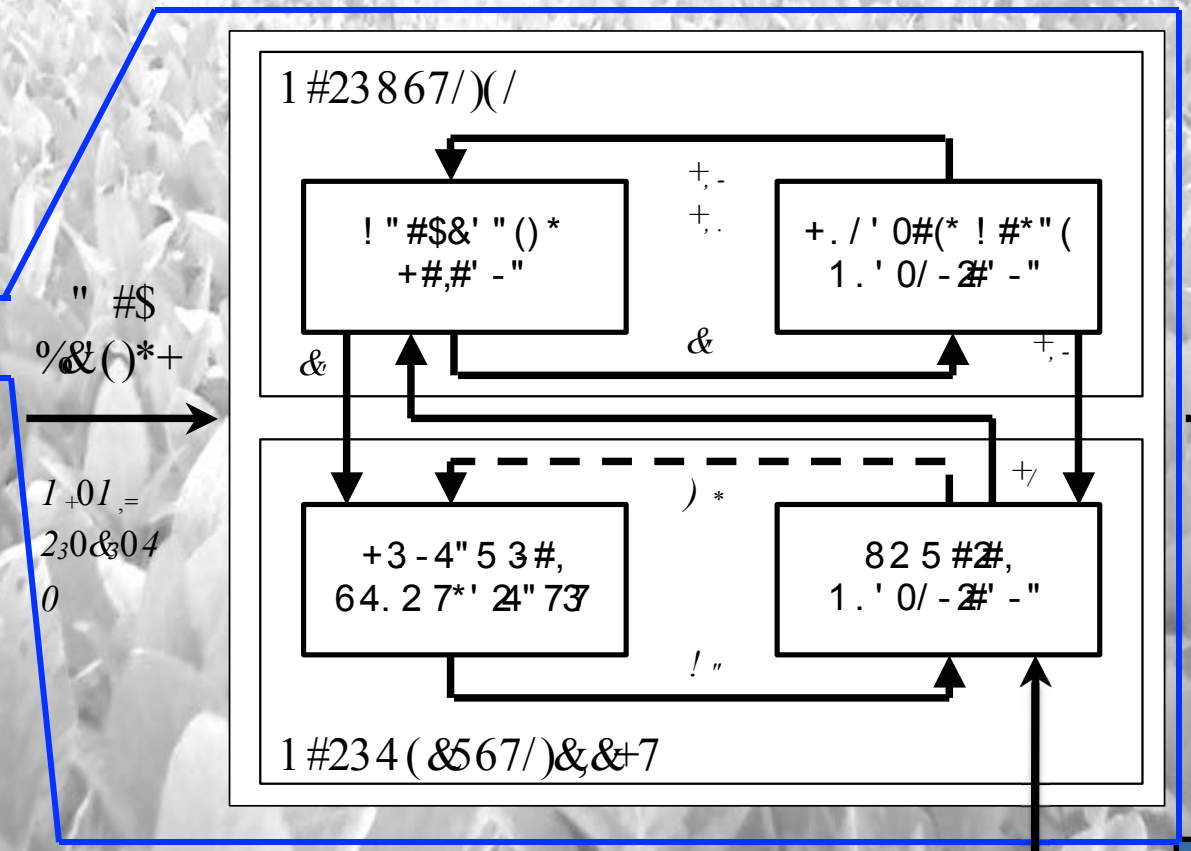
Mean Momentum EquaPon:

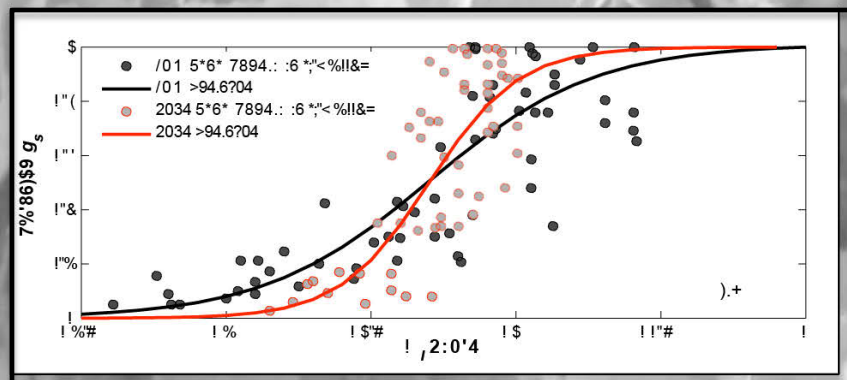
$$-K_m \frac{d^2u}{dz^2} - \frac{dK_m}{dz}\frac{dU}{dz} + \frac{1}{2}C_d L U|U| = 0$$

Eddy Diffusivity:

$$K_m = l_m^2 \left|\frac{du}{dz}\right|$$

Leaf-level energy balance –ecophysiology coupling



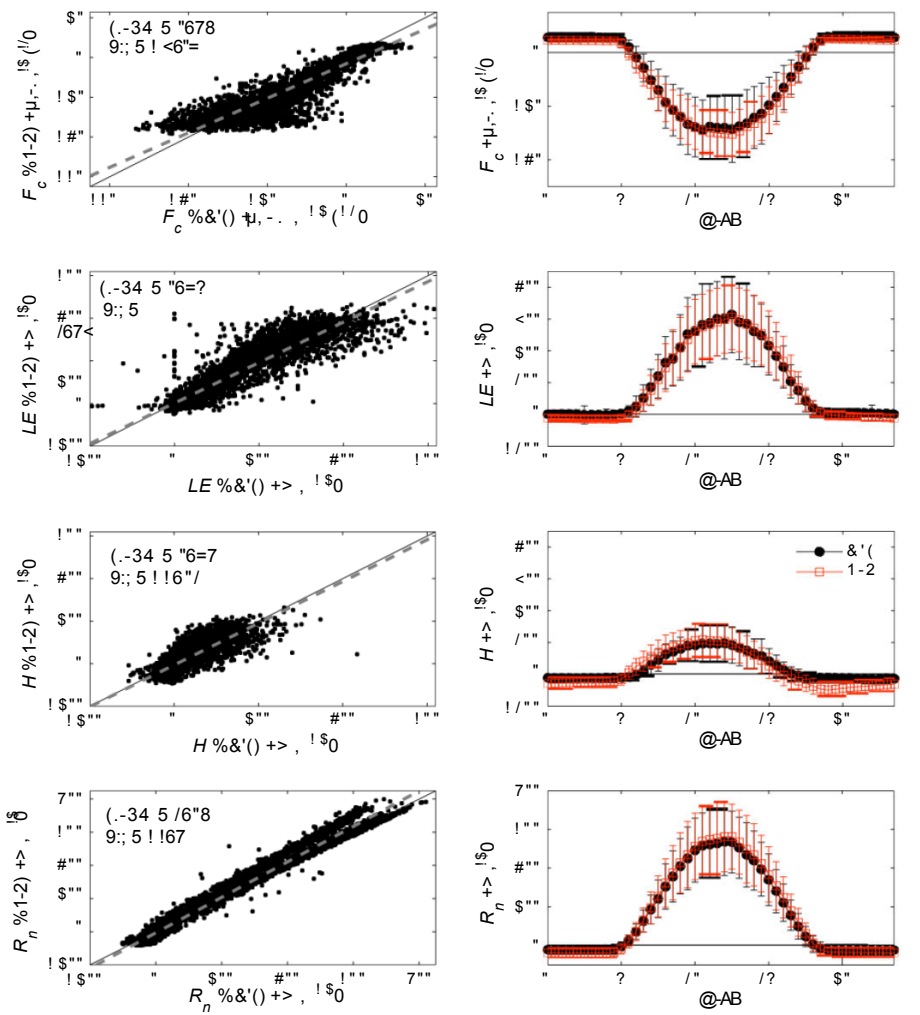


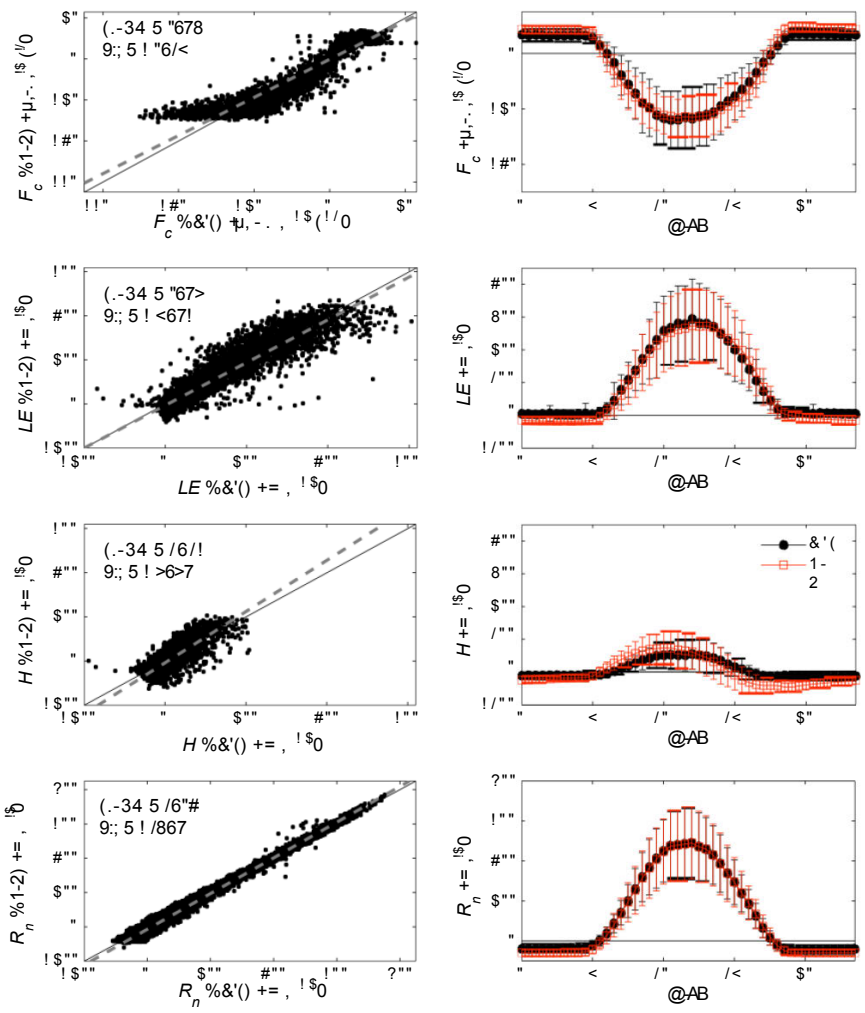
Data from Bunce [2004]

Eddy Flux ValidaPon

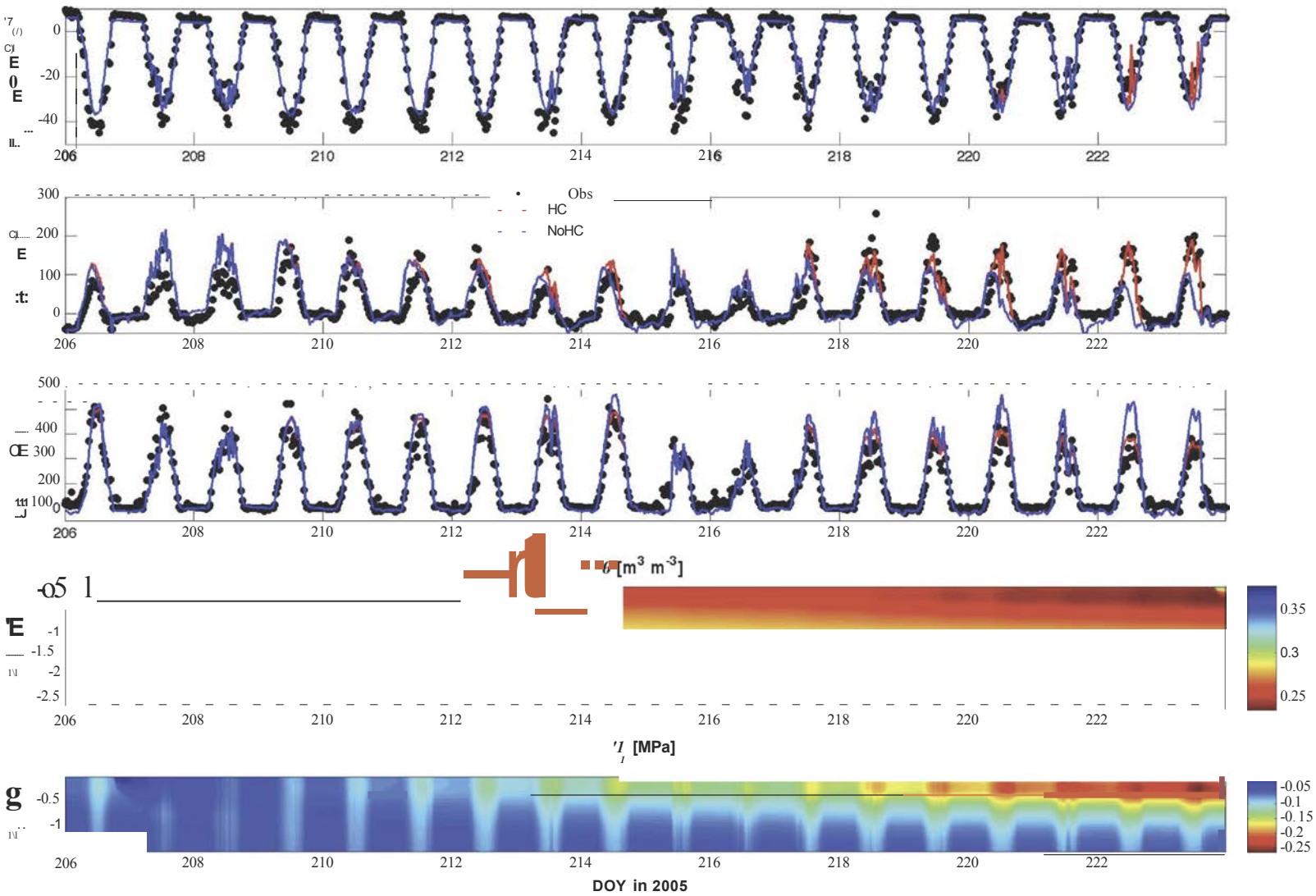
Maize:
6192 half-hour periods

Soybean:
7488 half-hour periods





Example Effect of Moisture Deficit: Maize



Layer ce:

$\frac{L_v g_{vt}}{P_a}$ + $Tt + M_e$

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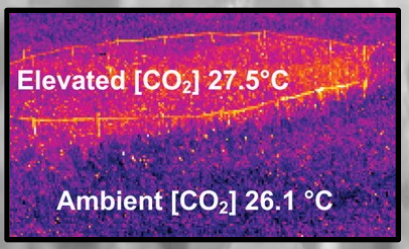
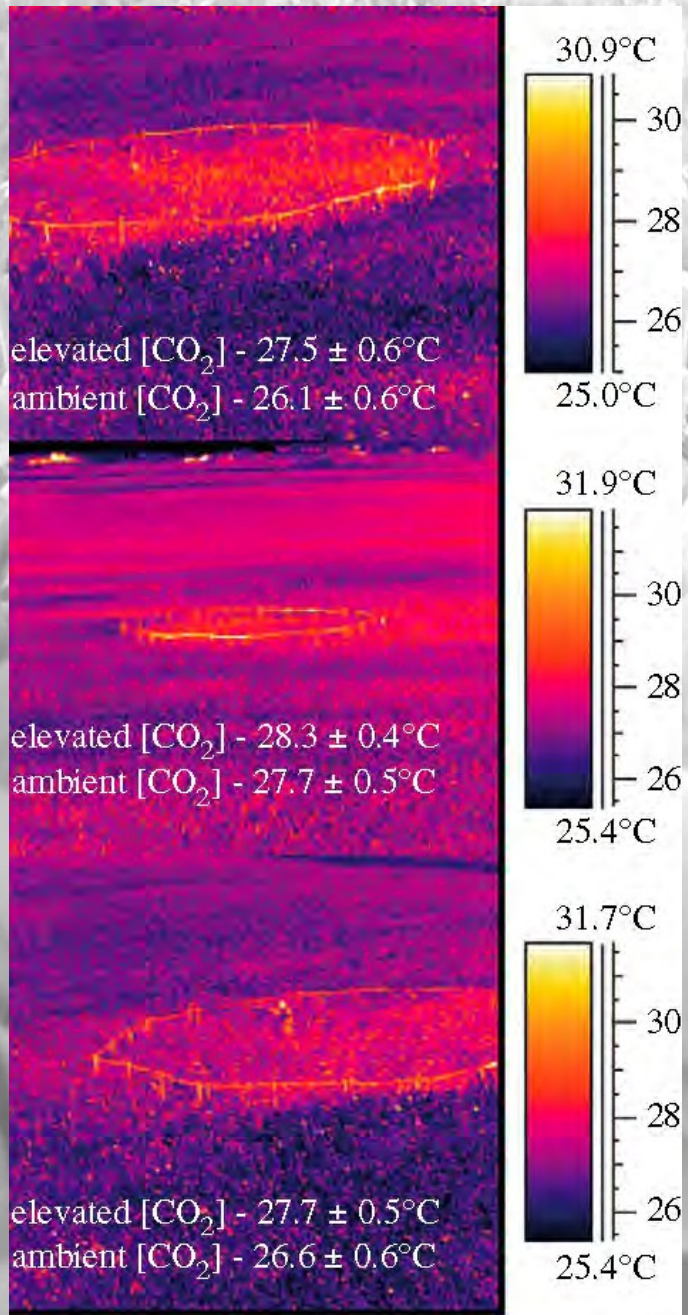
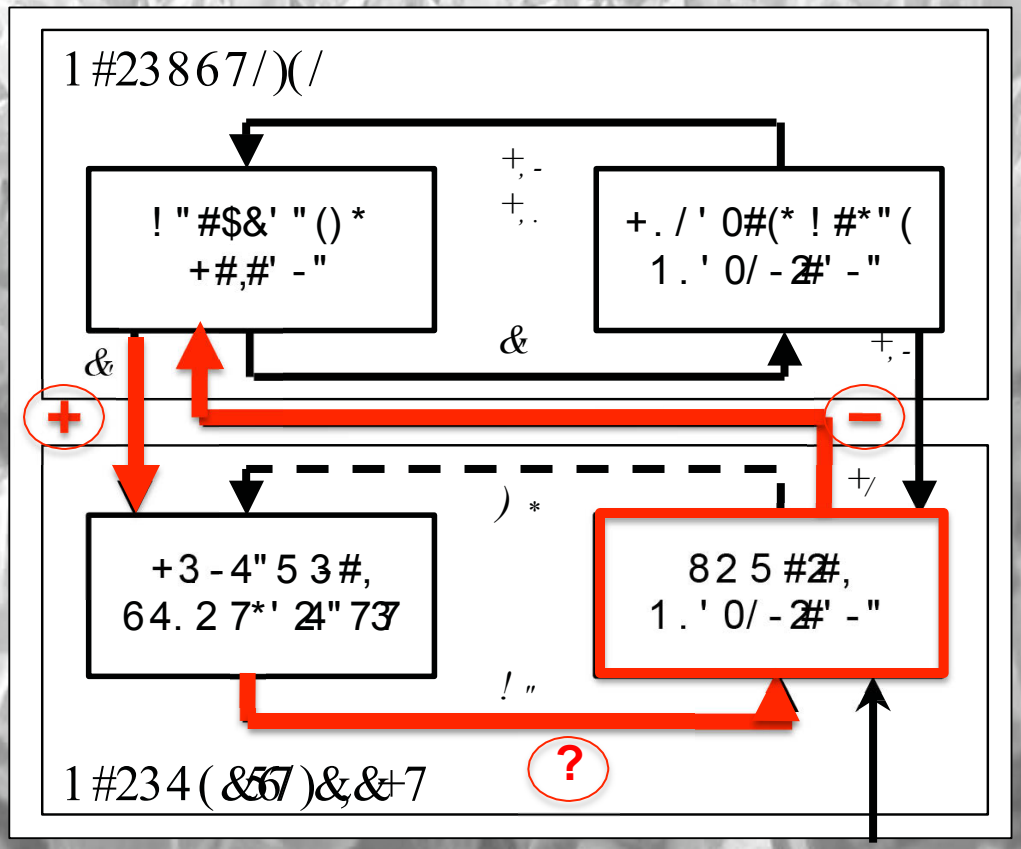


AcclimaPon Responses to Elevated CO_2



Ecophysiological Adjustment

Soybean (C3) and Maize (C4)



$$g_s = f_{sw} \cdot m \frac{A_n \cdot h_s}{C_s} + b$$

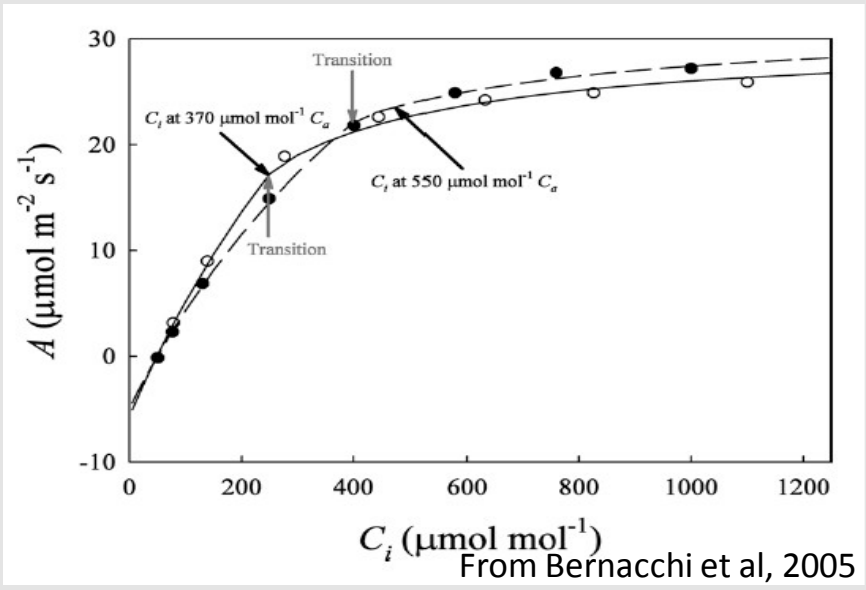
From Leakey et al, Proc. Royal Soc. B, 2009

AcclimaPon Responses to Elevated CO_2

Biochemical Acclima6on

(PhotosynthePc Down-RegulaPon)

Soybean (C3) only



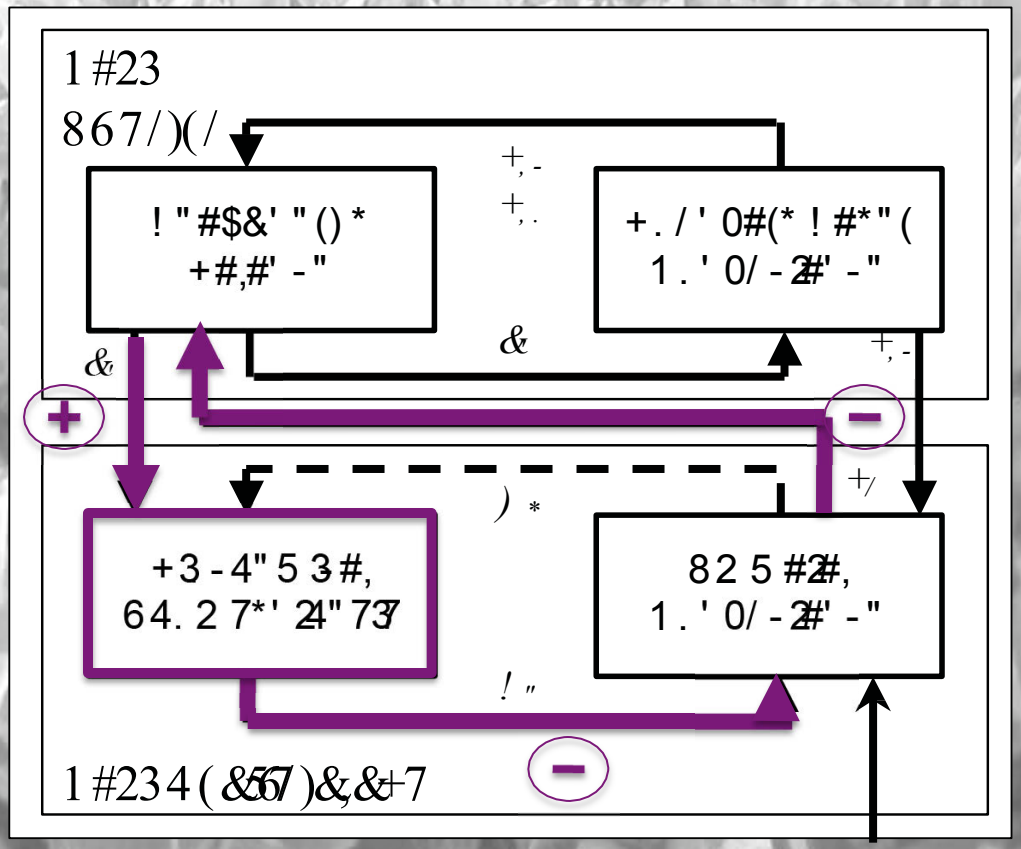
From Bernacchi et al, 2005

$$A_n = \left(1 - \frac{\Gamma^*}{C_i}\right) \min[W_c, W_j] - R_d$$

$$W_j = \frac{J \cdot C_i}{4.5C_i + 10.5\Gamma^*}$$

$$W_c = \frac{V_{cmax} \cdot C_i}{C_i + K_c\left(1 + \frac{O}{K_o}\right)}$$

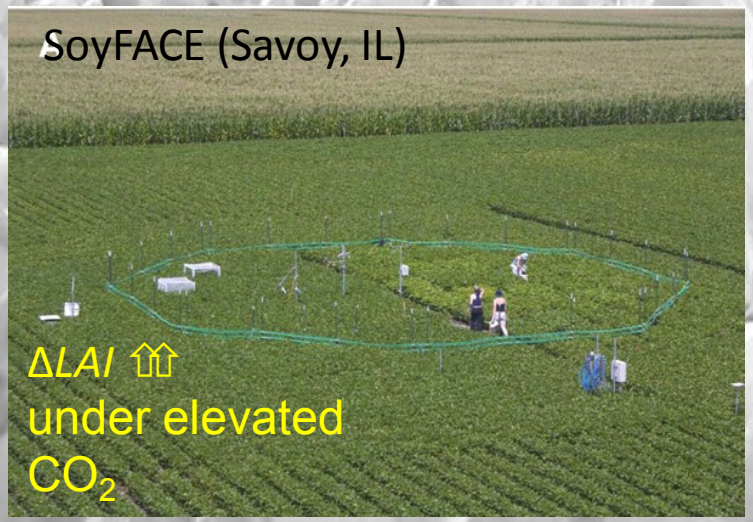
From Farquhar et al, 1981

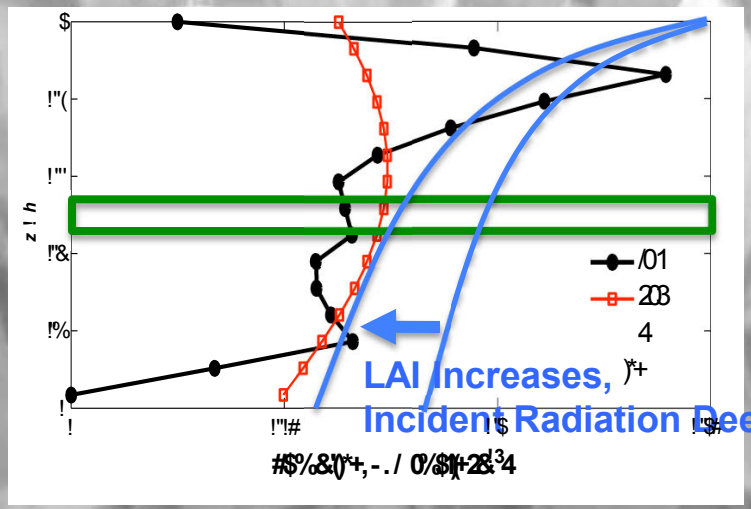


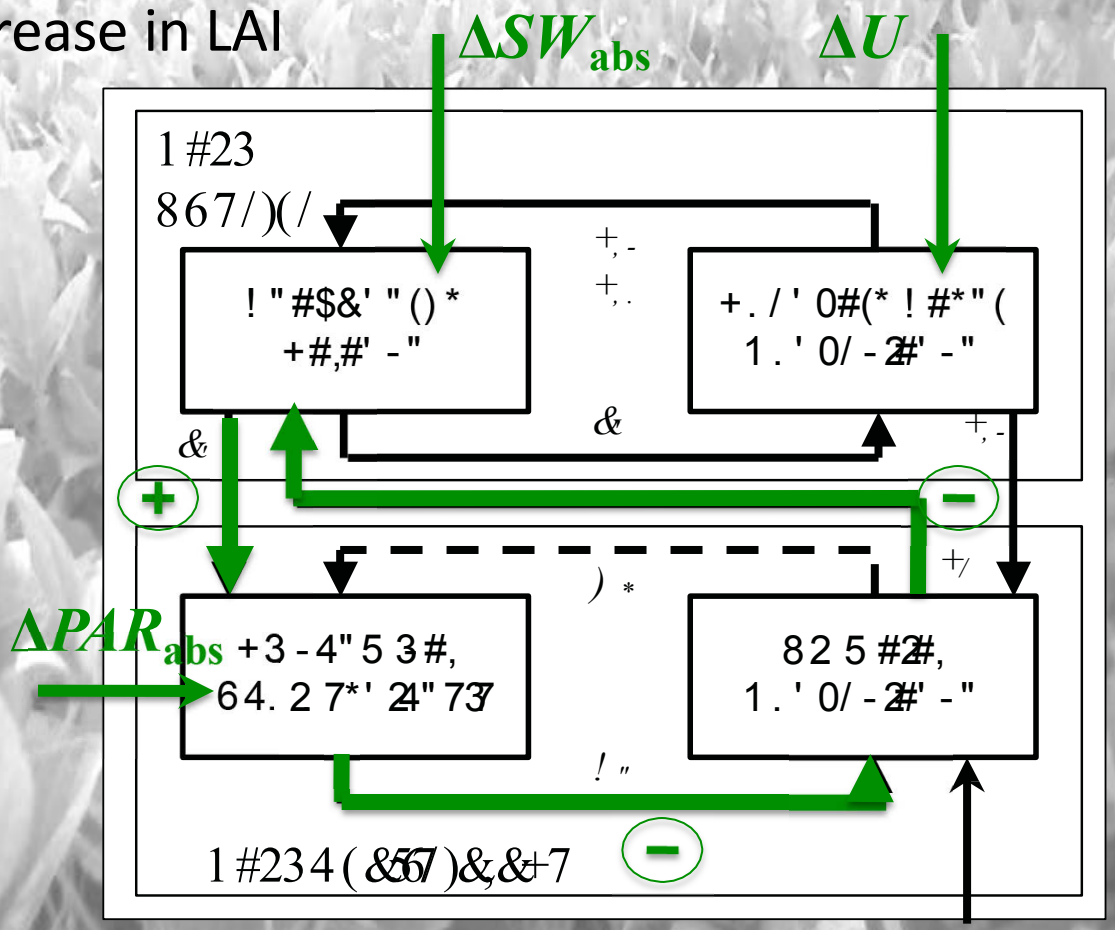
AcclimaPon Responses to Elevated CO_2

Structural Augmenta6on

Soybean (C3) only →→10% increase in LAI



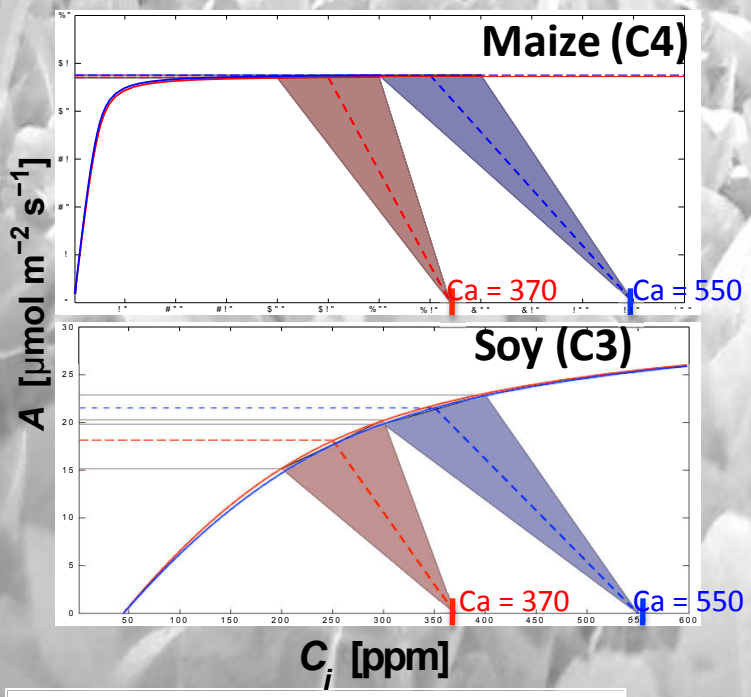




AcclimaPon Responses to Elevated CO_2

Increase in Photosynthe6c Substrate

Soybean (C3) only

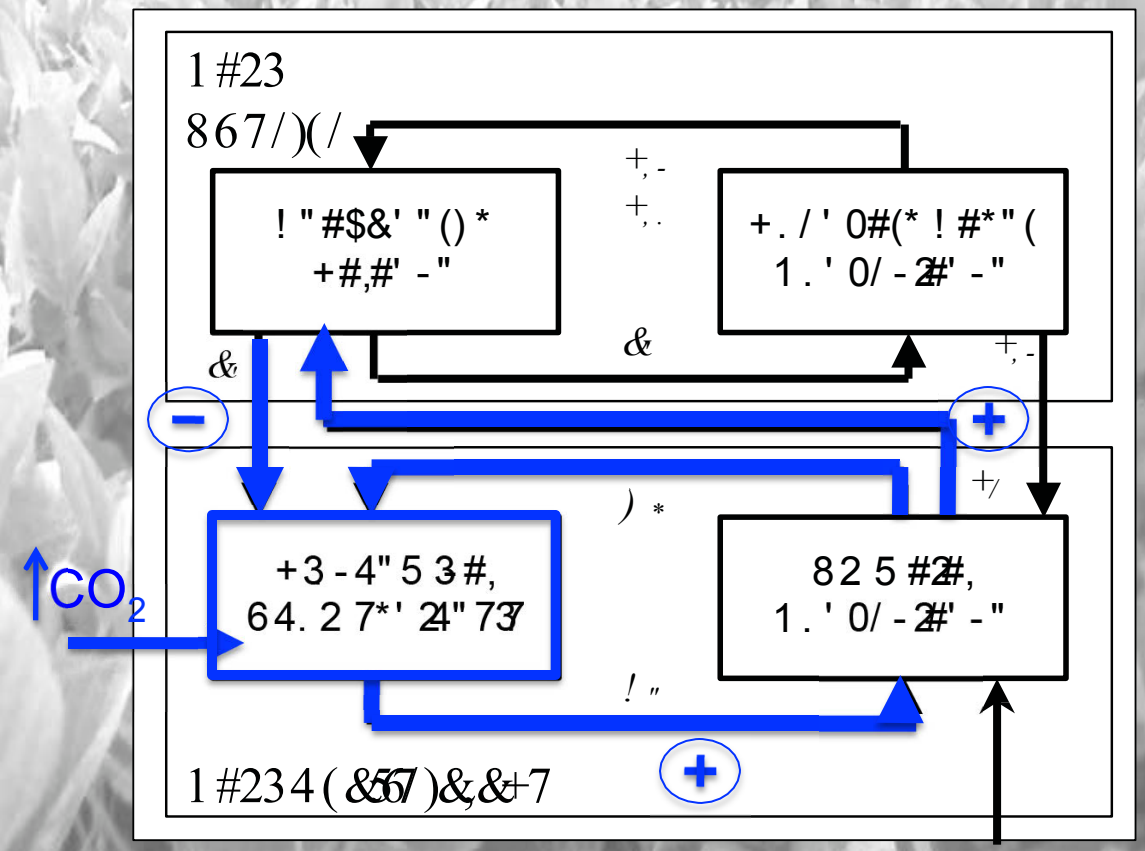


$$A_n = \left(1 - \frac{\Gamma^*}{C_i}\right) \min[W_c, W_j] - R_d$$

$$W_j = \frac{J \cdot C_i}{4.5C_i + 10.5\Gamma^*}$$

$$W_c = \frac{V_{cmax} \cdot C_i}{C_i + K_c\left(1 + \frac{O}{K_o}\right)}$$

From Farquhar et al, 1981



SimulaPon Scenarios for AcclimaPon Analysis

Soy:

1)All observed acclima- o n s:

Ecophysiological: stomatal closure due to elevated CO_2

Structural: 10% increase in LAI

Biochemical: 5% down-regulaPon in V_{cmax}

2) No Structural

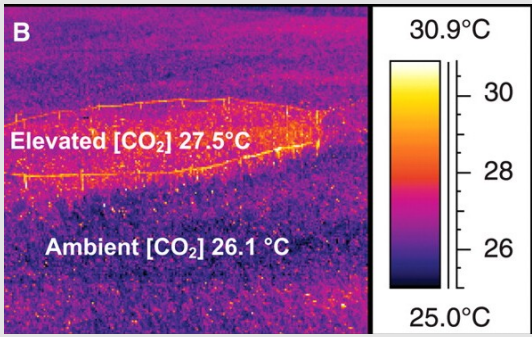
Ecophysiological and Biochemical

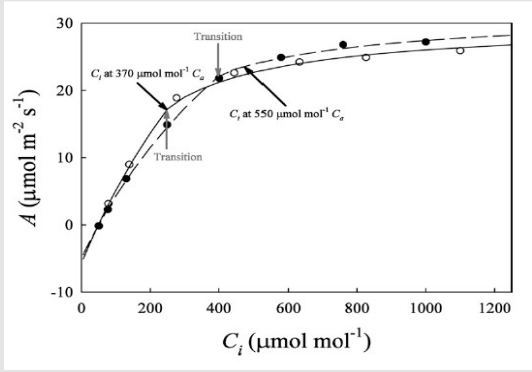
3) No Structural and No Biochemical: Ecophysiological only

Maize:

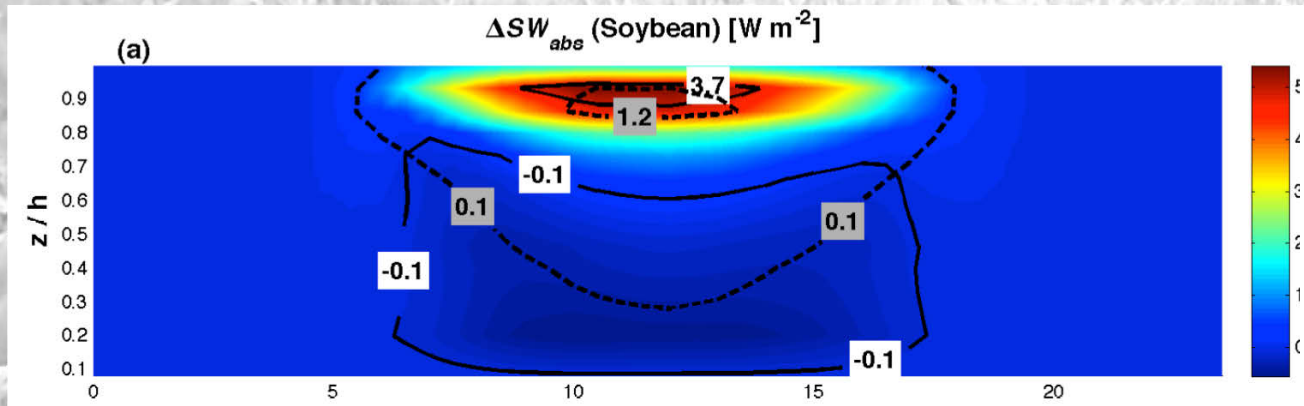
Only Ecophysiological acclimaPon observed

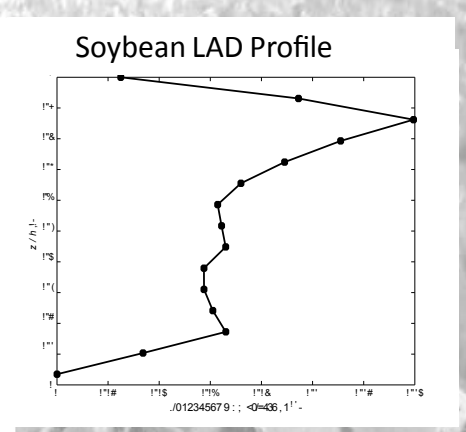
Note: Δ refers to (Elevated – Ambient) differences throughout remainder of talk

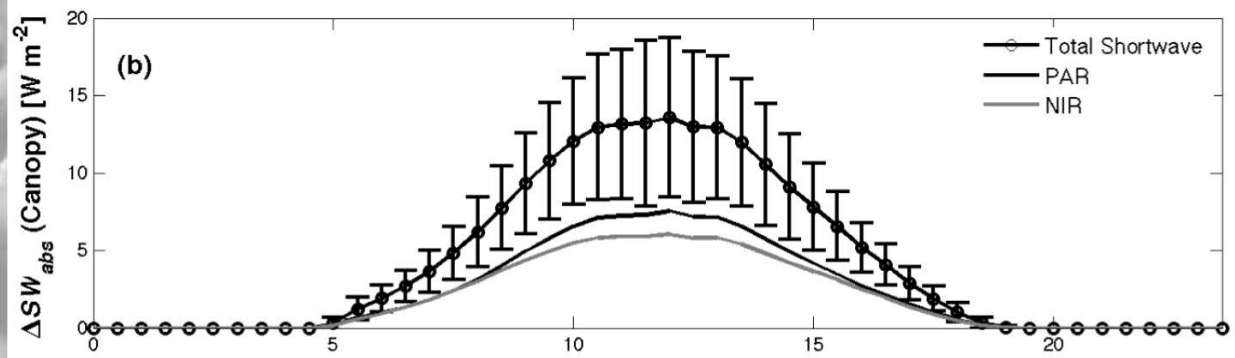


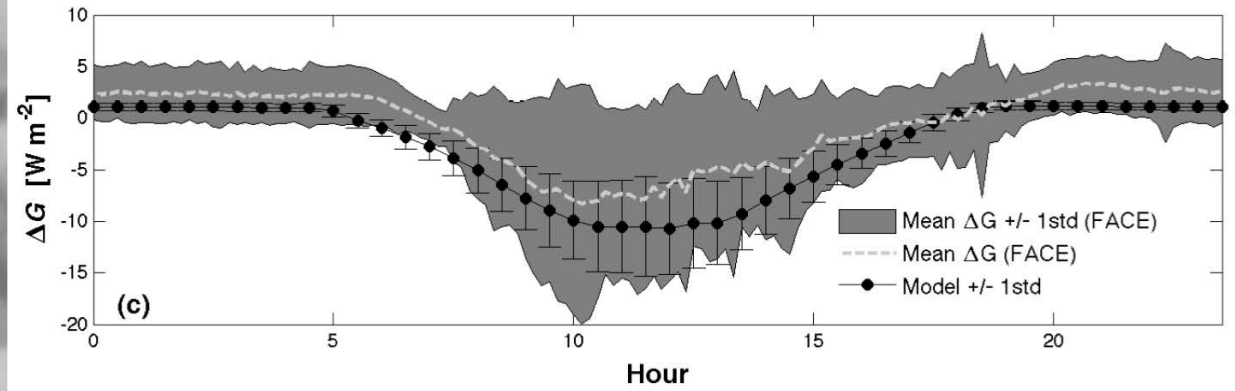


Soy Structural AcclimaPon and SW Regime

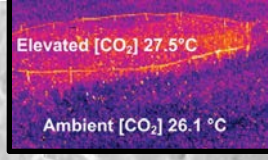








Soil Moisture ConservaPon



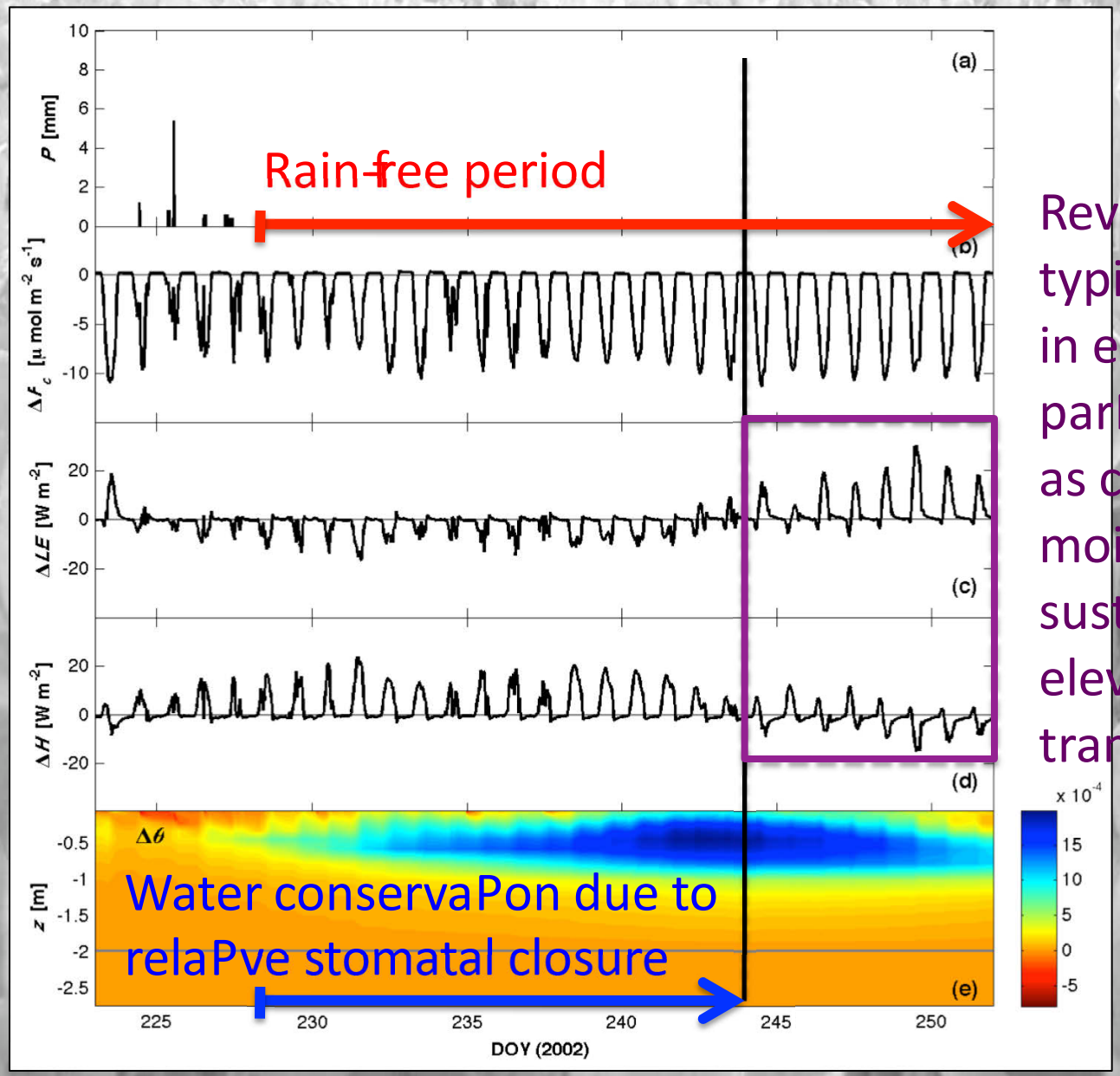
Precip:

Change in NEE:

Change in LE:

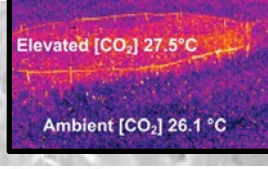
Change in H:

Change in Soil Moisture:



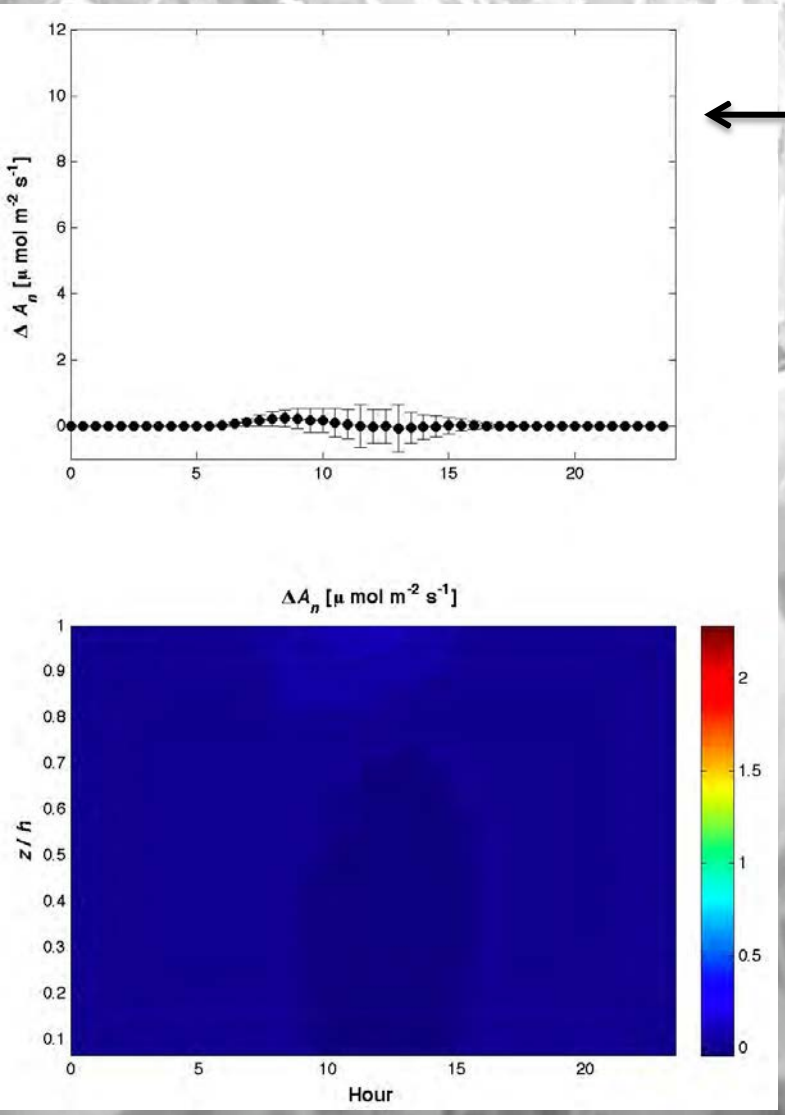
Reversal in typical changes in energy parPPoning as conserved moisture sustains elevated CO_2 transpiraPon

Net Carbon Dioxide Uptake



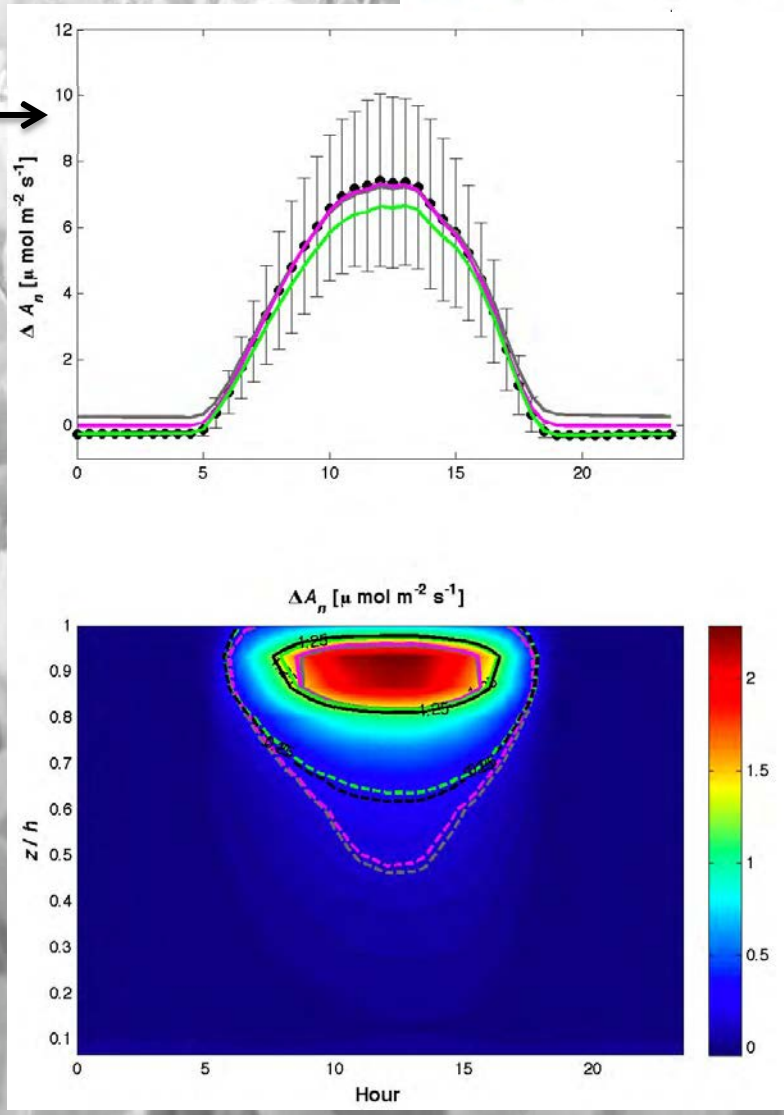
Maize:

Soy:

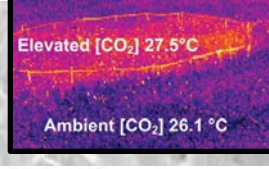


Canopy Integrated Flux

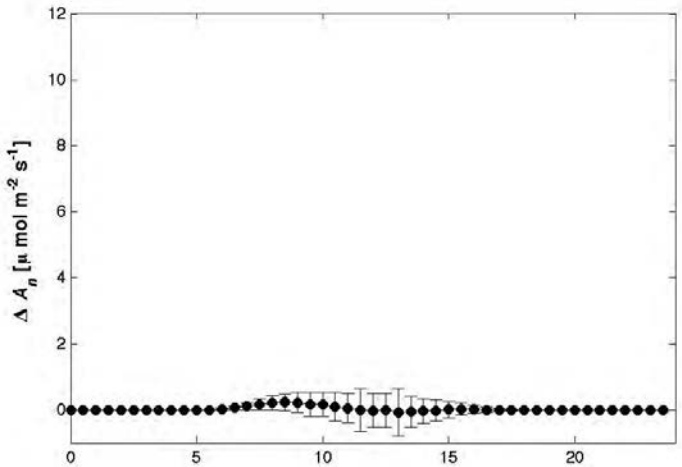
PosiPve values imply uptake

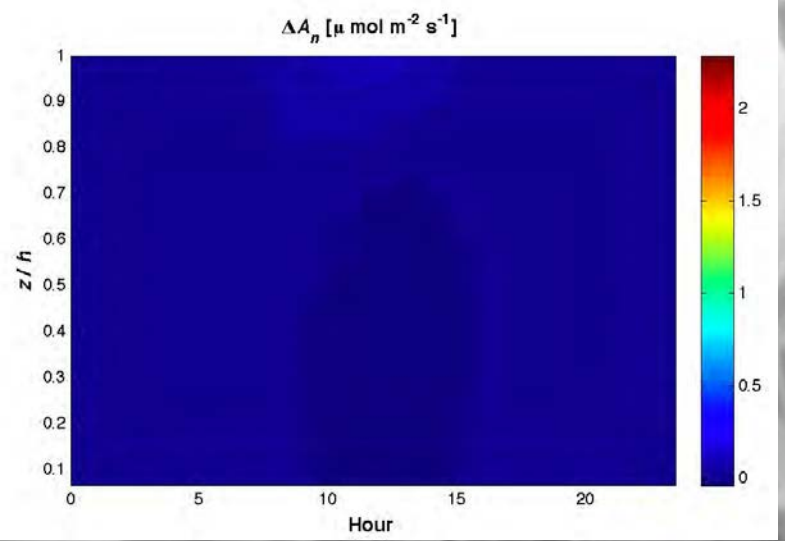


Net Carbon Dioxide Uptake



Maize:





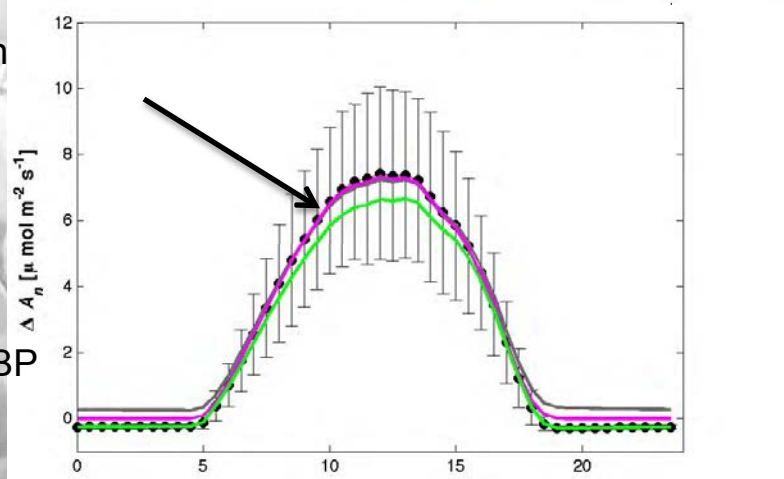
Increase in structure (*LAI*):

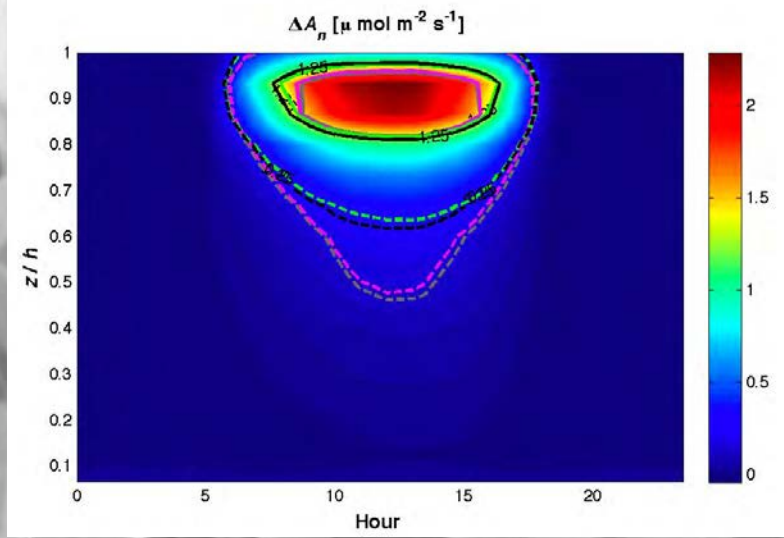
→→offsetting increase in canopy-top *A* & decrease in mid-canopy *A*

→→no significant effect of down-regulation

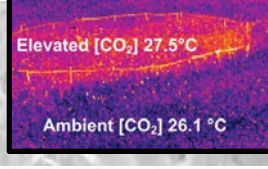
→→canopy uptake more sensitive to changes in RuBP limitation rate

Soy:





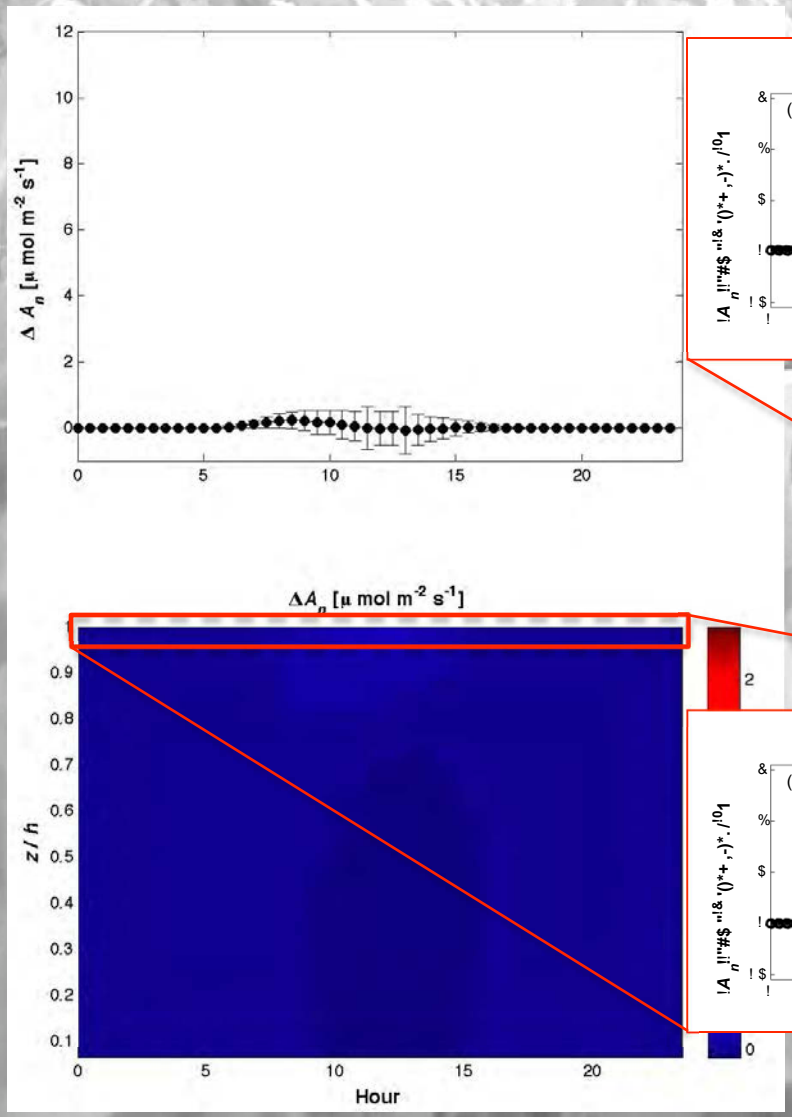
Net Carbon Dioxide Uptake

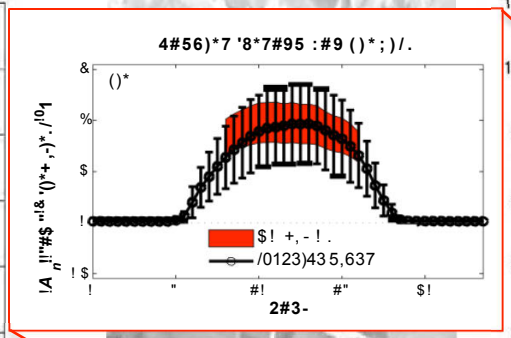


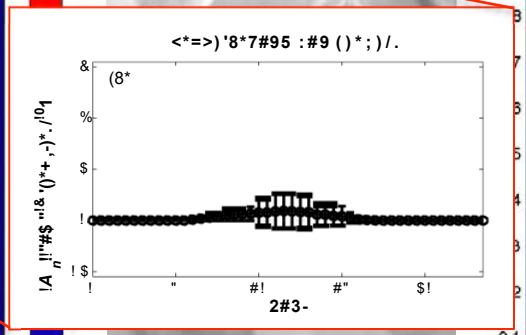
All Changes
No Struc
No Struc, No Biochem
All Changes, J_{max} Reduc

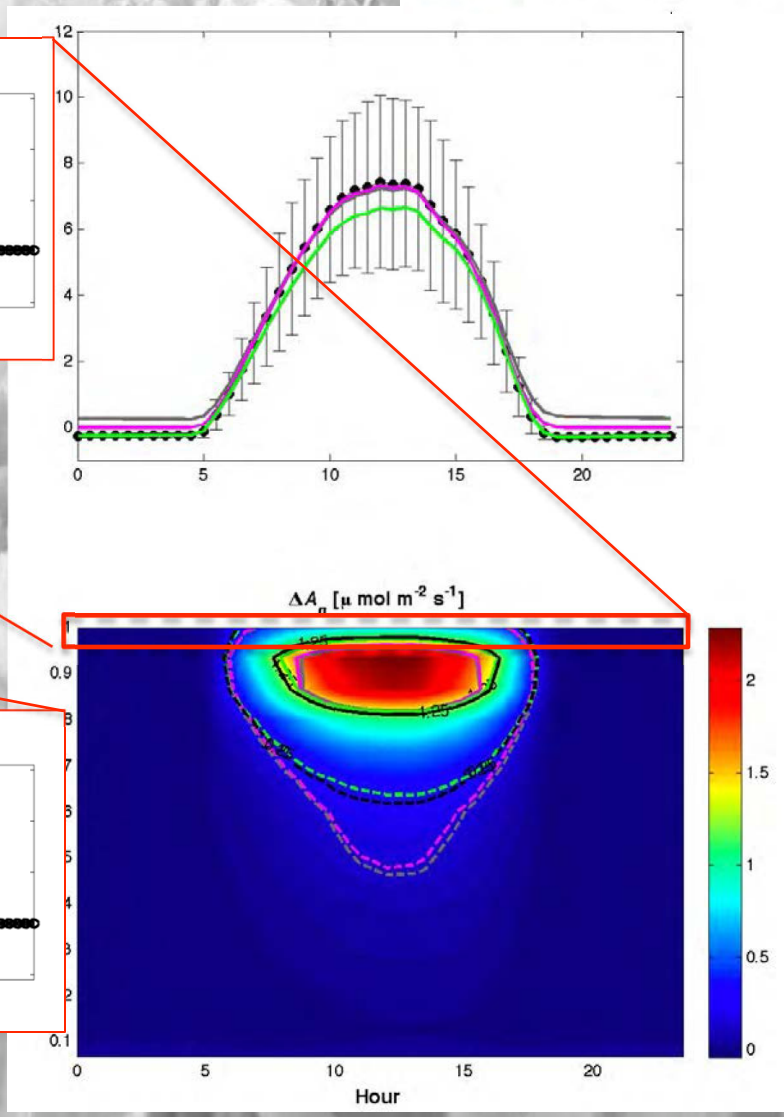
Maize:

Soy:

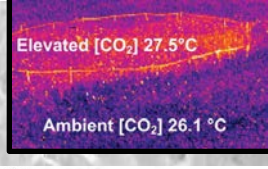








Stomatal Conductance Changes



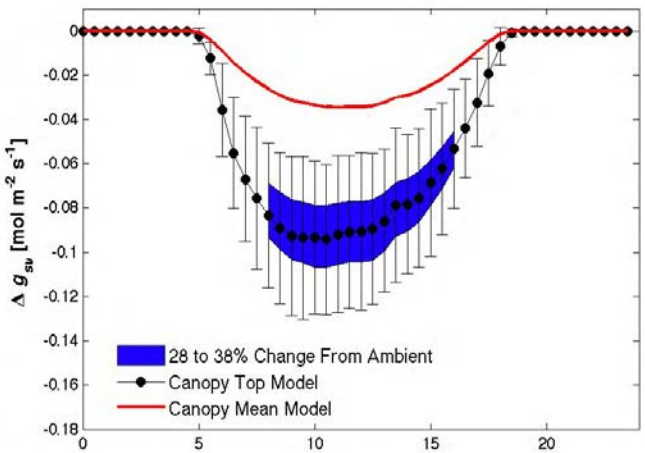
All Changes
No Struc
No Struc, No Biochem
All Changes, J_{max} Reduc

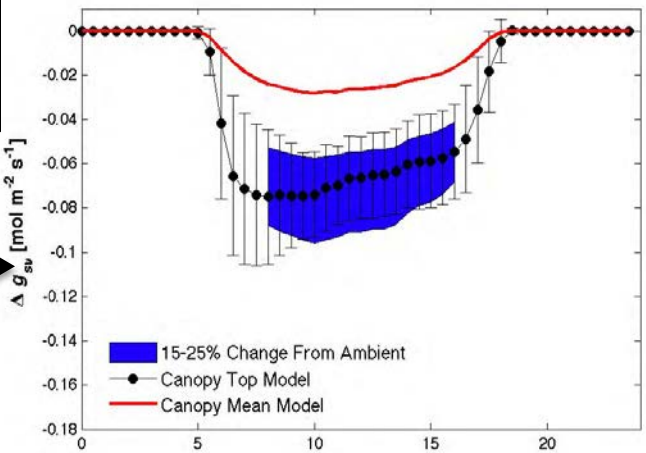
Maize:

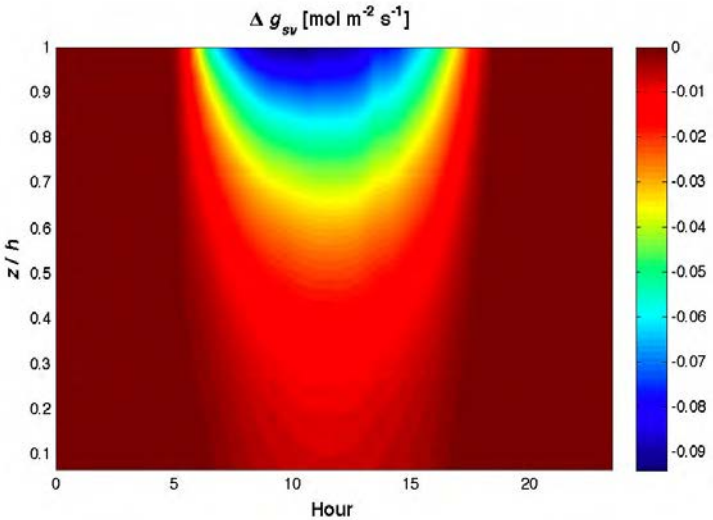
Soy:

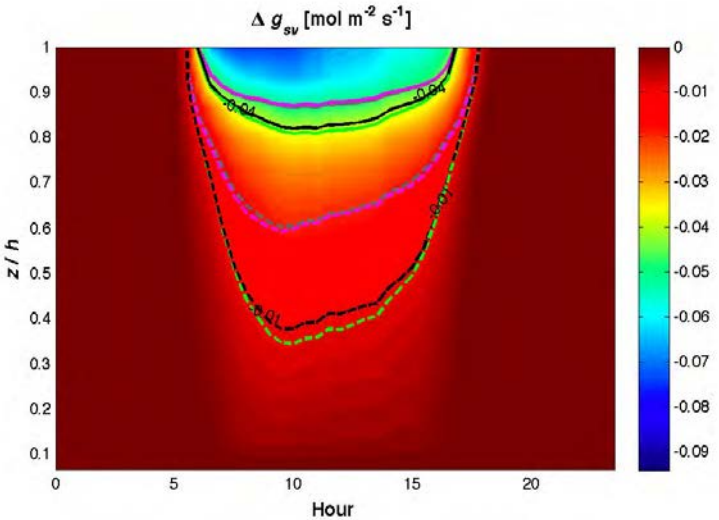
$$g_s = f_{sv} \cdot m \frac{A_n \cdot h_s}{C_s} + b$$

Canopy Top g_s

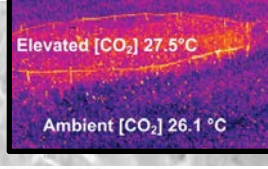






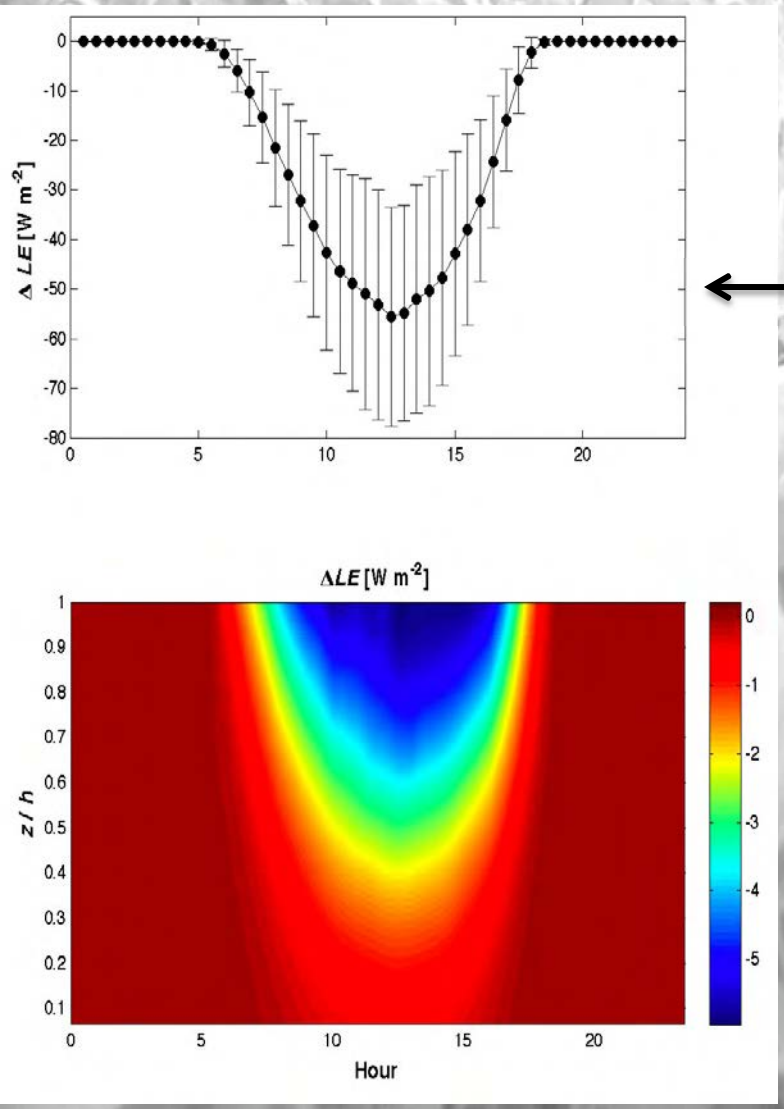


Latent Heat Flux Changes

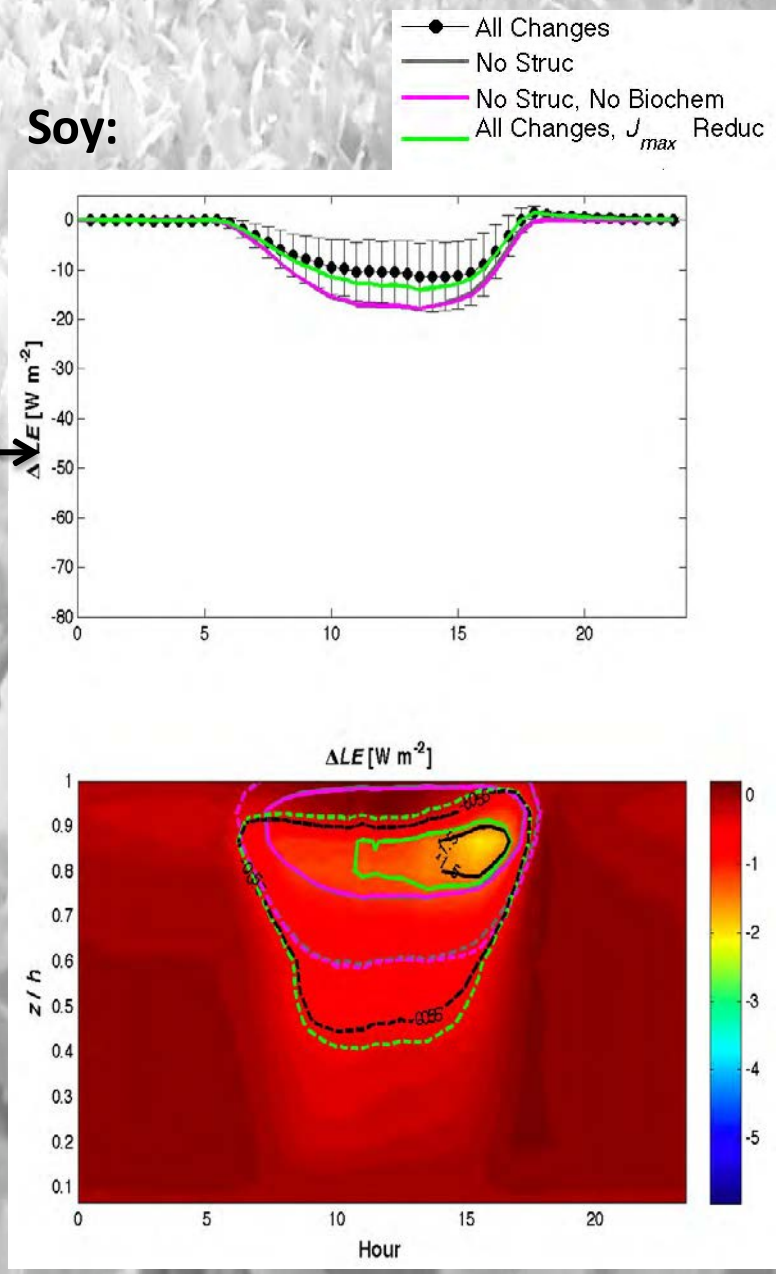


Maize:

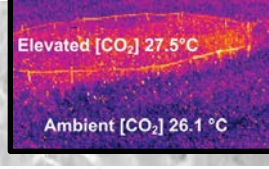
Soy:



Canopy Integrated Flux

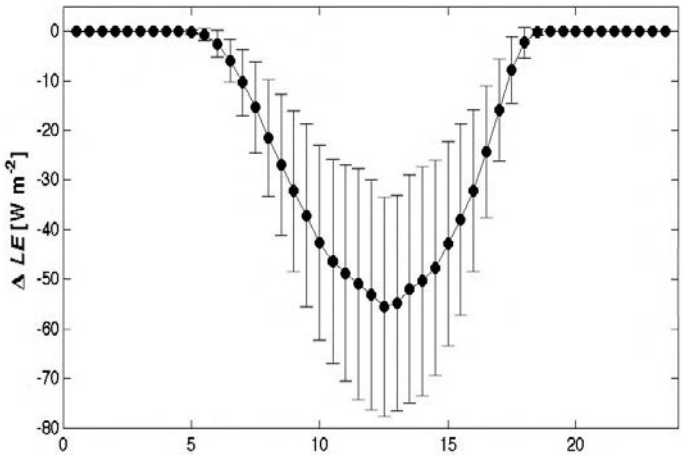


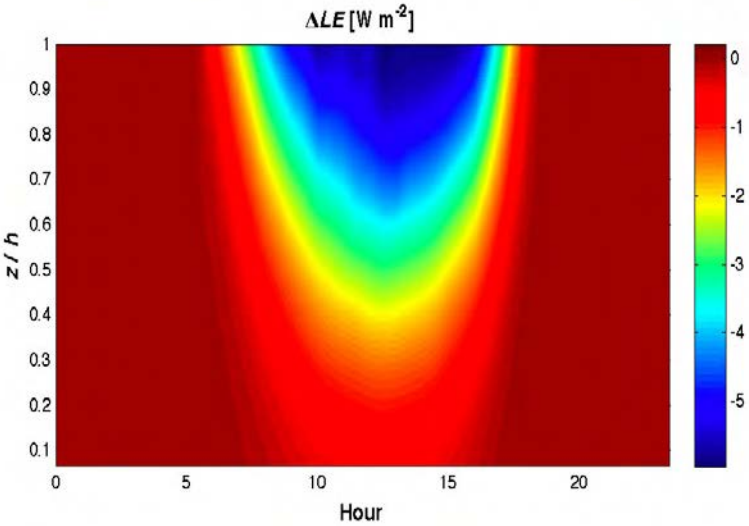
Latent Heat Flux Changes



All Changes
No Struc
No Struc, No Biochem
All Changes, J_{max} Reduc

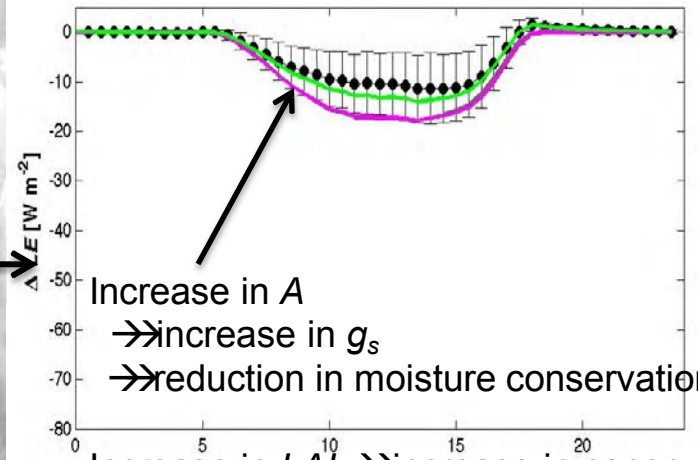
Maize:





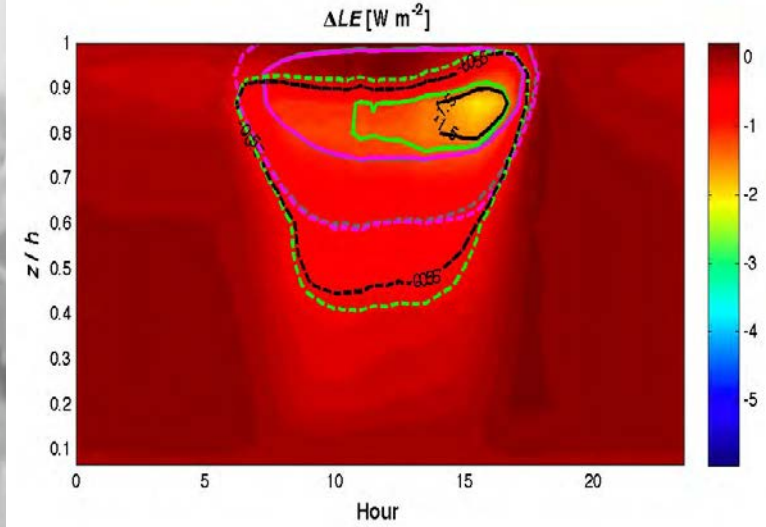
Canopy Integrated Flux

Soy:

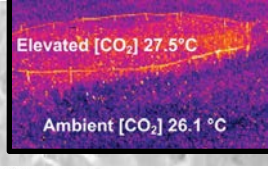


Increase in *A*
→→increase in g_s
→→reduction in moisture conservation

Increase in *LAI* →→increase in canopy-scale *LE*, reduction in stored H_2O

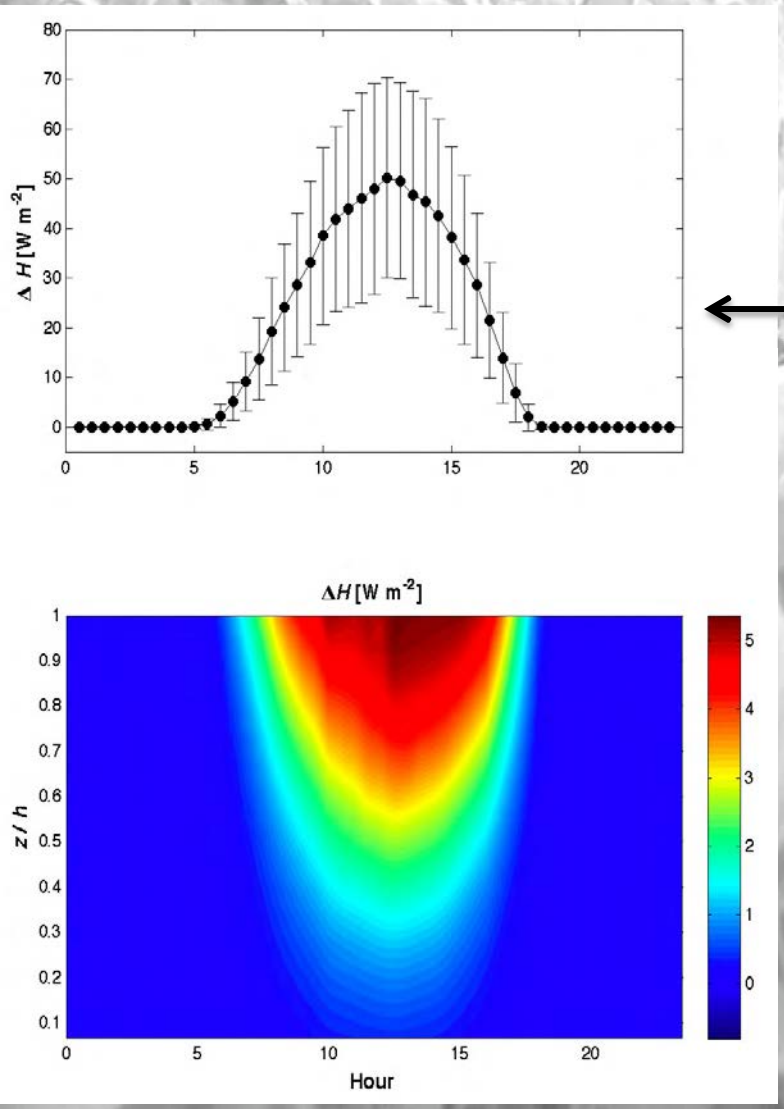


Sensible Heat Flux Changes

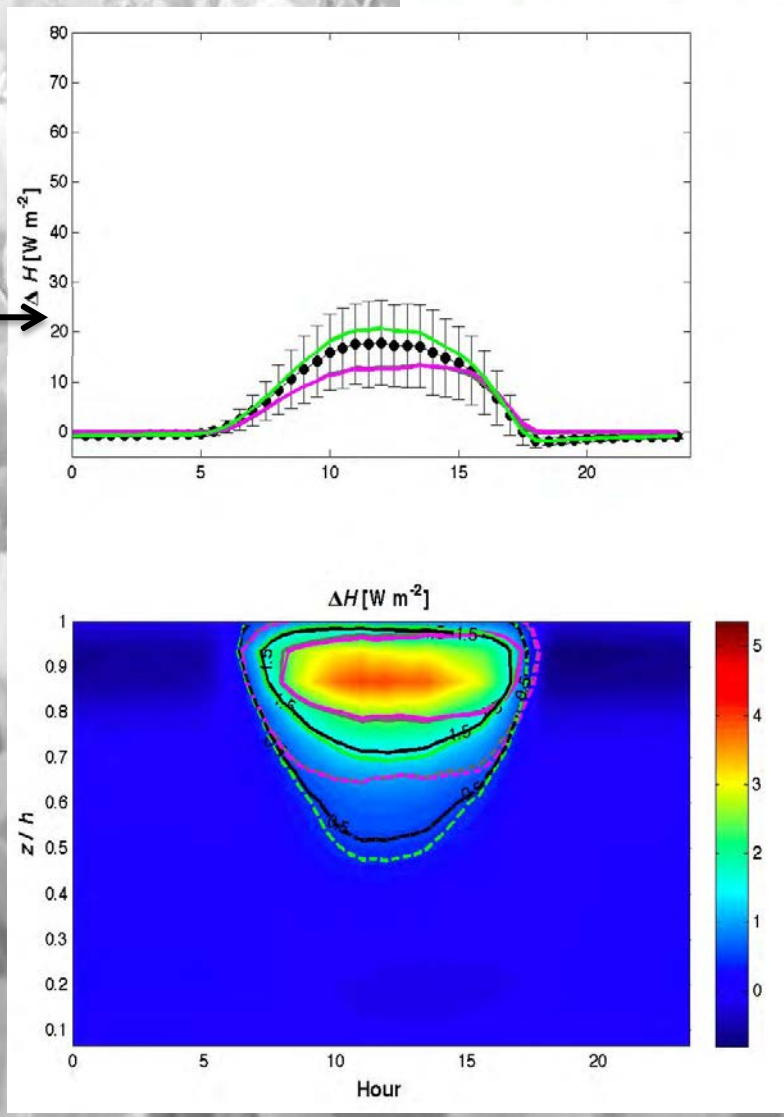


Maize:

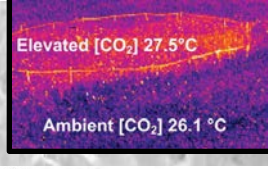
Soy:



Canopy Integrated Flux

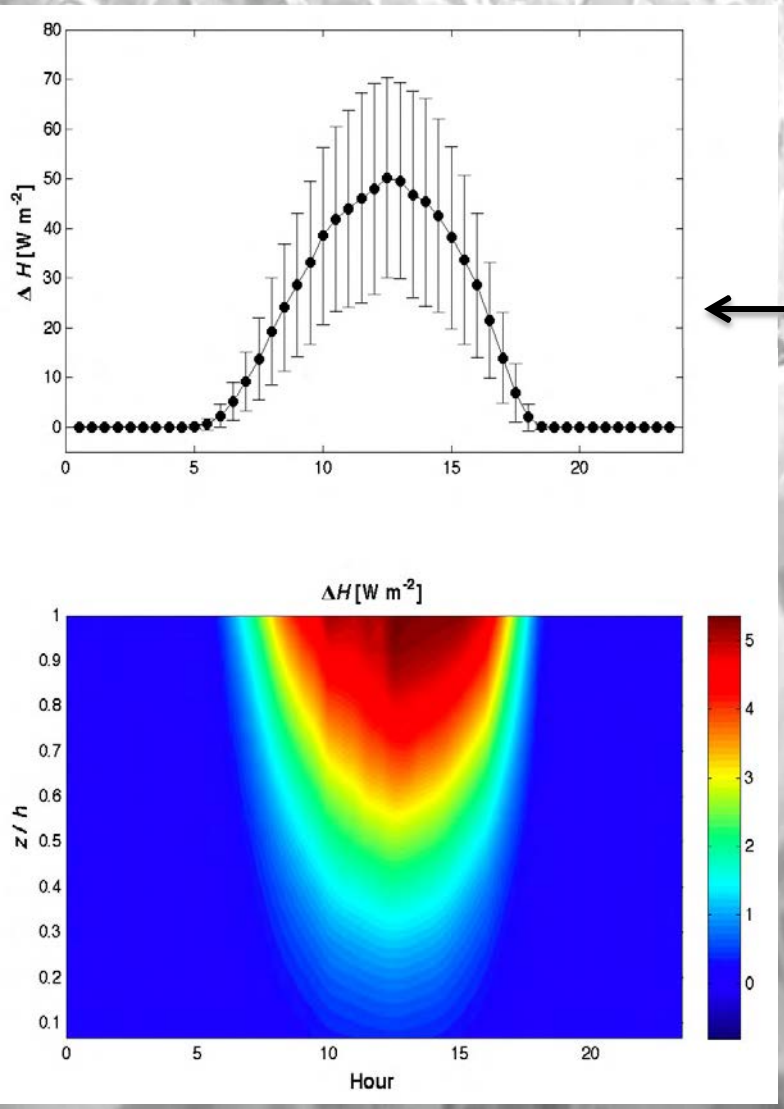


Sensible Heat Flux Changes

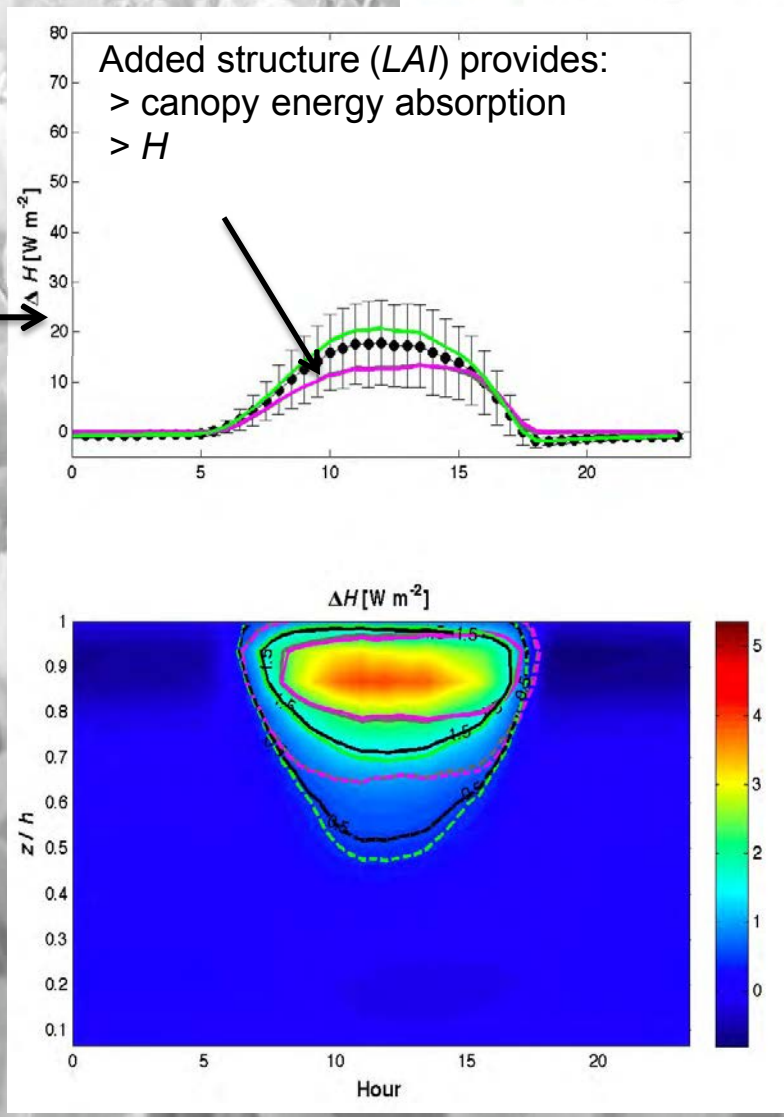


Maize:

Soy:



Canopy Integrated Flux



nature

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Vol 466 | Issue no. 7306 | 29 July 2010

How to feed a hungry world

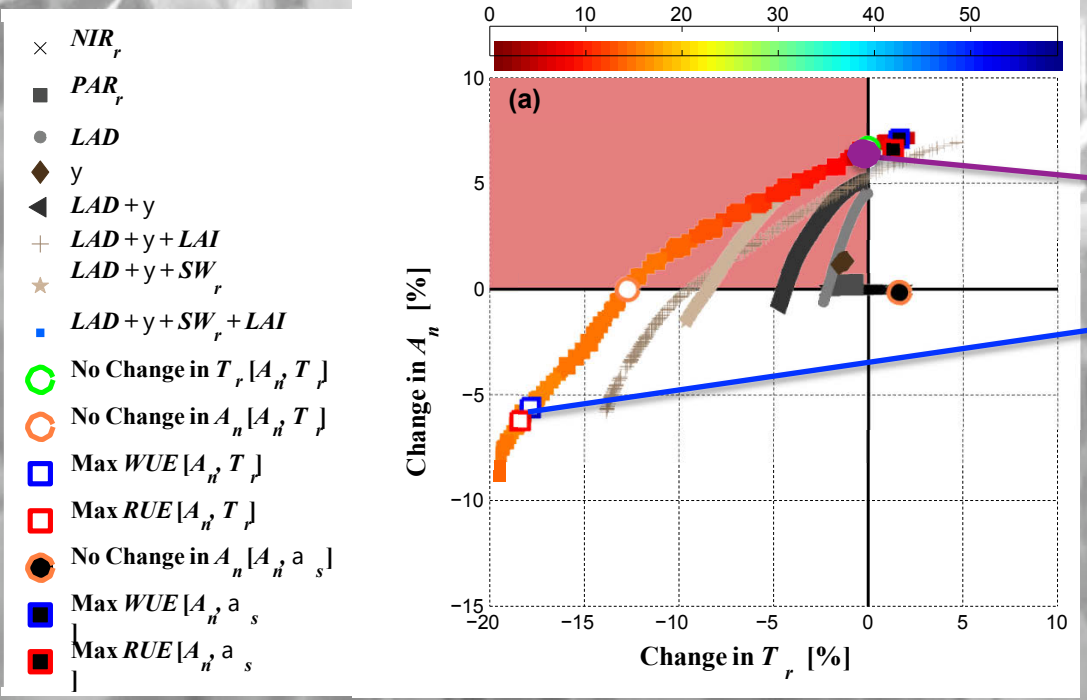
Producing enough food for the world's population in 2050 will be easy. But doing it at an acceptable cost to the planet will depend on research into everything from high-tech seeds to low-tech farming practices.

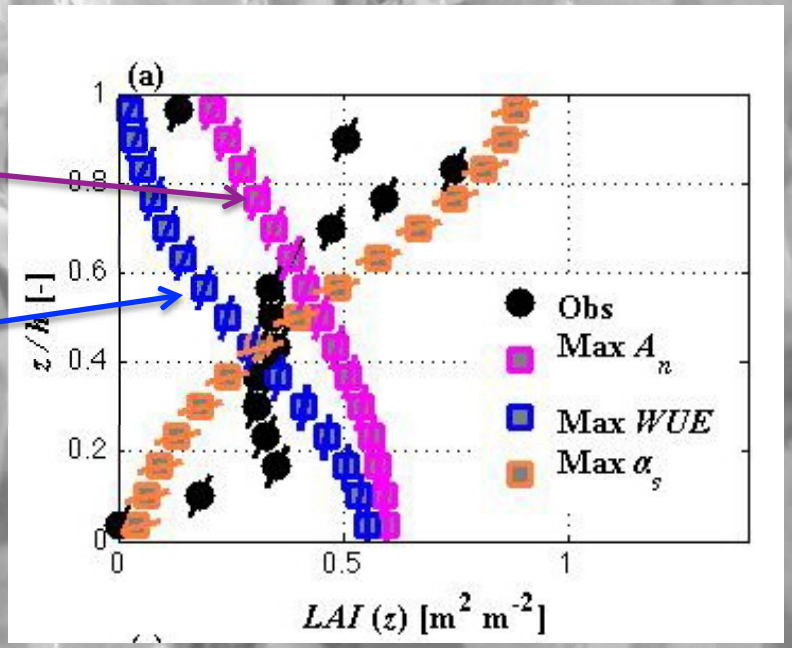
Peak water limits to freshwater withdrawal and use

Peter H. Gleick[1] and Meena Palaniappan

Pacific Institute, 654 13th Street, Oakland, CA 94612

PNAS, 2010

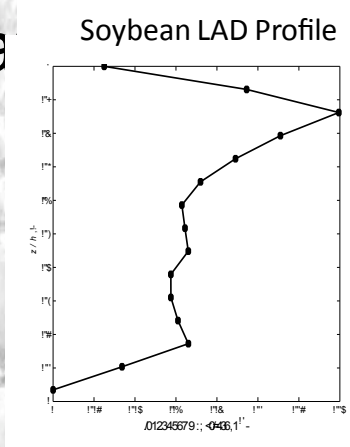


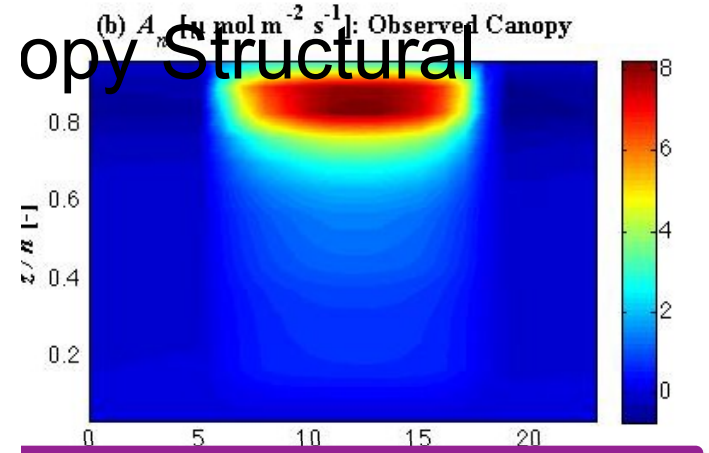


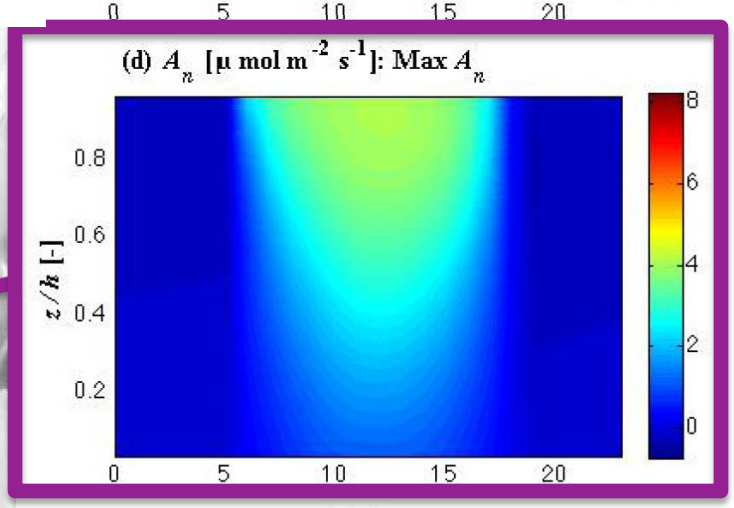
Multi-Objective Optimiza opy Structural Properties

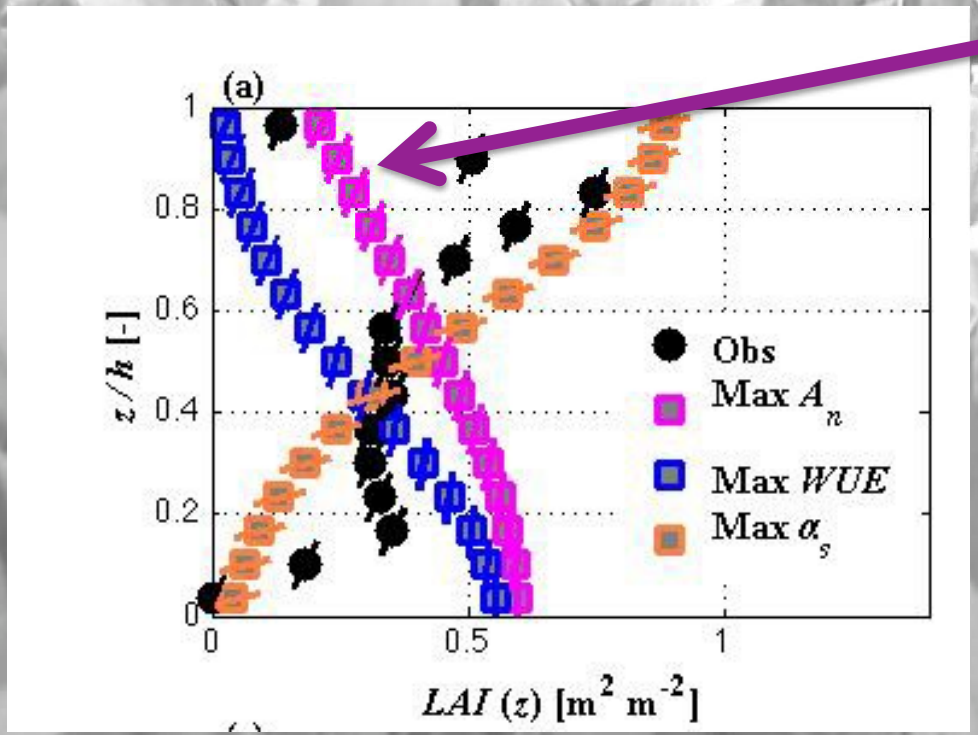
1) Increase crop productivity

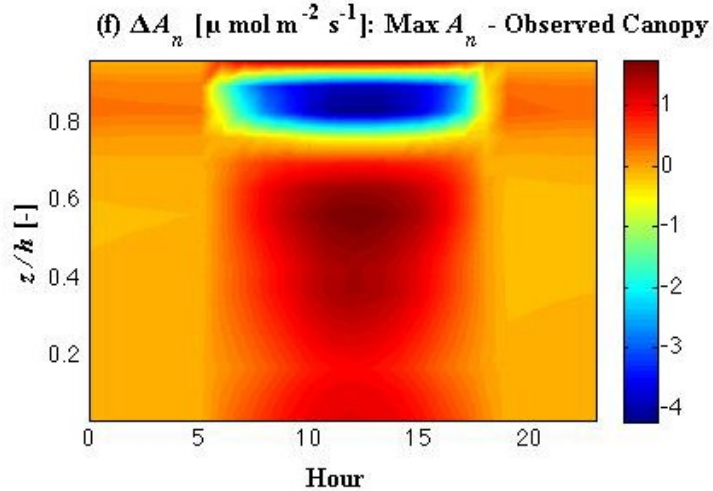
2) Decrease H_2O use











Concluding Points (Modeling Canopy-Atmosphere Exchange)

- MLCan presents a synthesis of principles governing canopy-atmosphere exchange, including leaf-level physical and ecophysiology, root and soil processes that control gas exchange through stomatal closure under moisture stress
  - resolves canopy and soil spaces verPcally
  - provides flexibility with respect to photosynthePc metabolism

- Demonstrated good agreement over 3 growing seasons each of soy (7488 half-hourly data points) and corn (6192 half-hourly data points)

- Canopy structure played a significant role in canopy-atmosphere exchange of both crops
  - Upper-canopy LAD maximum resulted in most of the energy capture and gas exchange occurring in this region of the soy canopy
  - More uniformly distributed corn canopy allowed absorbed radiaPon to be more efficiently used, with less saturaPon of A_n as R_g increased

- Both crops become more water use efficient as moisture stress increases

- C4 metabolism resulted in corn canopy photosynthesis being more resilient to moisture stress

Concluding Points (Canopy Responses to Elevated CO_2)

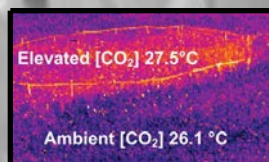
- Modeled gas exchange and leaf state responses to elevated CO_2 in good agreement with SoyFACE observaPons for both C3 and C4 crops

- Net canopy An, LE and H were increased 24%, decreased by 5% and increased 37% at mid-day for soy. Structural acclimaPon & increase in substrate availability offset much of the LE reducPon that would have otherwise occurred.

- Net canopy An, LE and H were increased 1.5%, decreased by 16% and increased 47% at mid-day for corn. These energy balance modificaPons have potenPally significant consequences for ABL development and feedbacks between the ABL and canopy funcPoning.

- Structural acclimaPon results in greater SW energy absorpPon in light-saturated upper-canopy
  - Negligible impact on carbon uptake
  - ReducPon in soil heat flux
  - ParPally offsets reducPon in transpiraPon due to ecophysiological acclimaPon

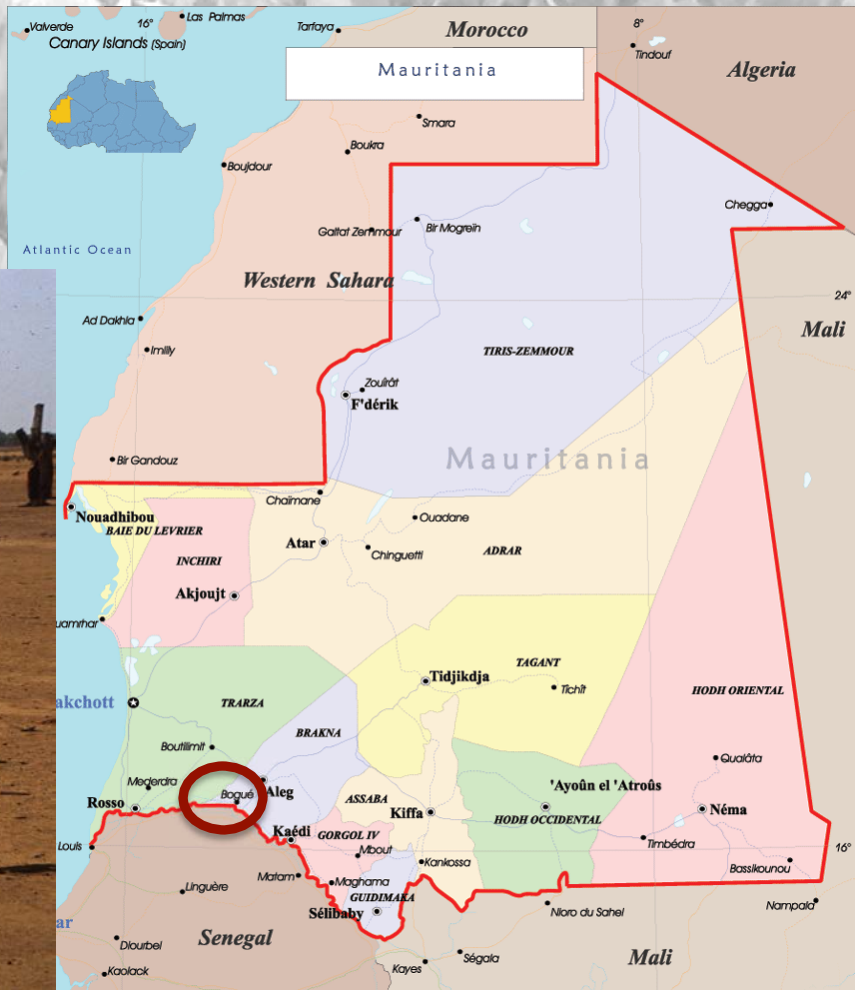
- NegaPve feedback with dayPme ABL results in reduced effect of elevated CO_2 on energy balance parPPoning. Greatest effect occurs for maize relaPve to soy.



Acknowledgements

JRC and CCFAS for organizing this workshop

Amor Ines, Francois Kayitakire, James Hansen and Workshop Conveners!

National Science Foundation
WHERE DISCOVERIES BEGIN

NSF Carbon and Water Cycle Program
NSF InternaPonal Research Fellowship Program