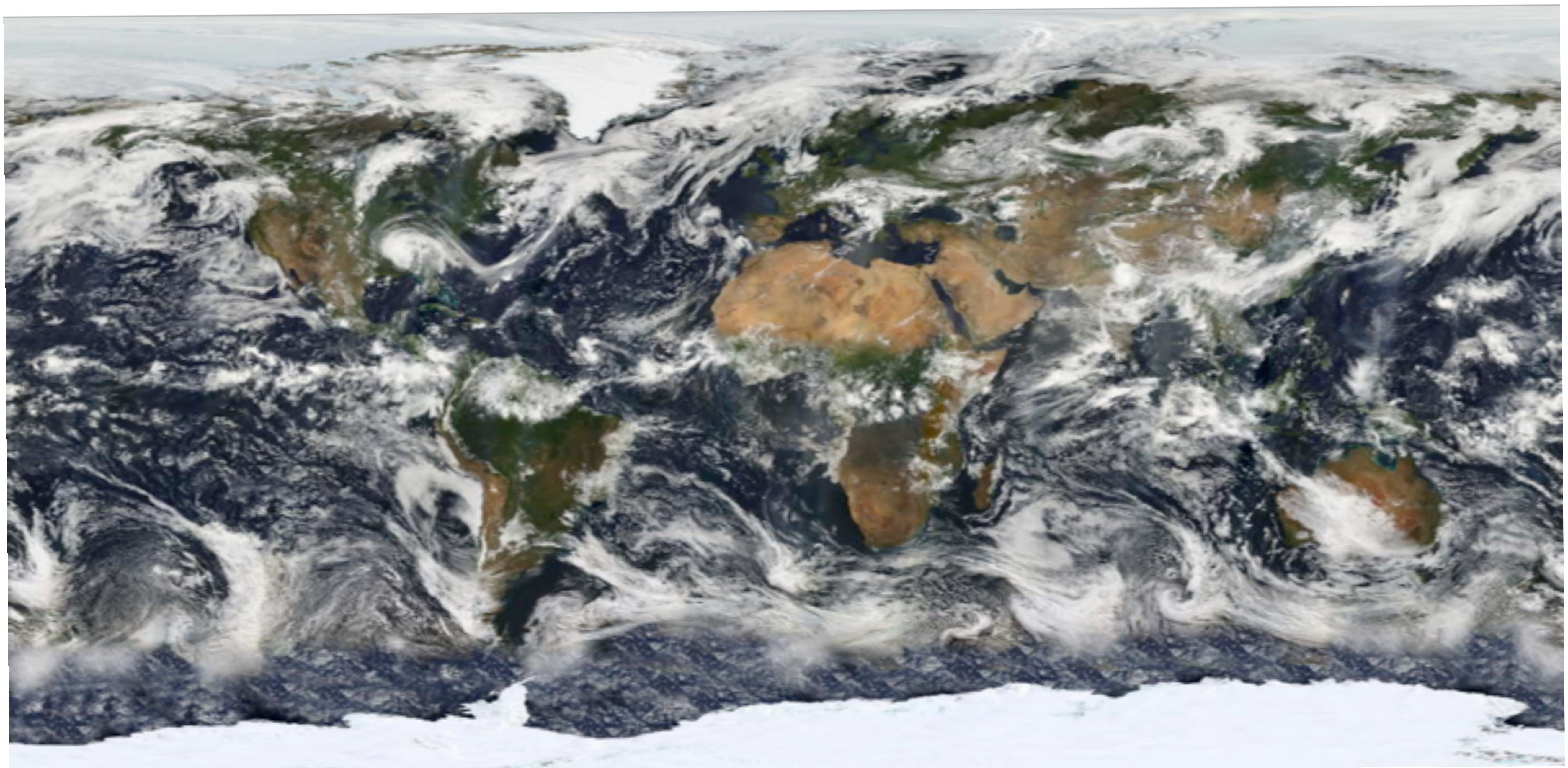
FIFE and BOREAS Reunion

CARNEGIE INSITUTION FOR SCIENCE
DEPARTMENT OF GLOBAL ECOLOGY

Physiology leaf to Orbit: Joe Berry

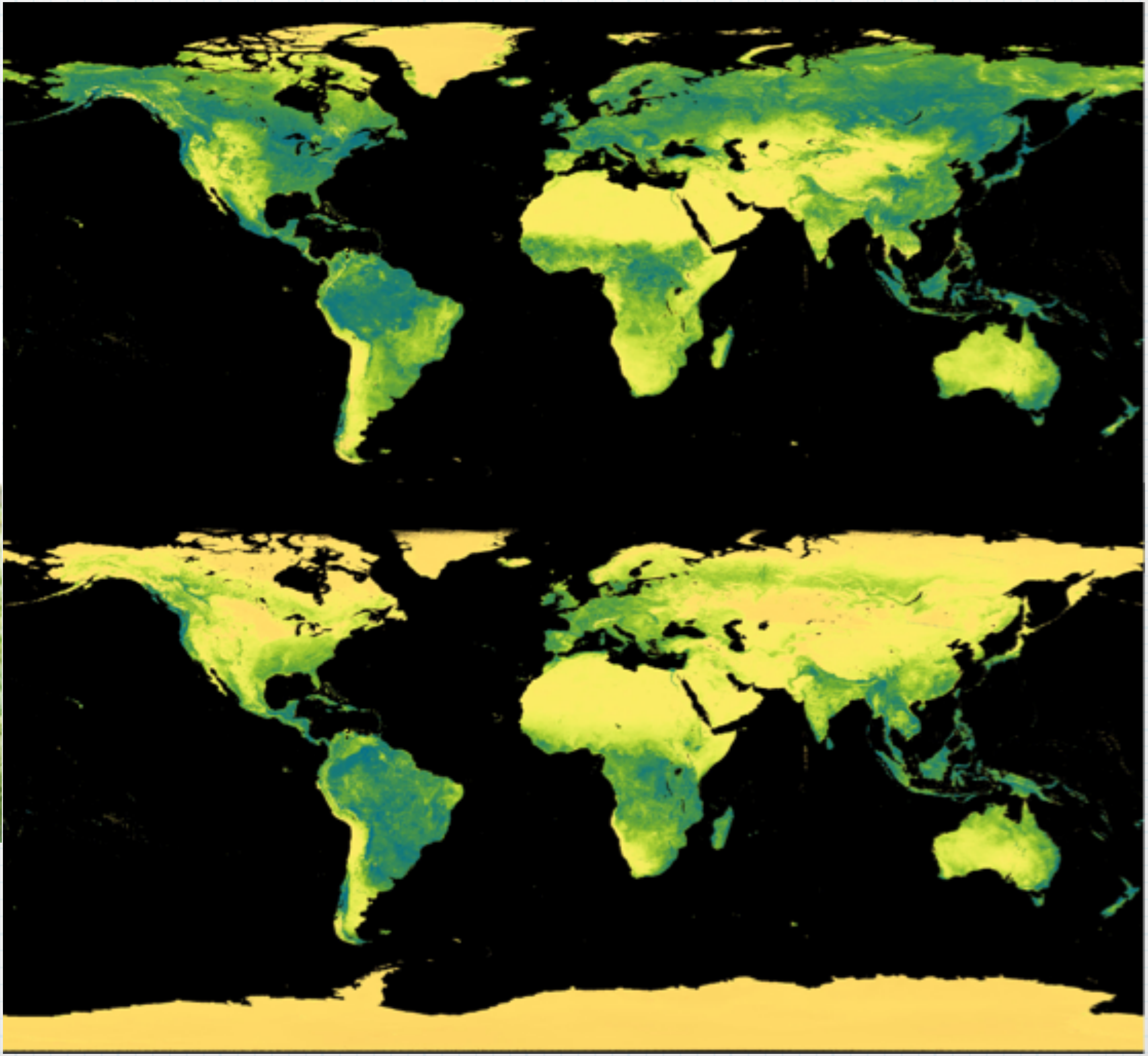


AVHRR

and

NDVI

Jim Tucker



The Global Carbon Cycle

Inez Fung

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. C2, PAGES 1281–1294, FEBRUARY 20, 1983

Three-Dimensional Tracer Model Study of Atmospheric CO_2: Response to Seasonal Exchanges With the Terrestrial Biosphere

I. Fung,[1] K. Prentice,[2] E. Matthews,[3] J. Lerner,[3] and G. Russell

Institute for Space Studies, NASA/Goddard Space Flight Center, New York, New York 10025

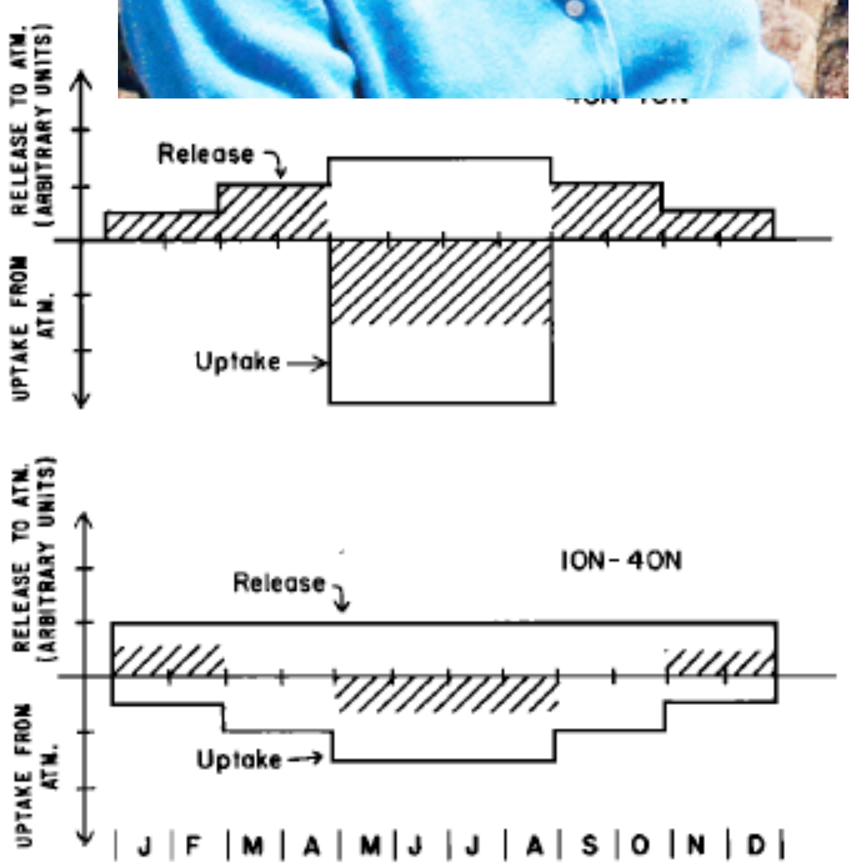


Fig. 3. Seasonality of biospheric uptake and release of CO_2 [after *Azevedo*, 1982] employed in experiment 3.

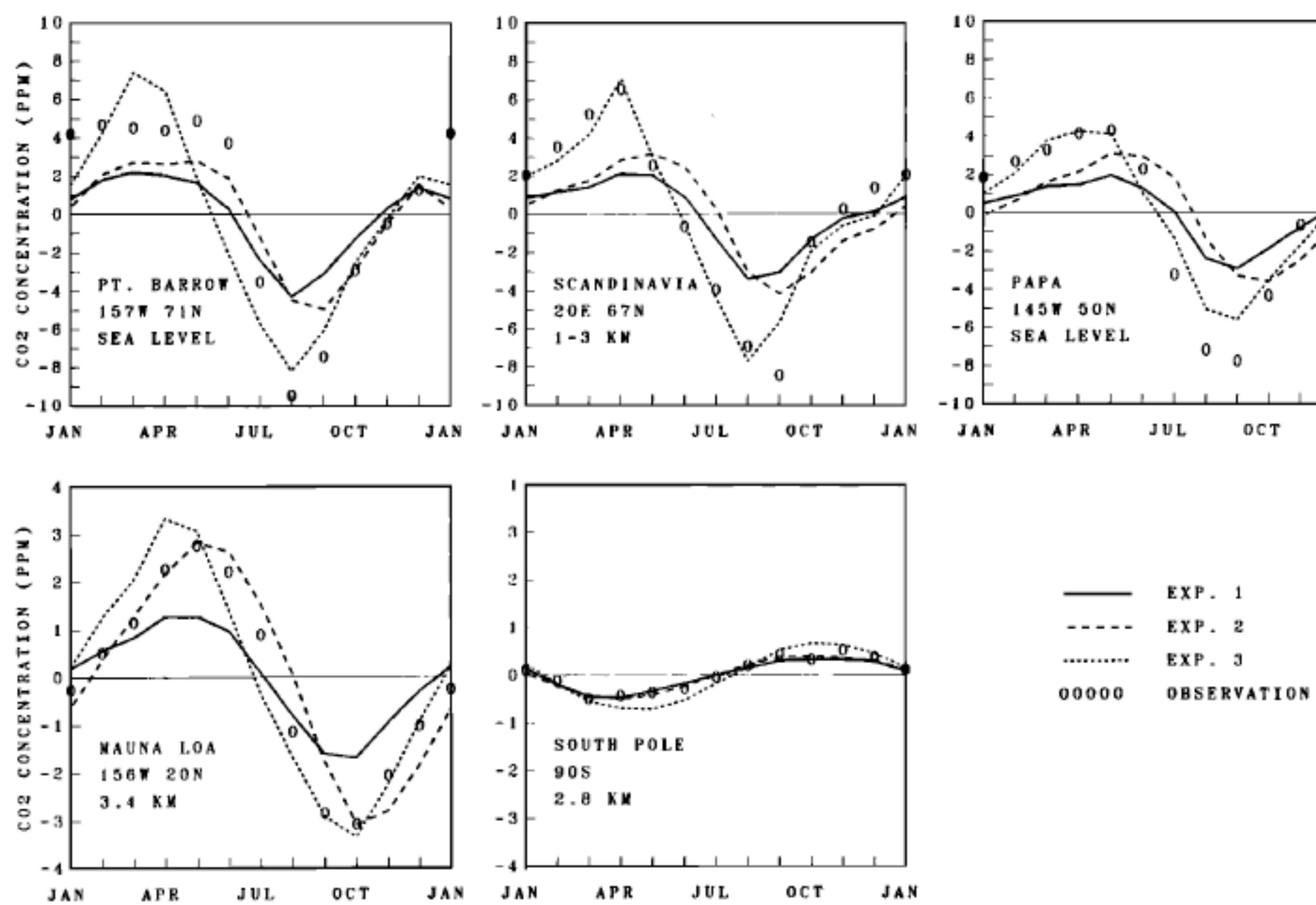
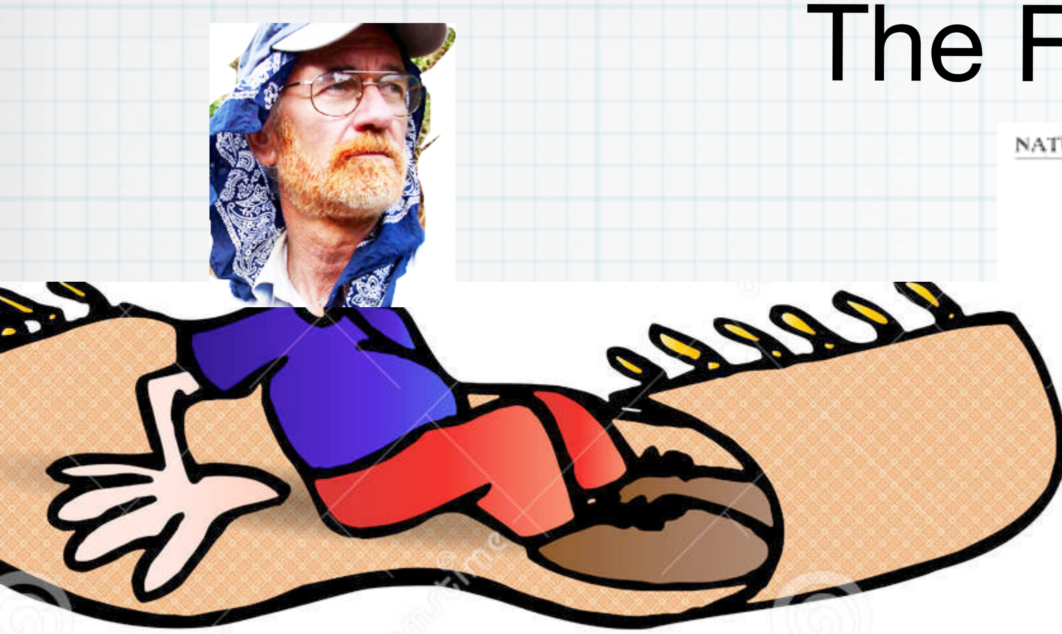


Fig. 4. Model simulated and observed annual cycles of CO_2 at five locations. Observations for Point Barrow, Papa, Mauna Loa, and the south pole are taken from *Pearman and Hyson* [1980] and that for Scandinavia from *Bolin and Bischof* [1970].

The Flying Carpet Plots



NATURE VOL. 319 16 JANUARY 1986

ARTICLES

Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index

C. J. Tucker*, I. Y. Fung†, C. D. Keeling‡ & R. H. Gammon§

* NASA/Goddard Space Flight Center, Code 623, Greenbelt, Maryland 20771, USA
JASA/Goddard Institute for Space Studies, New York, New York 10025, USA and Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York, New York 10964, USA
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§ NOAA/GMCC, Boulder, Colorado 80302, USA

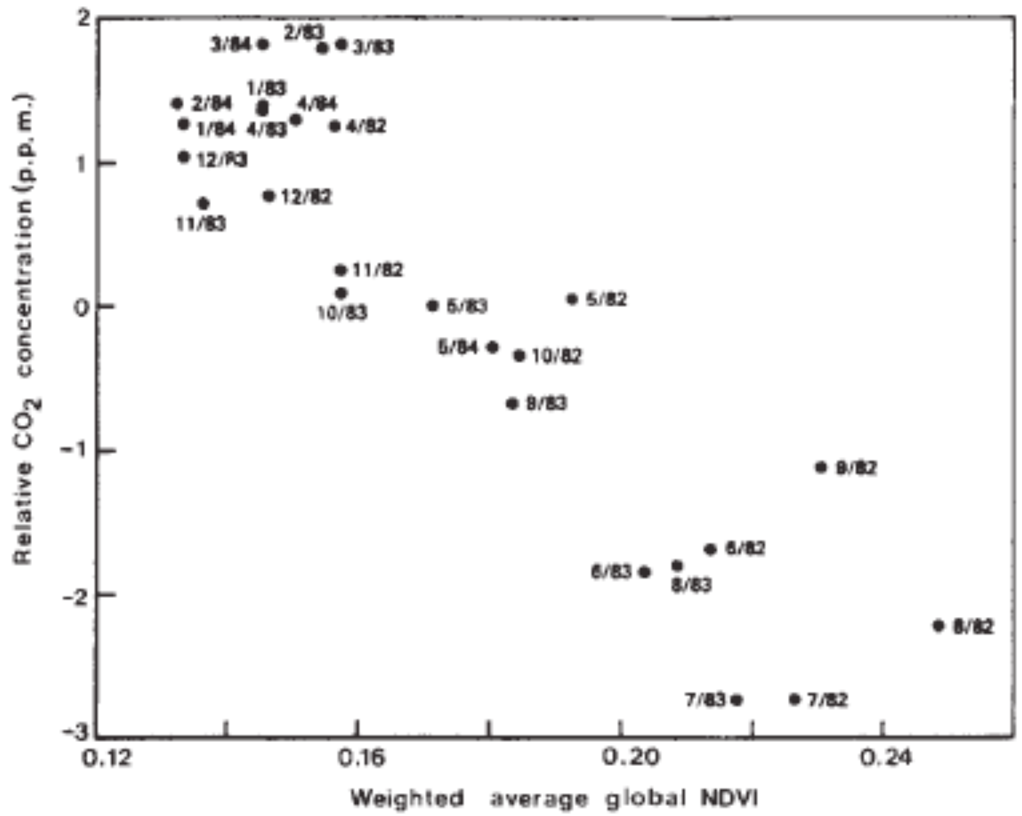


Fig. 4 The globally averaged atmospheric CO_2 concentration plotted against the globally averaged NDVI with a time lag of 1 month. The CO_2 data are from the global network of 20 NOAA/GMCC stations.

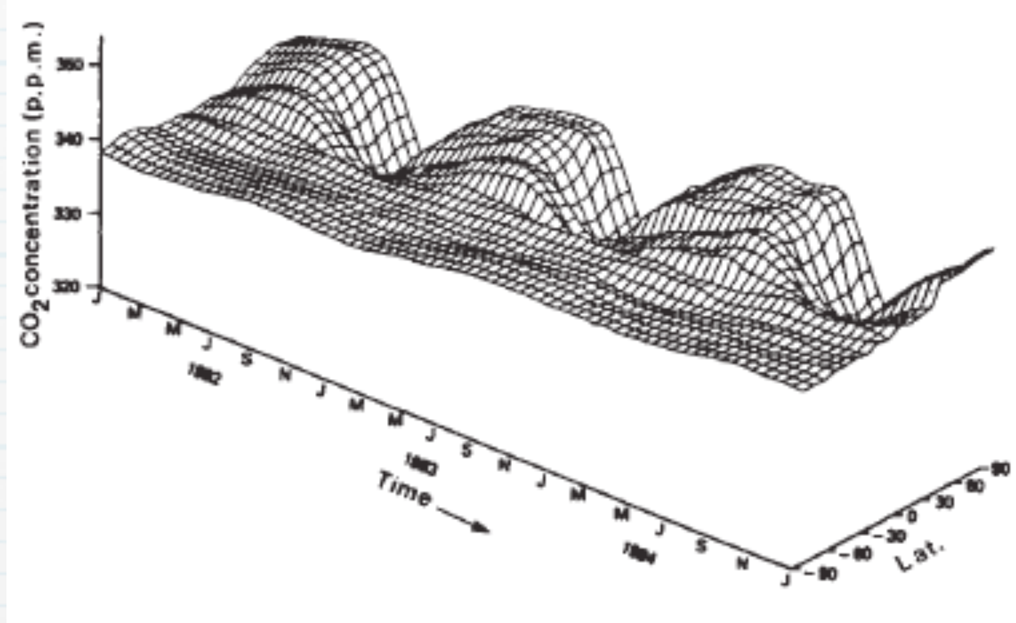
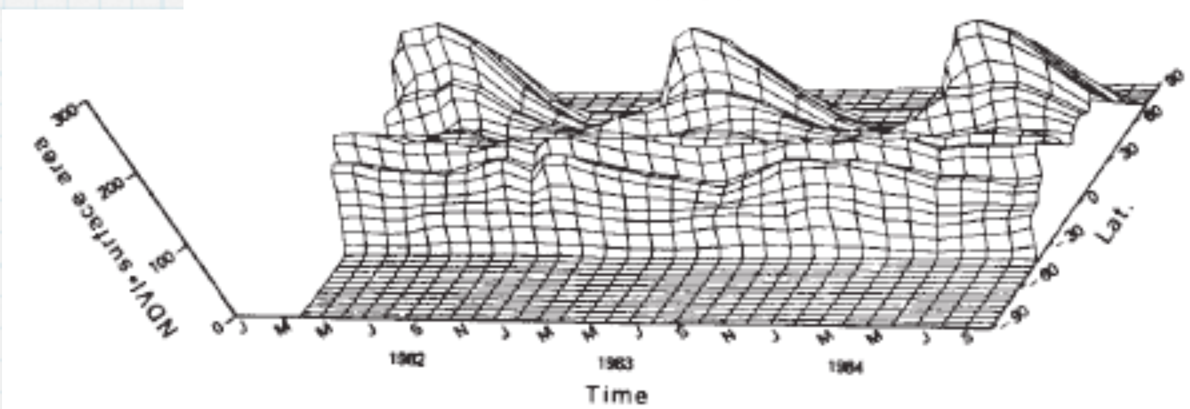


Fig. 1 Variation of global atmospheric CO_2 concentrations with latitude and time based on the NOAA/GMCC flask measurements for 1982–84.



Land-Surface Modeling

Canopy Conductance

Piers Sellers

A Simple Biosphere Model (SiB) for Use within General Circulation Models

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(Manuscript received 26 February 1985, in final form 5 September 1985)

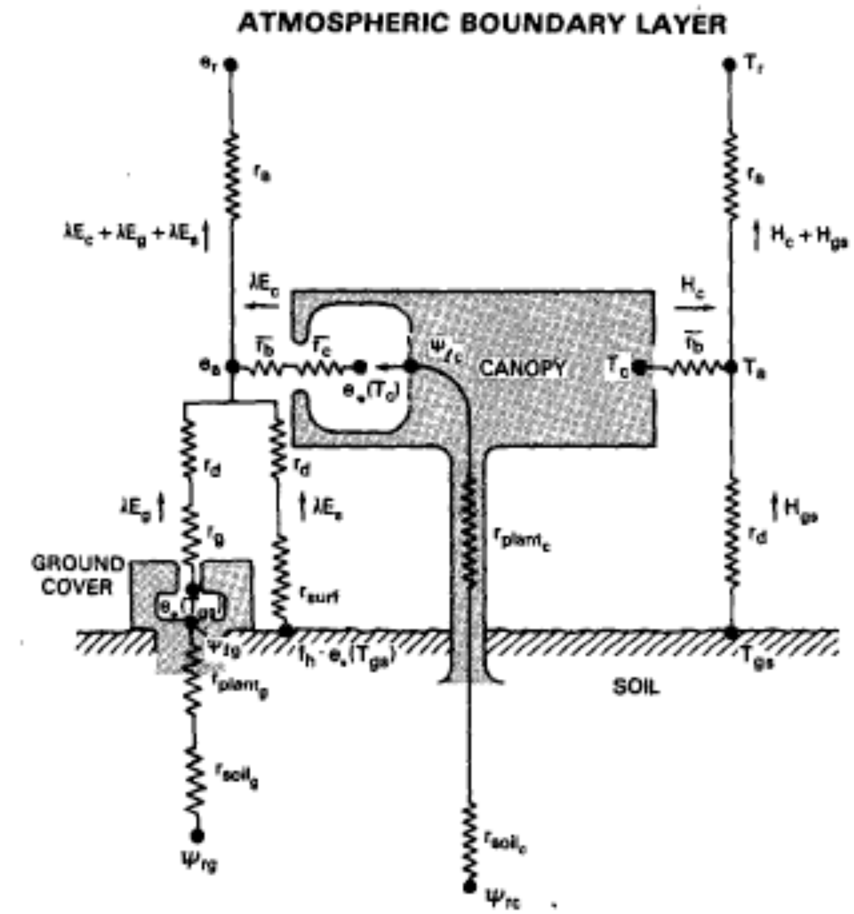
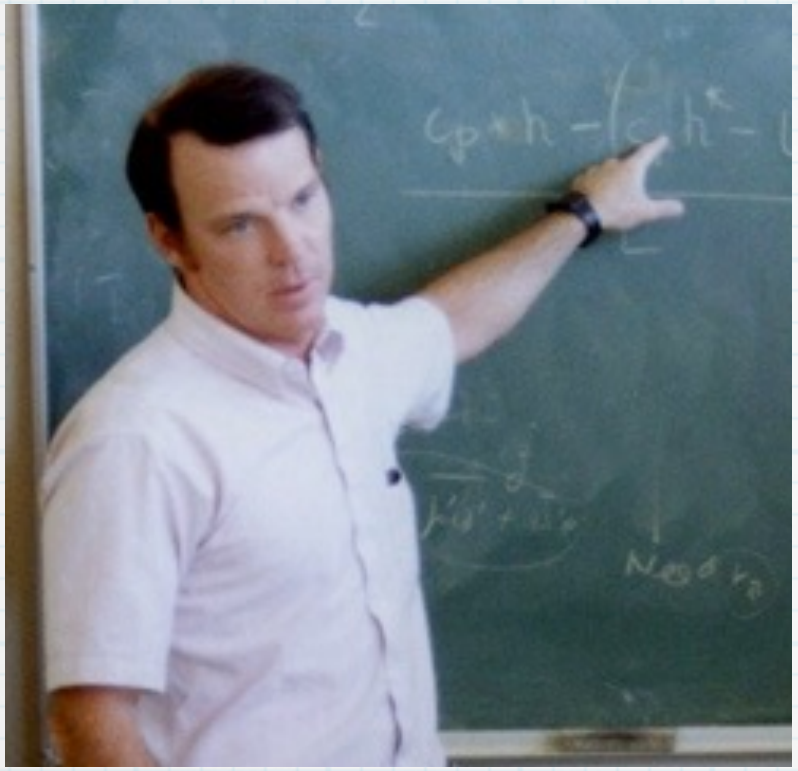


FIG. 2. Framework of the Simple Biosphere (SiB). The transfer pathways for latent and sensible heat flux are shown on the left- and right-hand sides of the diagram respectively. The treatment of radiation and intercepted water has been omitted for clarity. Symbols are defined in Table 2.

Dave Randall

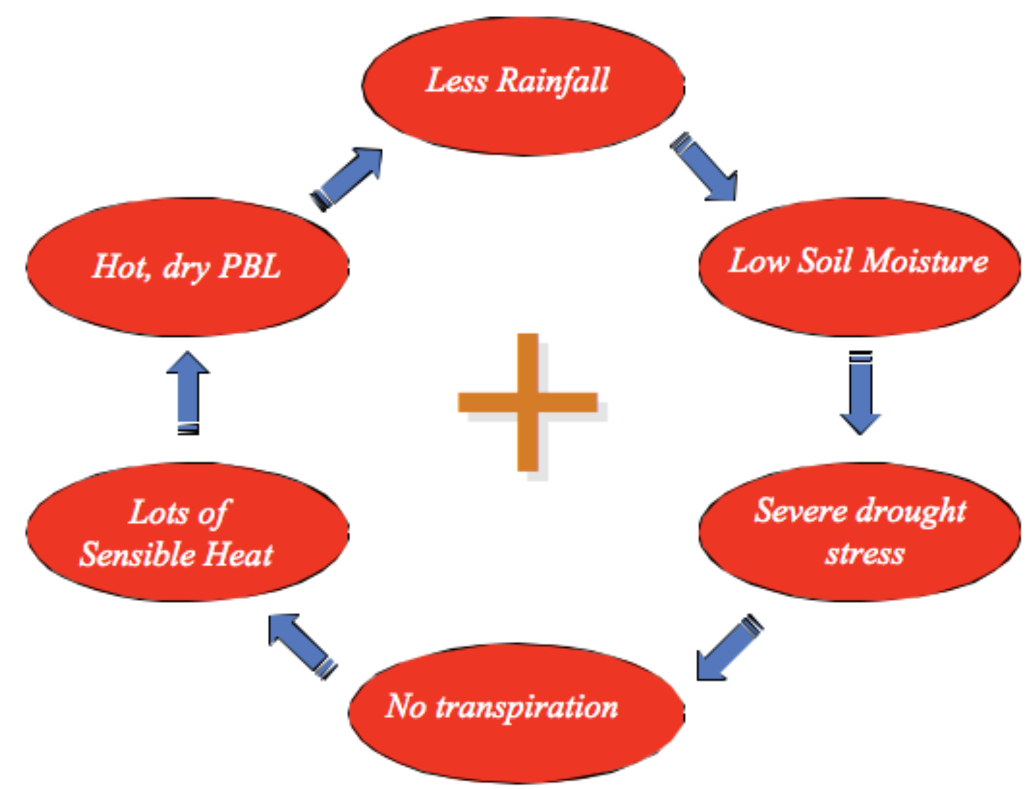
Effects of Implementing the Simple Biosphere Model in a General Circulation Model

N. Sato,* P. J. Sellers, D. A. Randall,** E. K. Schneider, J. Shukla,
J. L. Kinter III, Y-T. Hou and E. Albertazzi



SiB worked fine when run with "prescribed" climate.
However, when it was run in the climate model, the land areas of the planet dried up and became deserts.

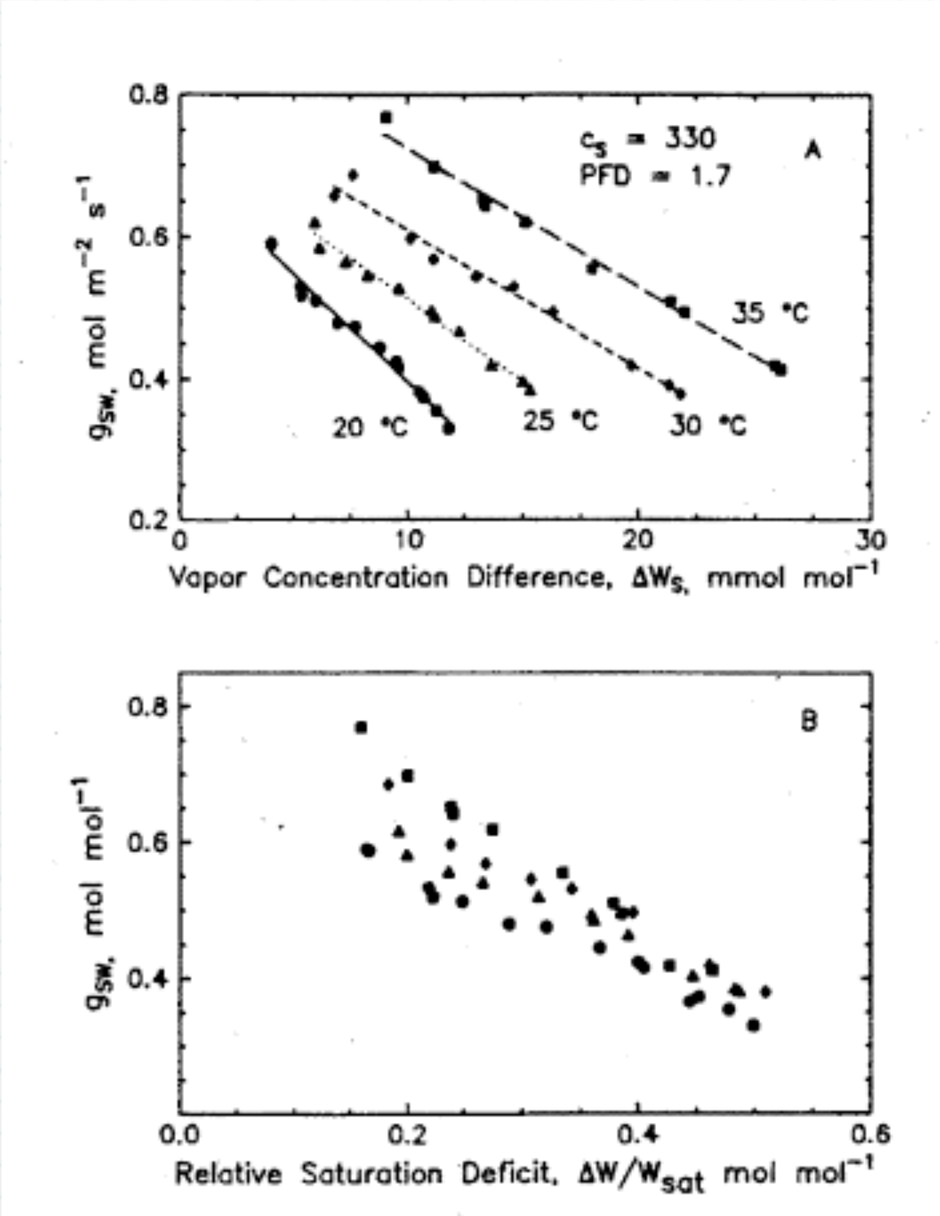
Precipitation and Ecosystem Stress:
A Positive Feedback Loop

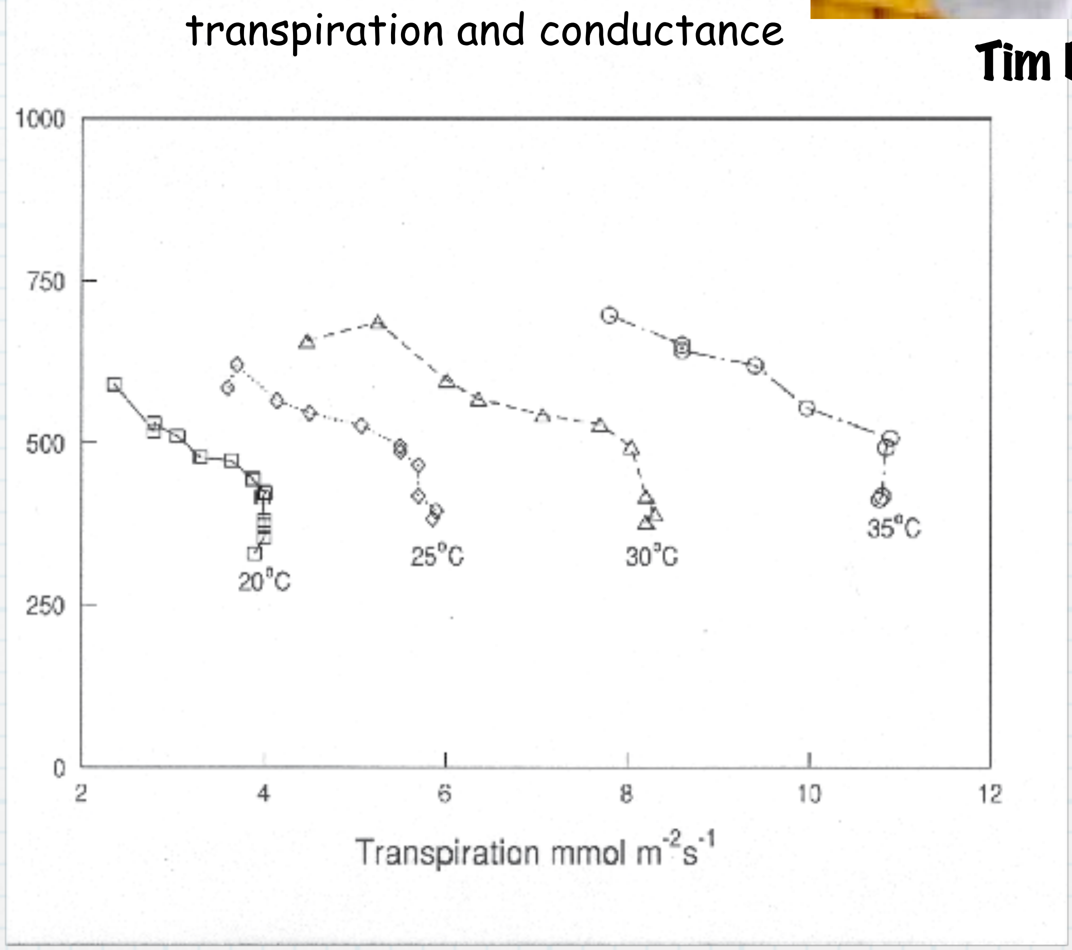


Dave referred to this as:
"Stomatal Suicide"

This gave us an opening to try to fix it with physiology.

Stomatal Conductance is a linear function of VPD but the sensitivity changes with temperature.

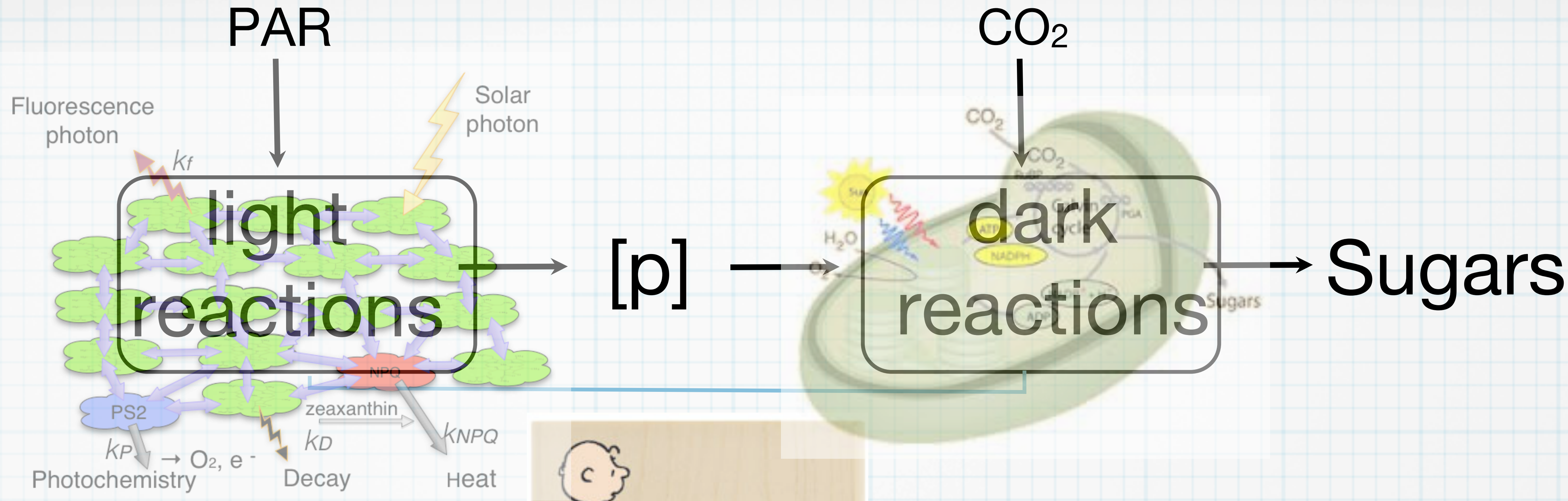


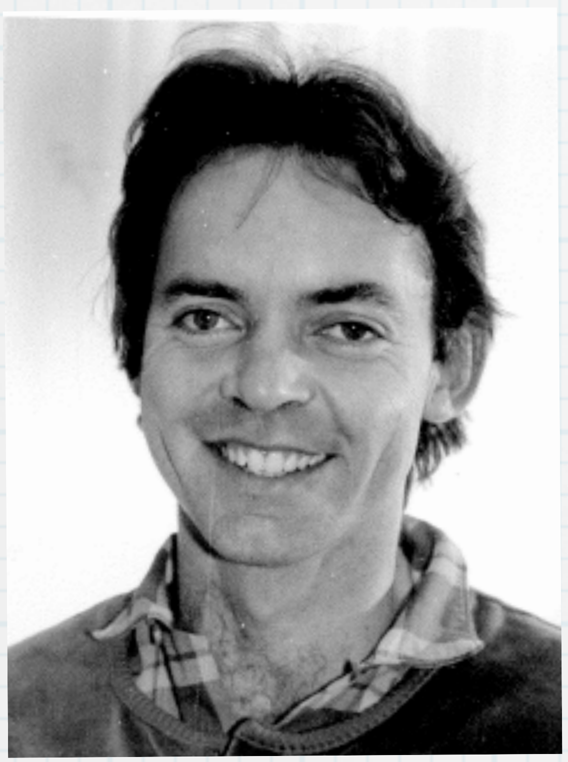


Tim Ball

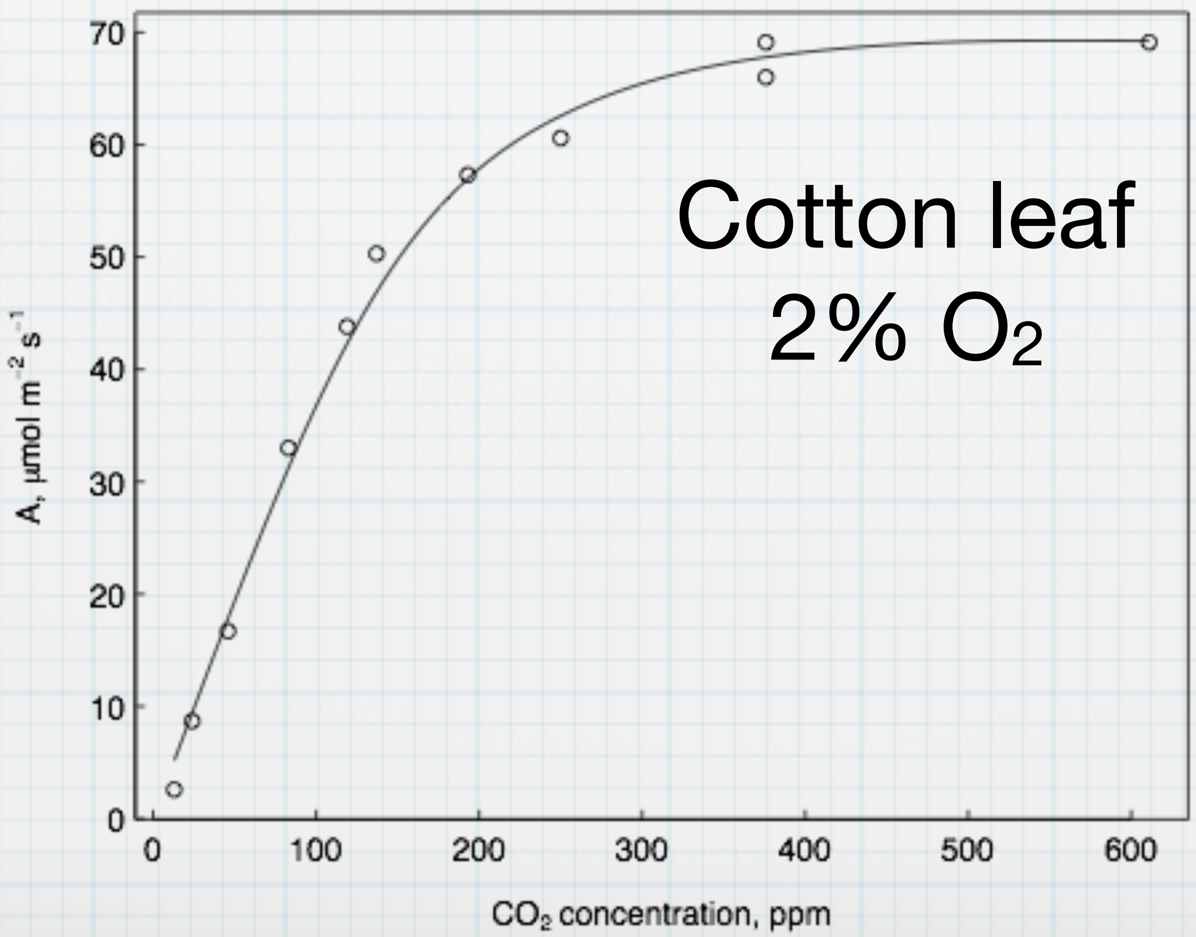
If this isn't taken into account, stomata shut when temperature increases, causing temperature to increase further.

Using our stomata-photosynthesis model "cured" stomatal depression.





Graham Farquhar



Susanne von Caemmerer

$$A \approx \min \begin{cases} J_E \\ J_C \\ J_S \end{cases}$$

C3

$$J_E = a \times \alpha \times Q_p \frac{p_i - \Gamma_*}{p_i + 2\Gamma_*}$$

$$J_C = \frac{V_m (p_i - \Gamma_*)}{p_i + K_c (1 + [O_2]/K_o)}$$

$$J_S = V_m / 2$$

C4

$$J_i = a \alpha_r f Q_p$$

$$J_c = p_i \left(k_p - \frac{L}{p_i} \right) / P$$

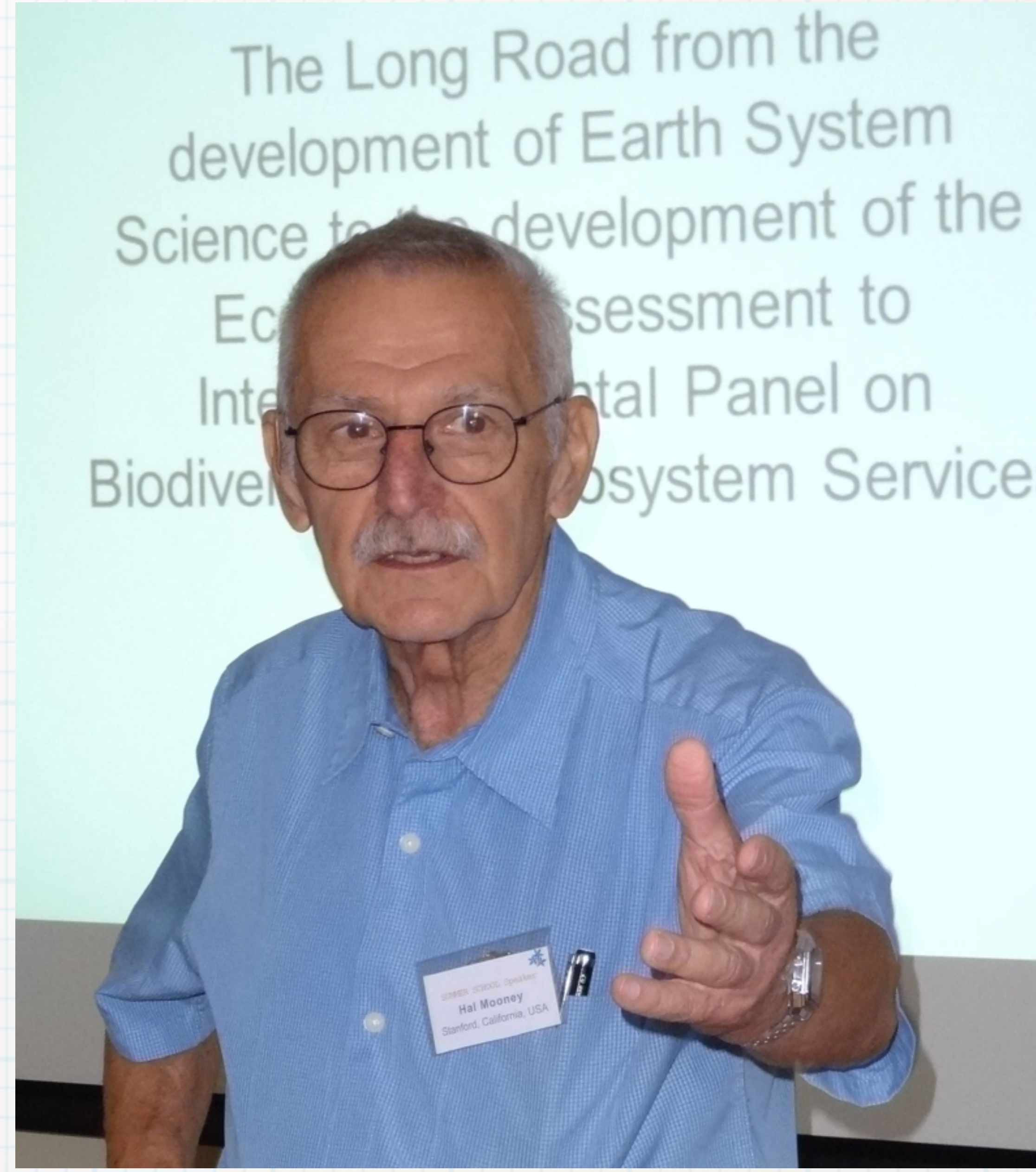
$$J_e = V_{max}$$

$$\theta J_P^2 - J_P (J_E + J_C) + J_E J_C = 0$$

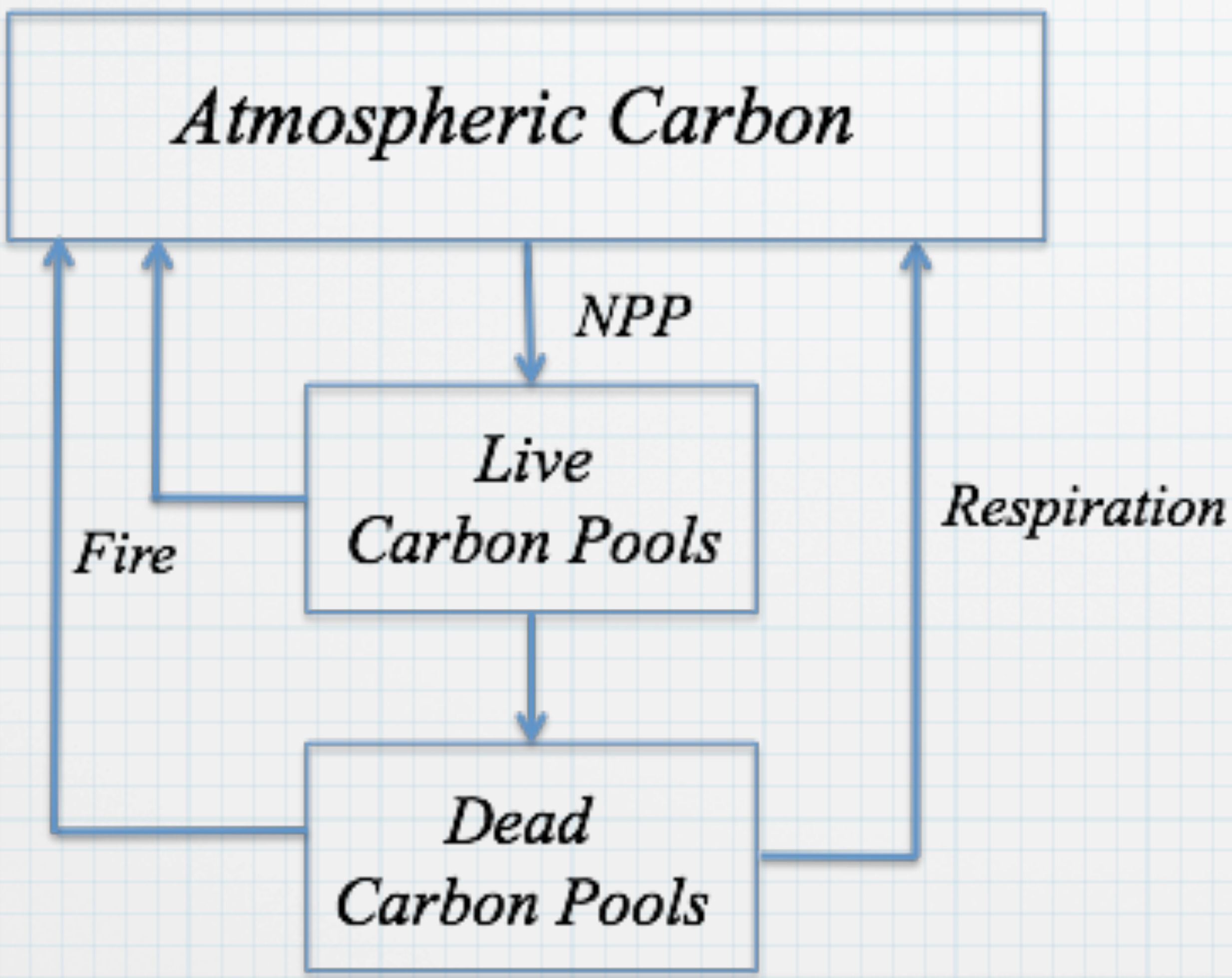
and

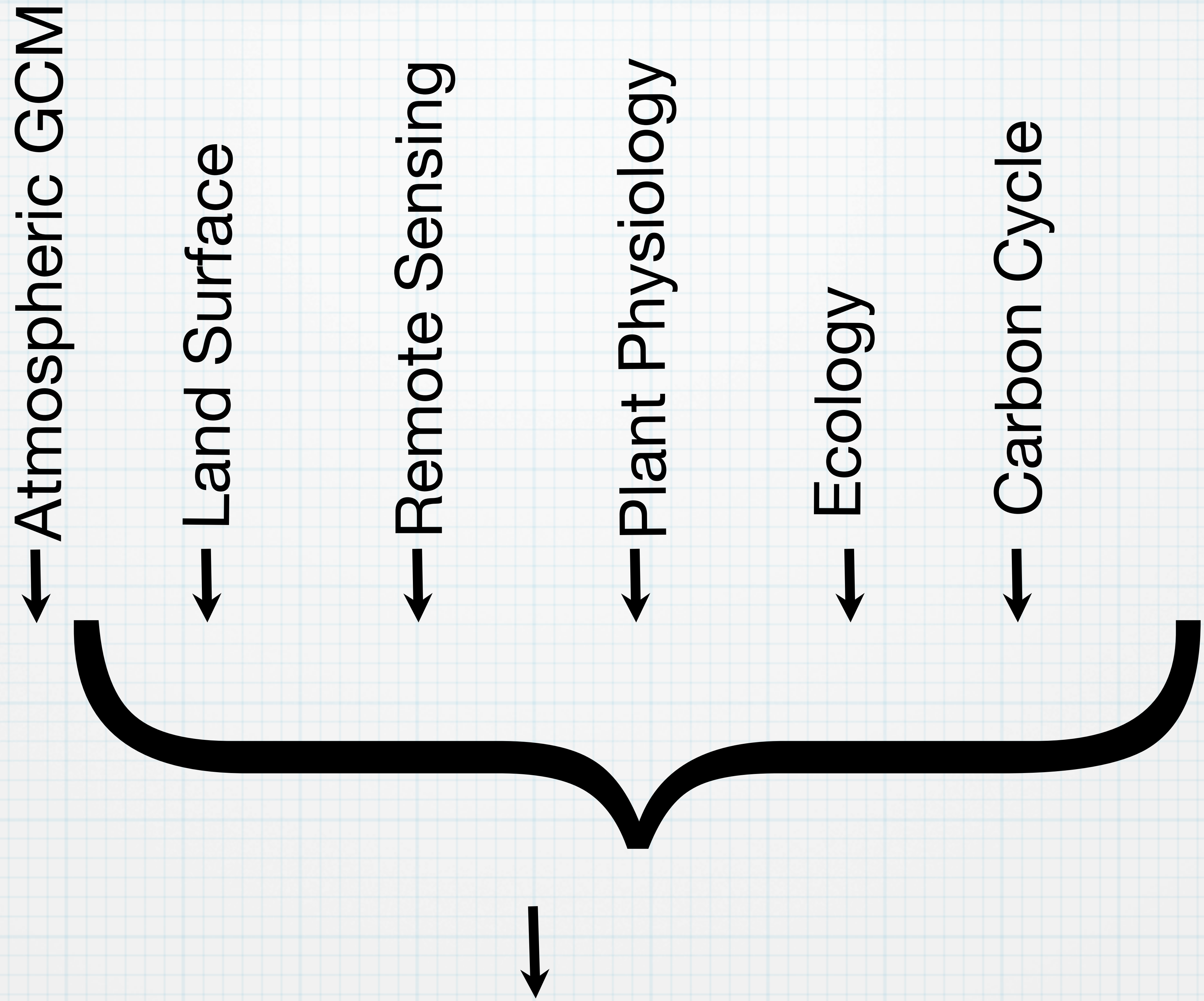
$$\beta A^2 - A (J_P + J_S) + J_P J_S = 0$$


Chris Field


The Long Road from the
development of Earth System

Hal Mooney

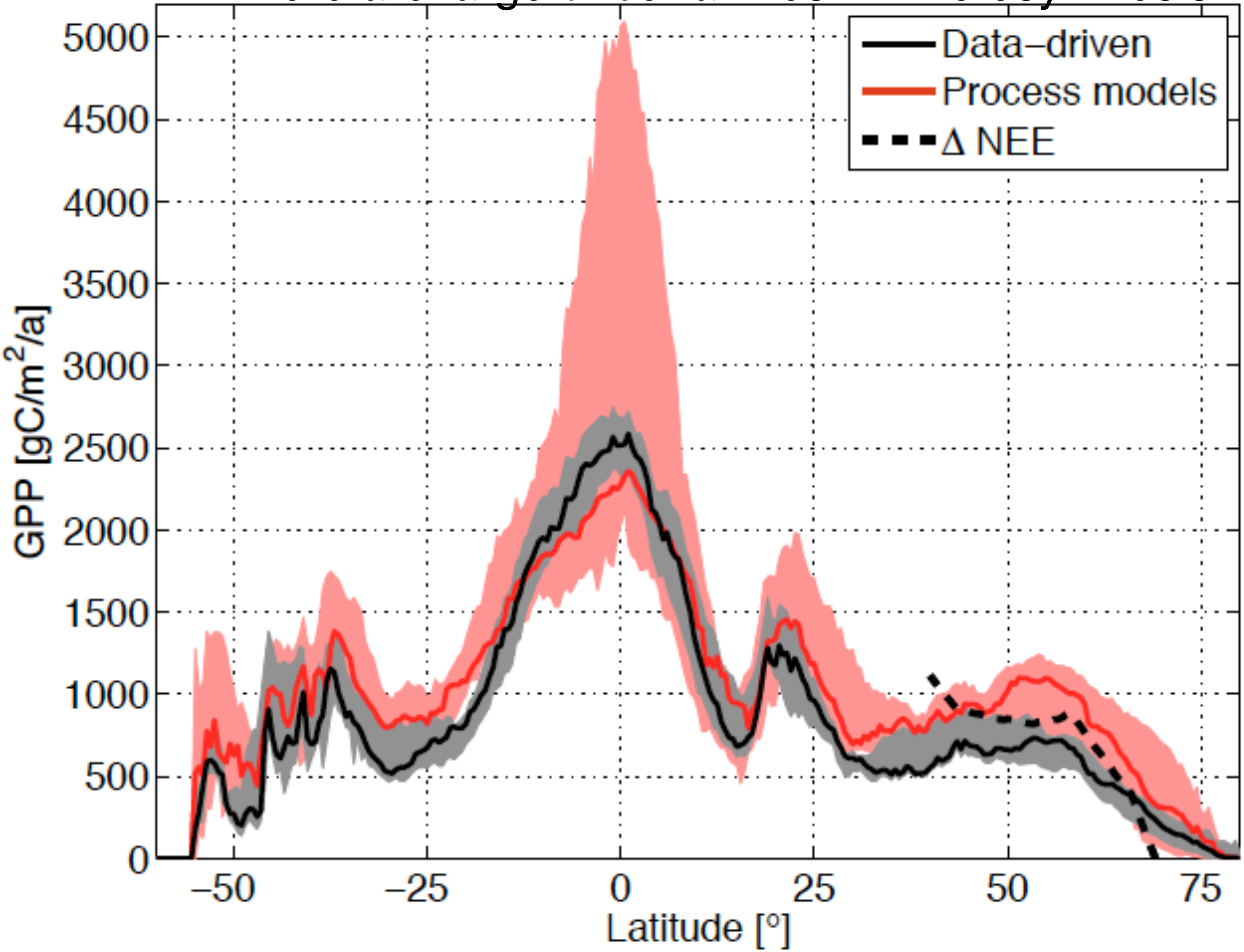

Atmospheric Carbon
NPP
Live
Carbon Pools
Fire
Respiration
Dead
Carbon Pools



The "Greening" of the CSU-GCM

(Sellers - Mooney EOS Team)

There are large uncertainties in Photosynthesis



Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., et al. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. SCIENCE,, 329(5993), 834–838. doi:10.1126/science.1184984

Sellers 1987, Quantitative Remote Sensing

$$\bar{\mu}\frac{dI\downarrow}{dL} + [1-(1-\beta)\omega]I\downarrow - \omega\beta I\uparrow$$

$$= \bar{\omega}\mu K(1-\beta_0)e^{-KL}, \qquad (2b)$$

$I\uparrow, I\downarrow =$ upward and downward diffuse radiative fluxes, normalized by the incident flux,

$\mu =$ cosine of the zenith angle of the incident beam,

$K =$ optical depth of direct beam per unit leaf area

$= G(\mu)/\mu,$

$G(\mu) =$ relative projected area of leaf elements in direction $\cos^{-1}\mu$,

$\bar{\mu} =$ average inverse diffuse optical depth per unit leaf area

$= \int_0^1 [\mu'/G(\mu'] \, d\mu',$

$\mu' =$ direction of scattered flux,

$\omega =$ scattering coefficient

$= \alpha + \tau,$

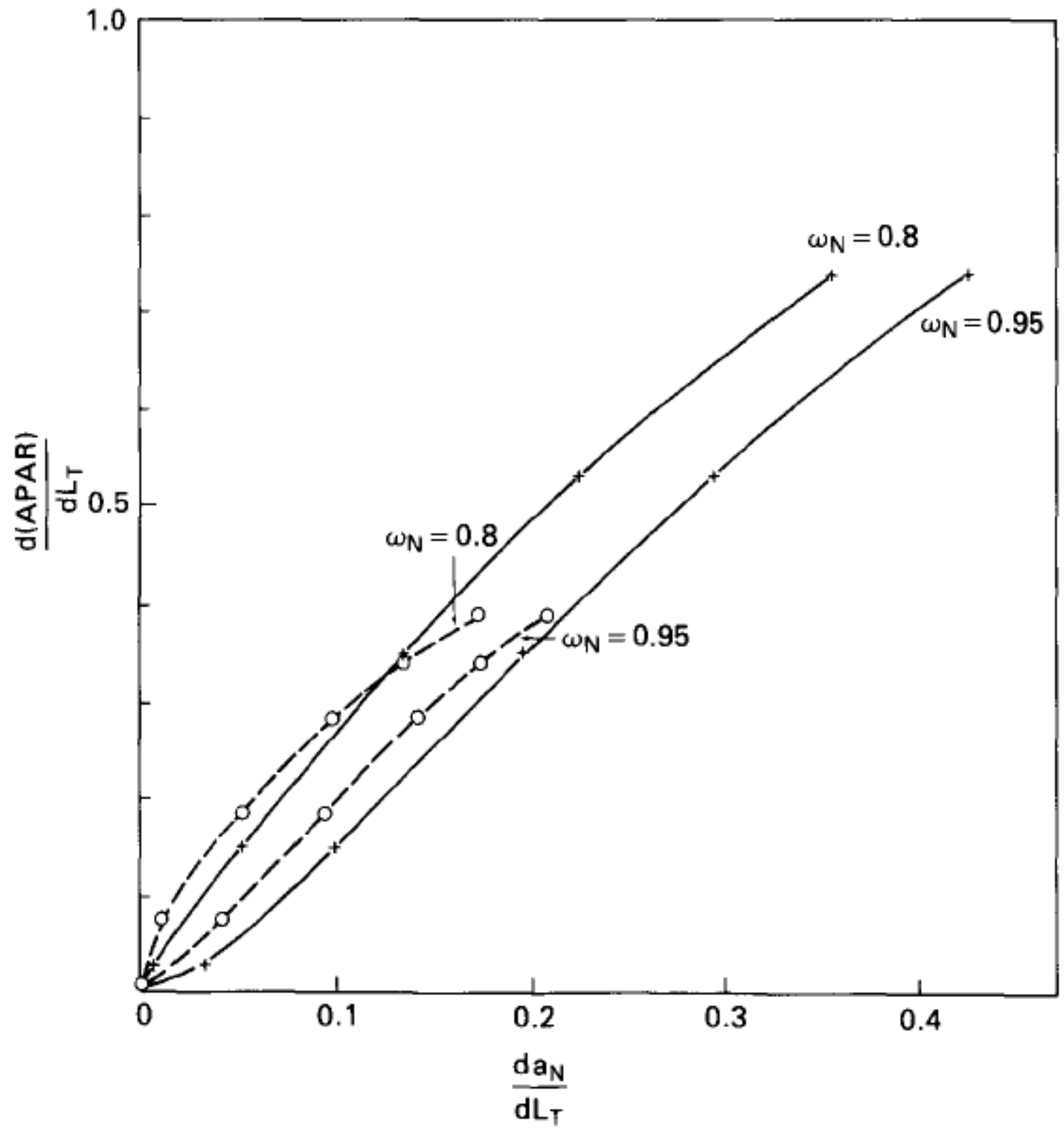
$\alpha =$ leaf element reflectance,

$\tau =$ leaf element transmittance,

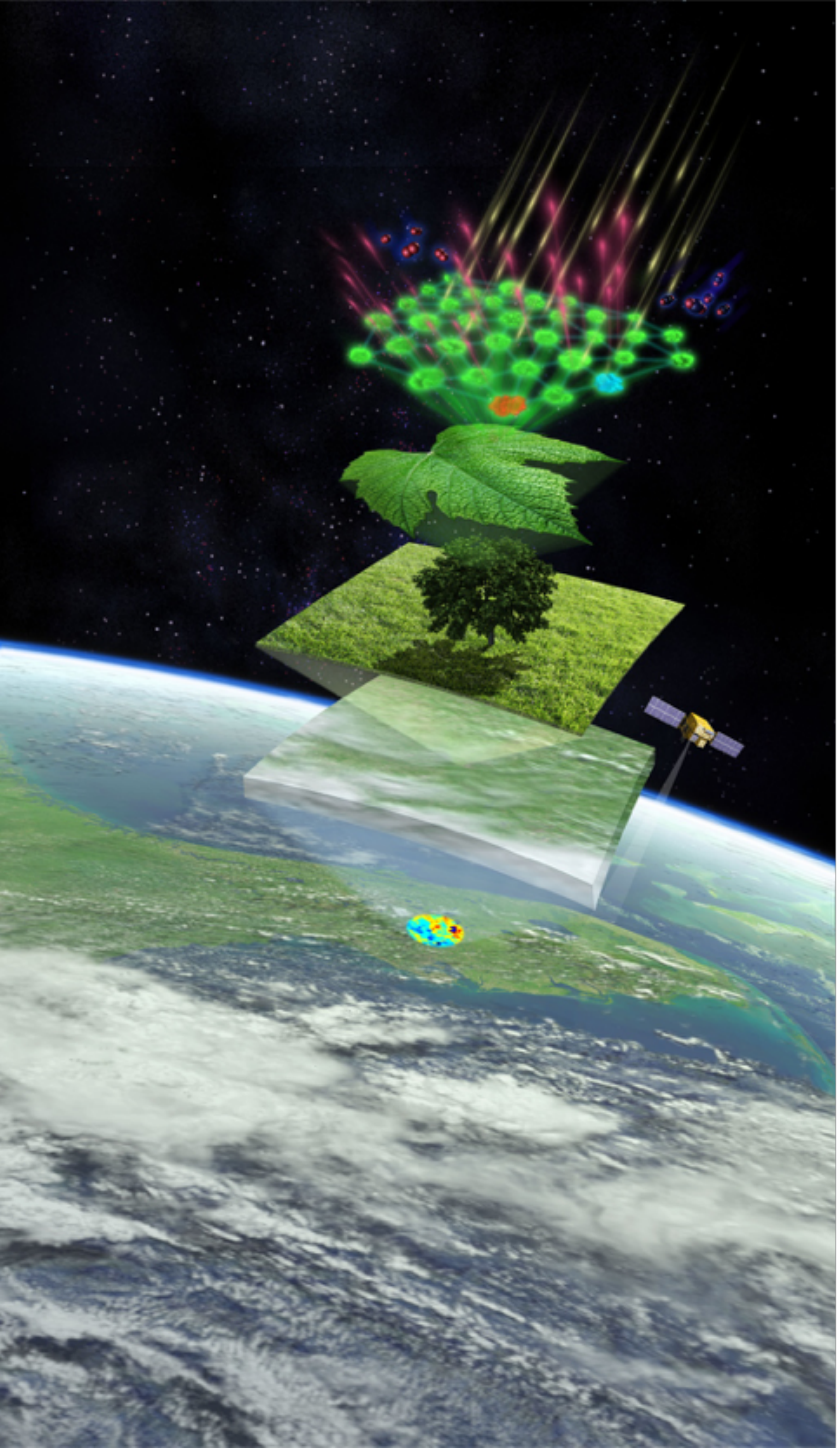
$L =$ cumulative leaf area index,

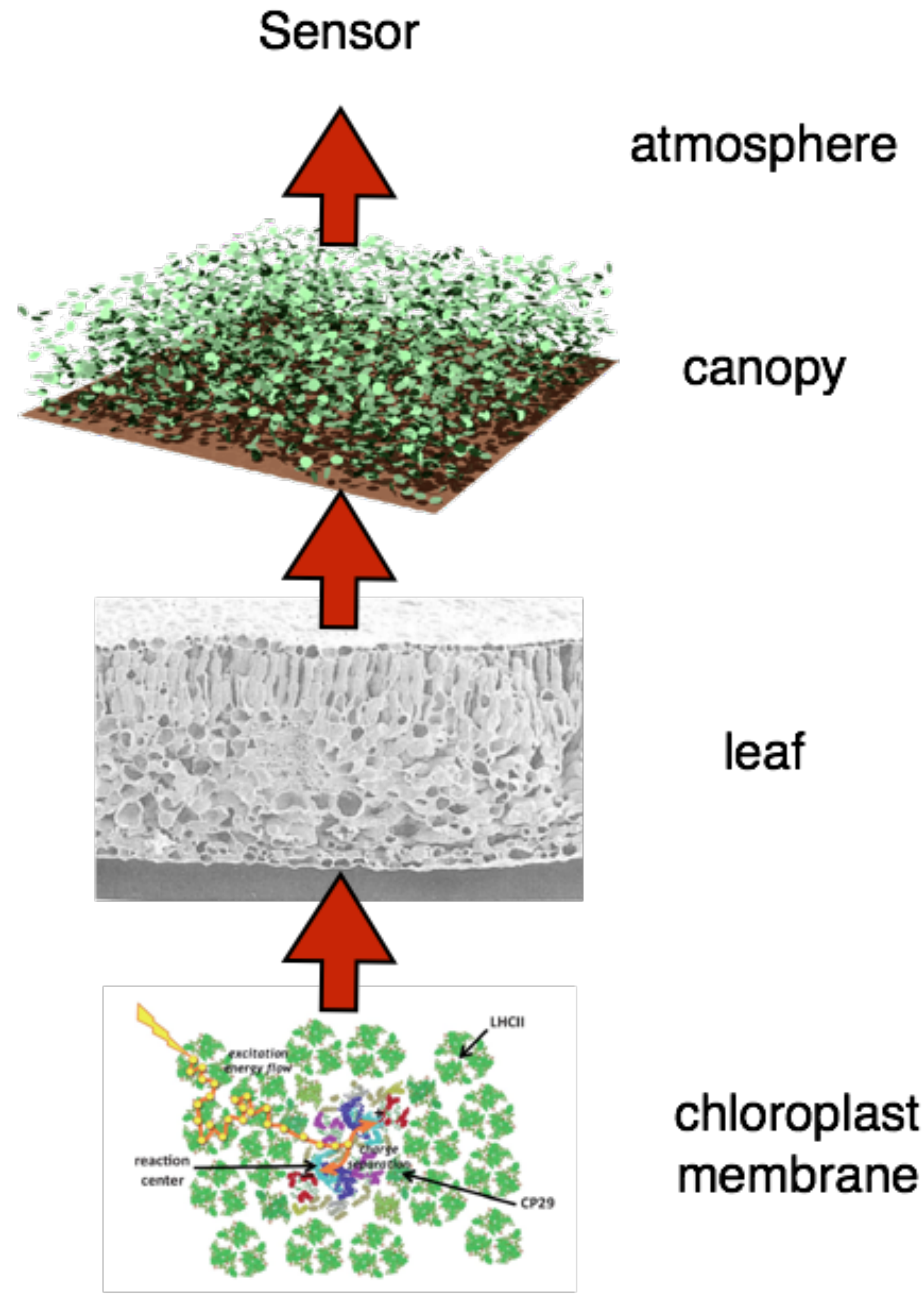
$\beta, \beta_0 =$ upscatter parameters for diffuse and direct beams, respectively.

Sellers showed that NIR reflectance is strongly correlated with APAR



However, NIR reflectance from other materials in mixed scene would contaminate this nice relationship.

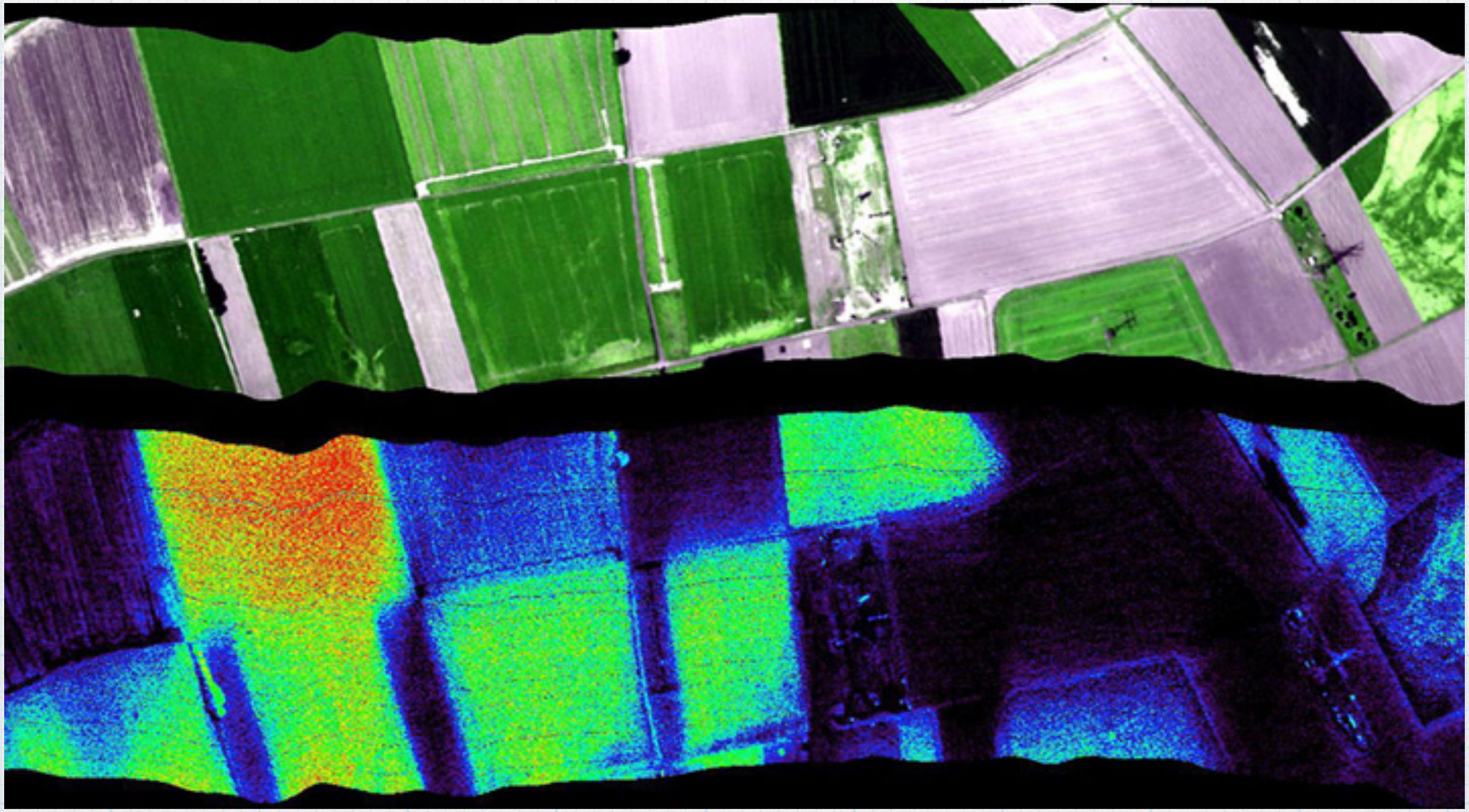




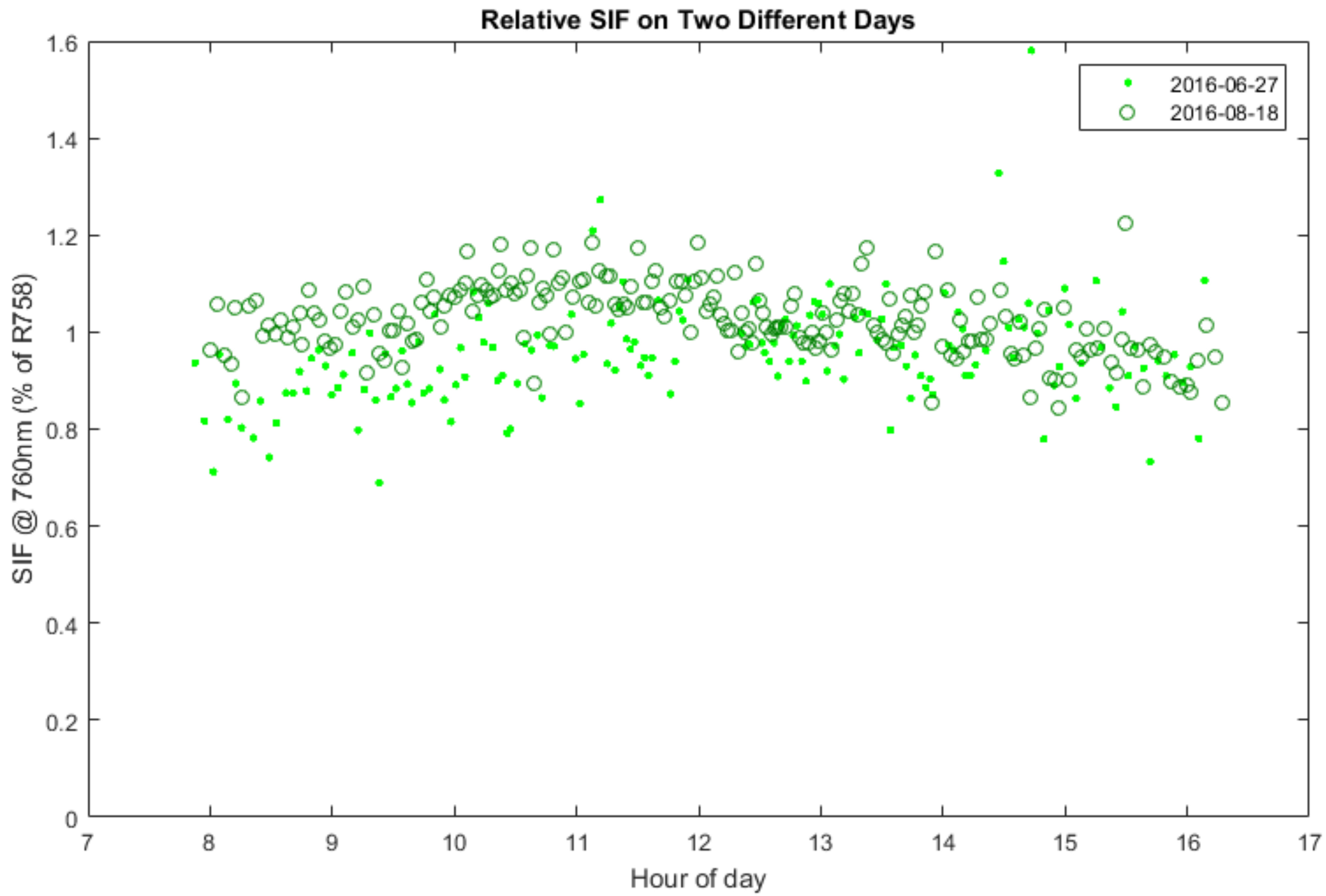
Fluorescence arriving at the sensor is emitted in the chloroplast and modified by radiation transport through a hierarchy of scales

HyPlant (aircraft) Image

- SIF is specific to vegetation
- SIF varies independently to greennees
- Variation is larger than expected

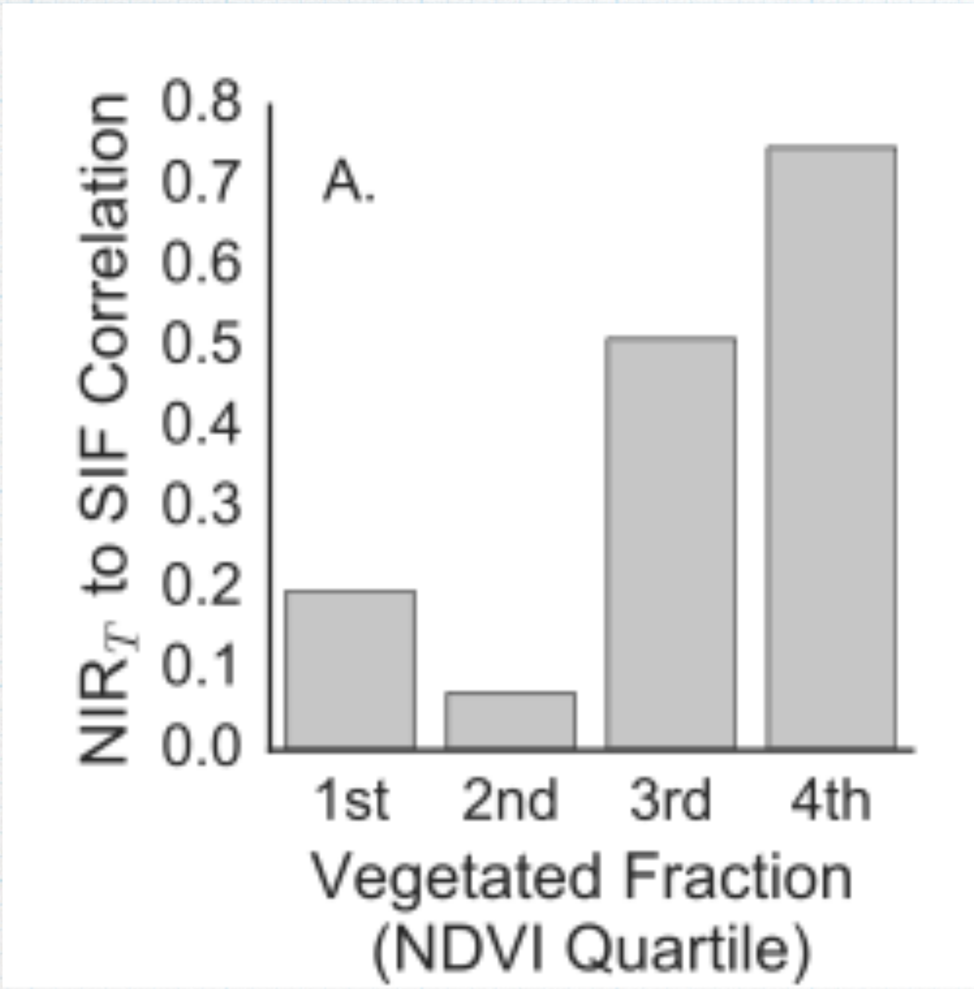


Uwe Rascher

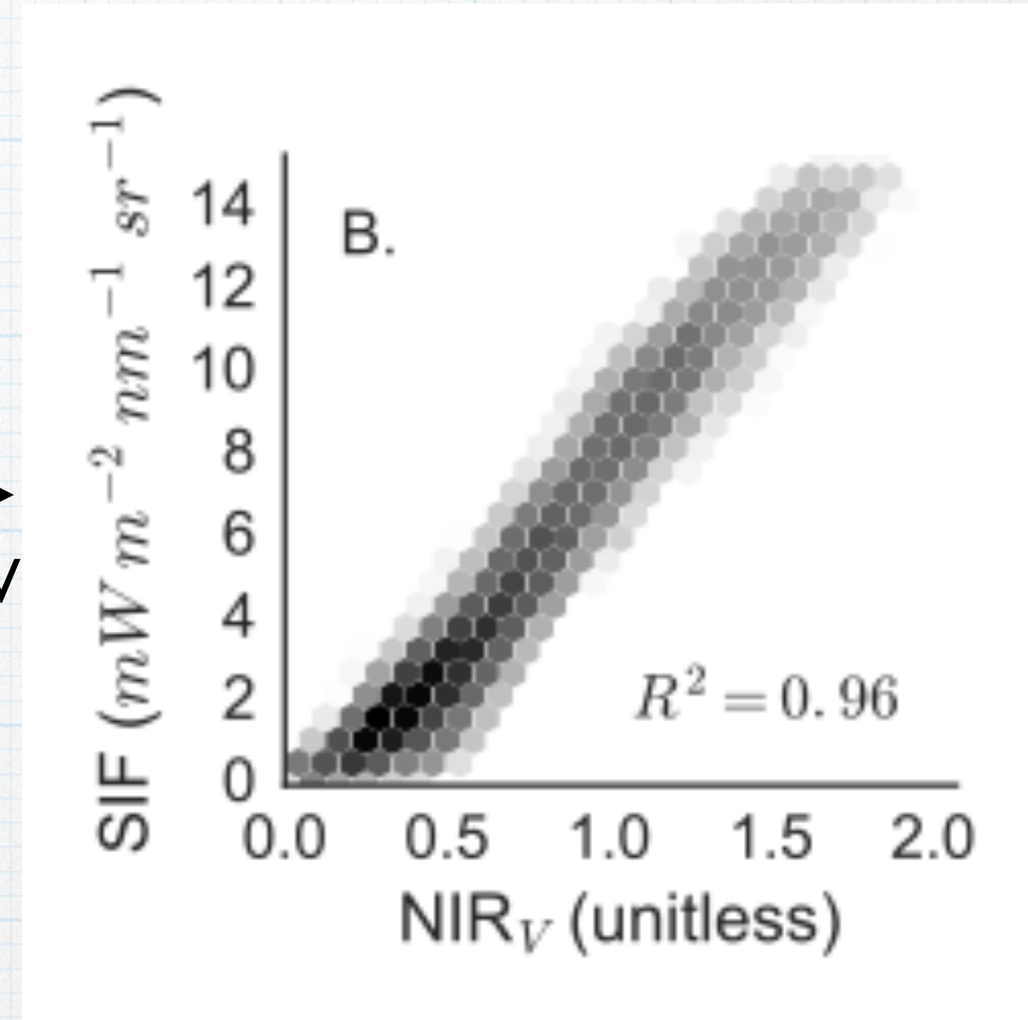


Relative SIF on Two Different Days
2016-06-27
2016-08-18
SIF @ 760nm (% of R758)
Hour of day
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
7
8
9
10
11
12
13
14
15
16
17

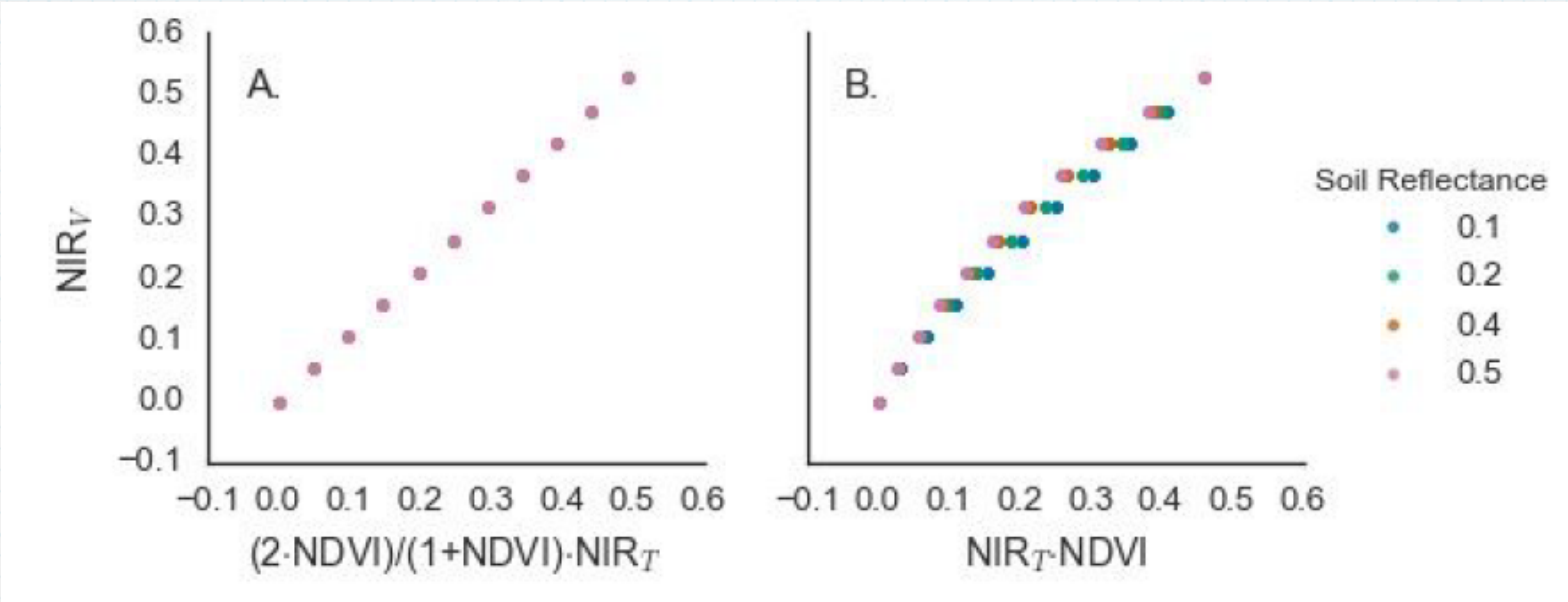
SIF Correlates with NIR Reflectance



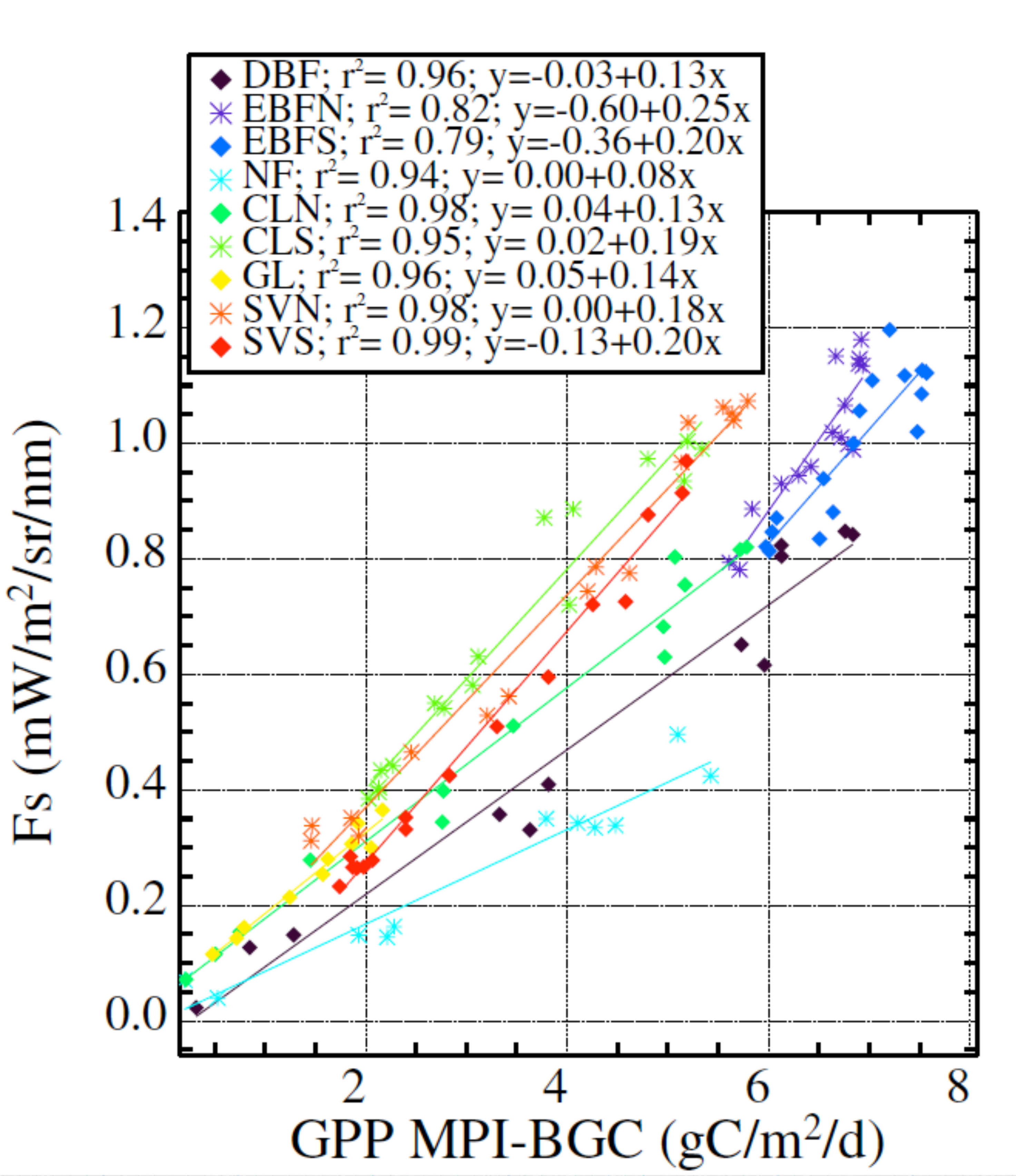
NIR_T * NDV



We have come up with a new way to use MODIS data to obtain a metric, the NIRv, which we consider to be the NIR refection from the vegetation of a mixed scene. It is approximated as NIRv =NIRt * NDVI and it correlates remarkably well with SIF and GPP.

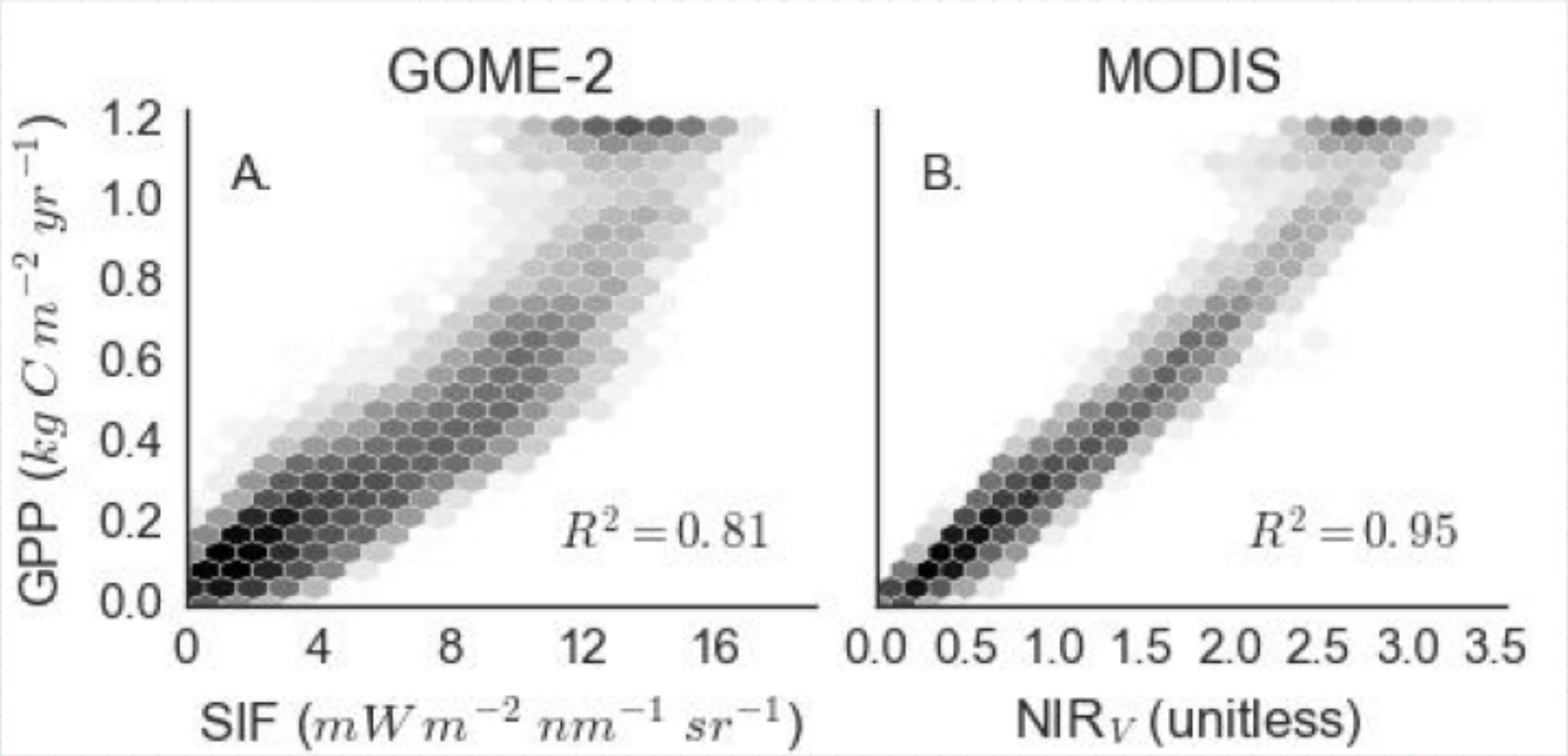

A.
B.
NIR_V
(2·NDVI)/(1+NDVI)·NIR_T
NIR_T·NDVI
Soil Reflectance
0.1
0.2
0.4
0.5

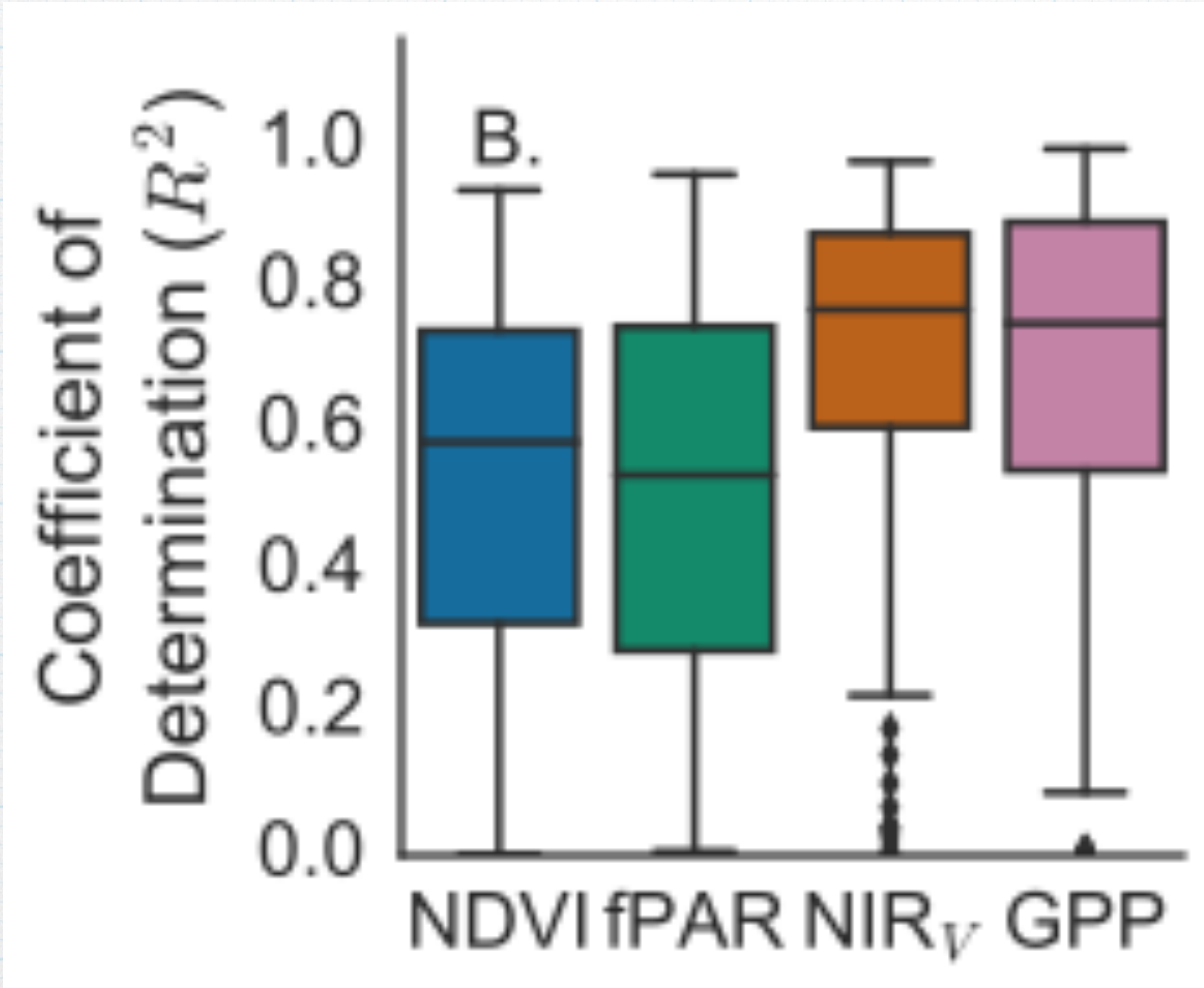
SIF Correlates Strongly with (MPI) GPP



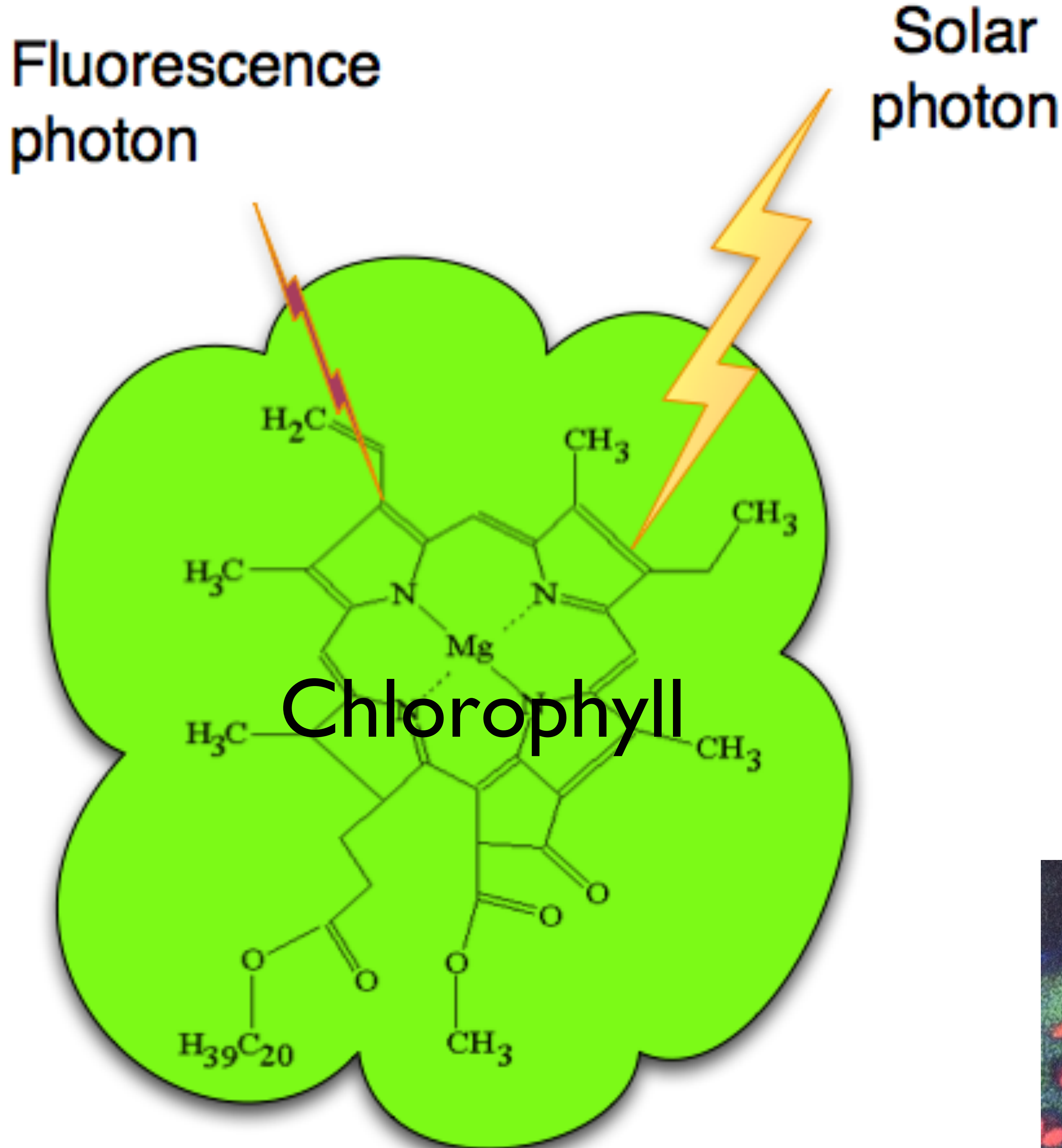
(Guanter et al., Remote Sensing of Environment **133** (2013) 52–61)

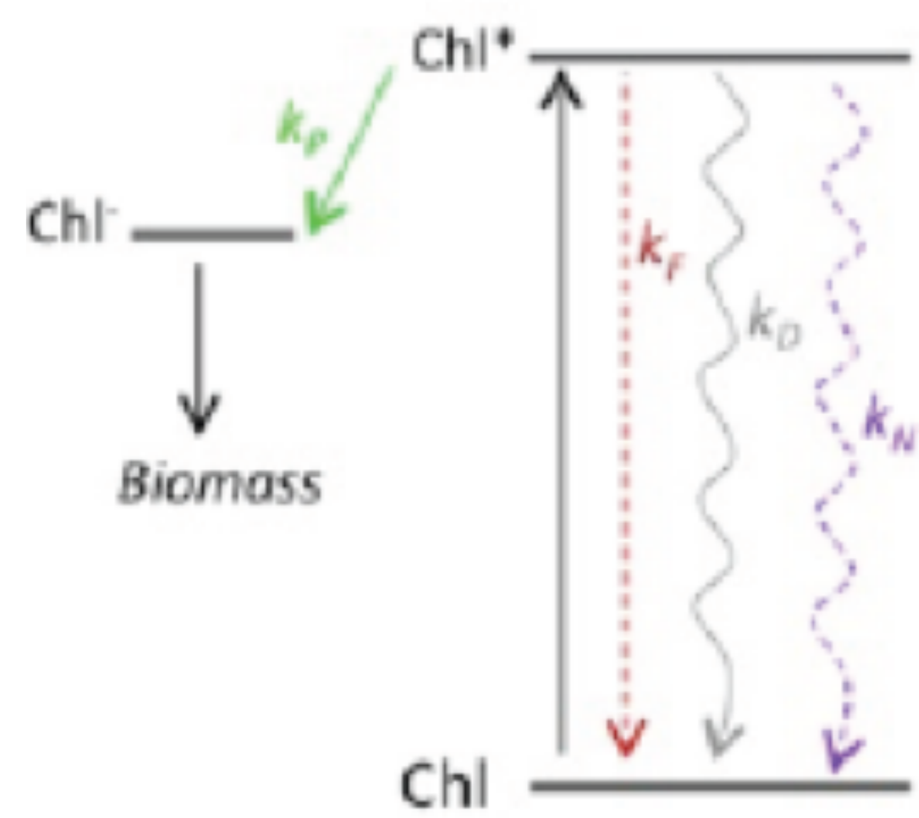
MPI-GPP at 0.5° *vs* SIF (GOME-2) or NIR_V (MODIS)




B.
Coefficient of Determination (R^2)
1.0
0.8
0.6
0.4
0.2
0.0
NDVI
fPAR
NIR$_V$
GPP

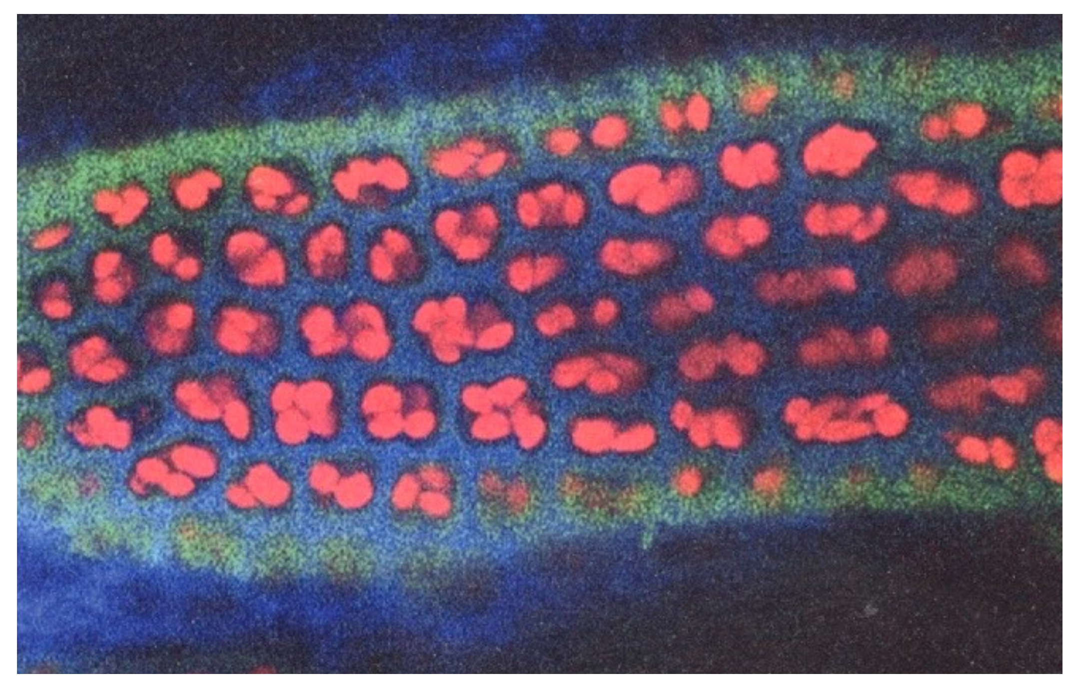
We have come up with a new way to use MODIS data to obtain a metric, the NIRv, which we consider to be the NIR refection from the vegetation of a mixed scene. It is approximated as $NIR_V = NIR_T * NDVI$ and it correlates remarkably well with SIF and GPP. This appears to be a subtle feature of canopy structure.

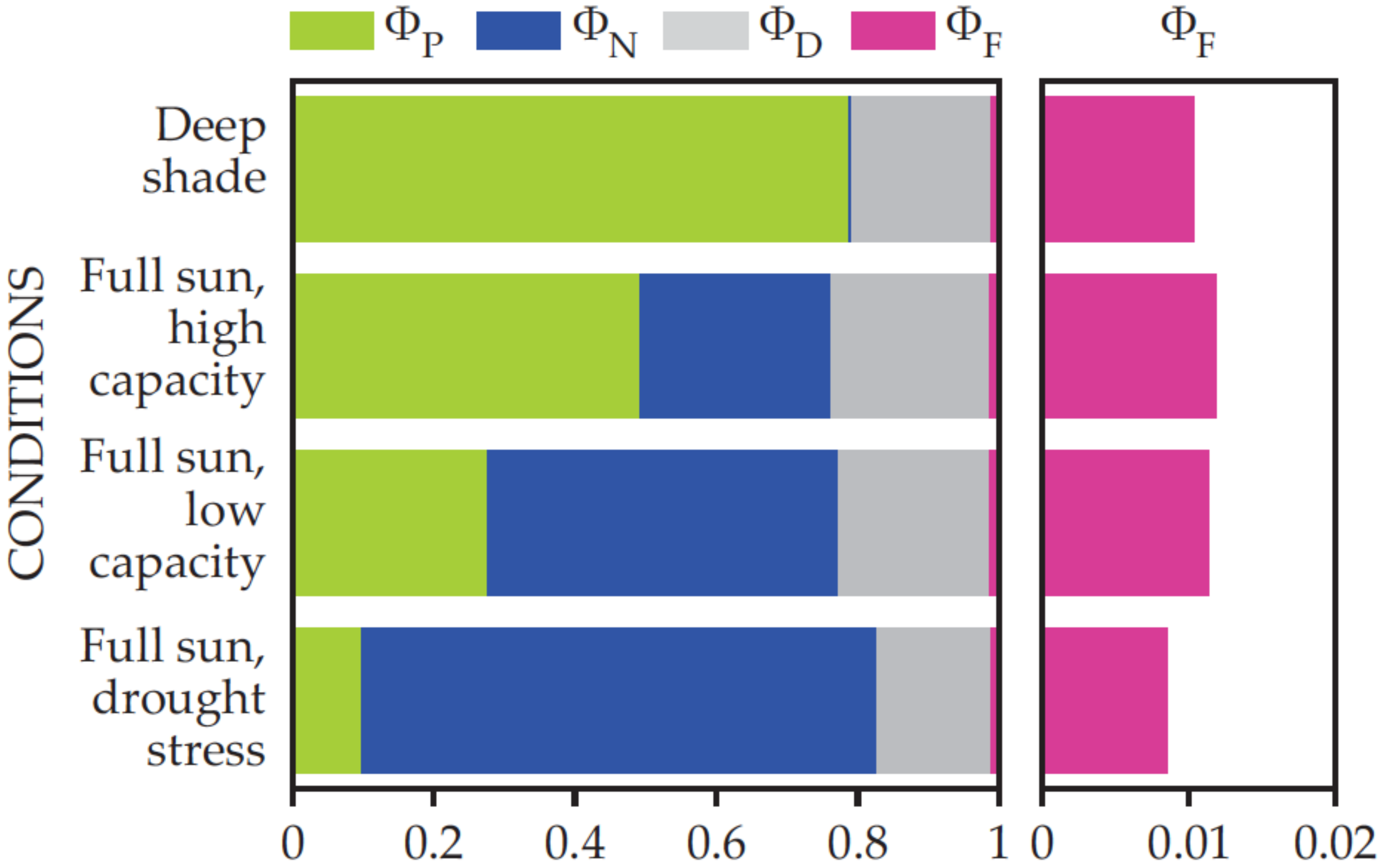




$$\Phi_F = K_F / K_T$$

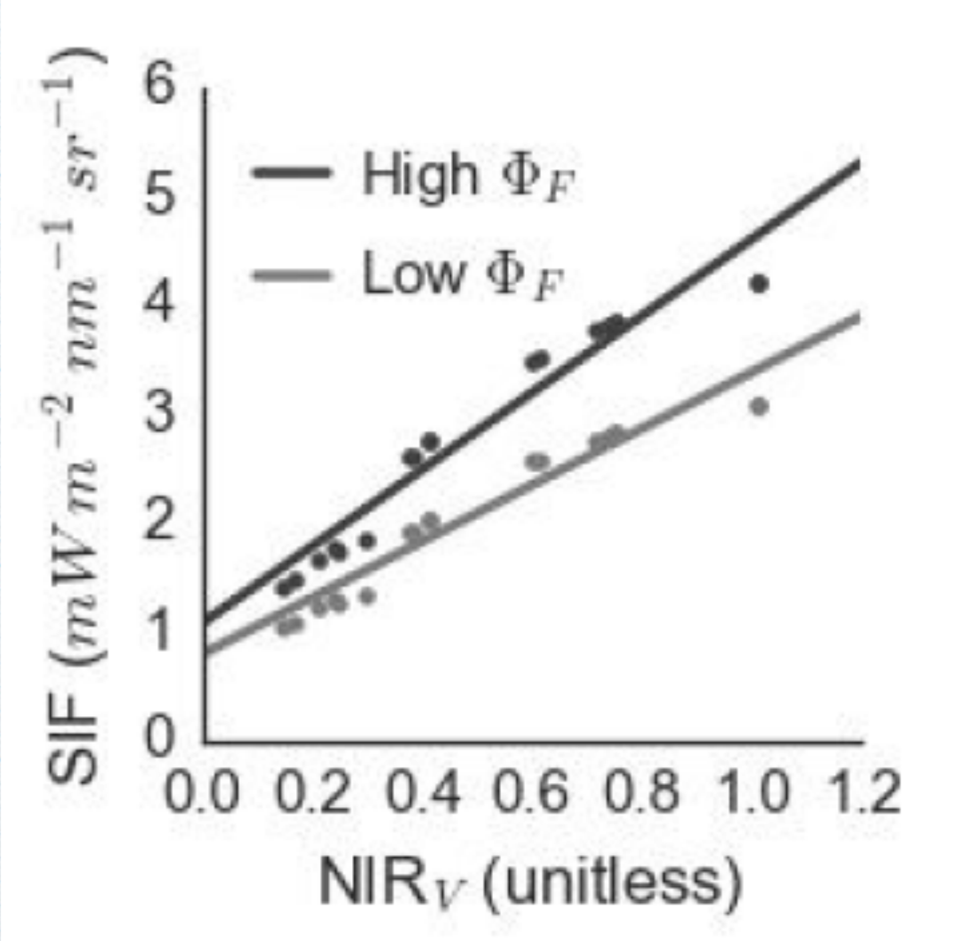
Where K_F is a constant





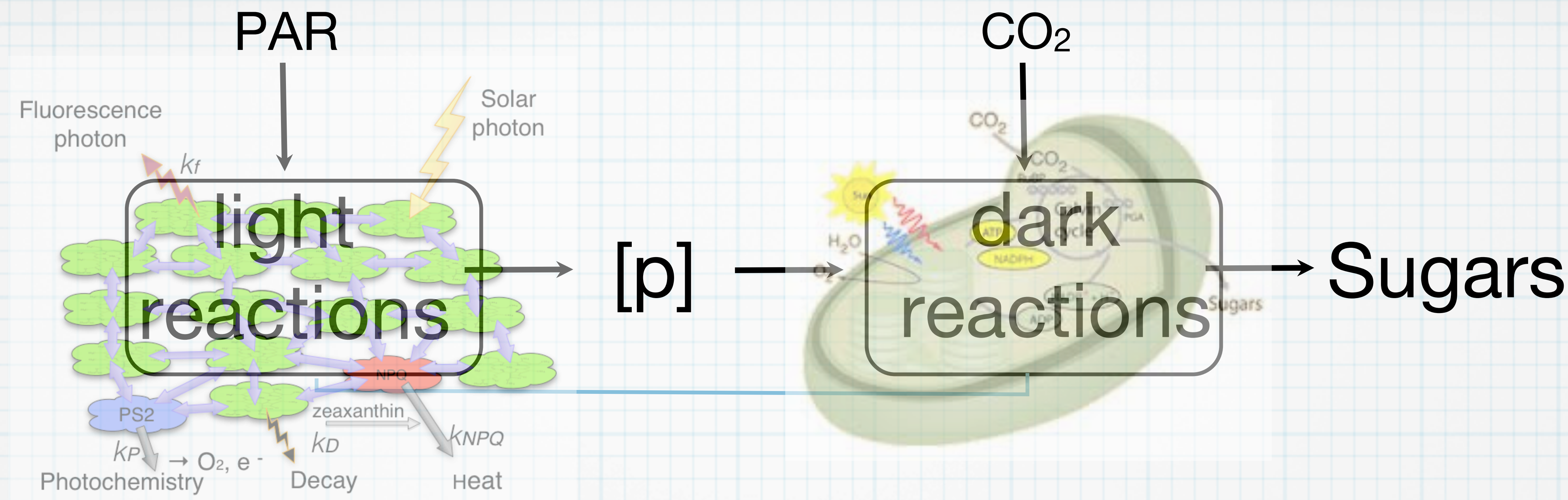
Schlau-Cohen, G. S., & Berry, J. (2015). Photosynthetic fluorescence, from molecule to planet. Physics Today, 68(9), 66–67. http://doi.org/10.1063/PT.3.2924

- Modeling studies with SCOPE indicate that NIR_V permits us to separate control of SIF into 2 components.
  - Physiological control of the fluorescence yield
  - Leaf display and light interception
- Remarkably BOTH seem to be correlated with GPP

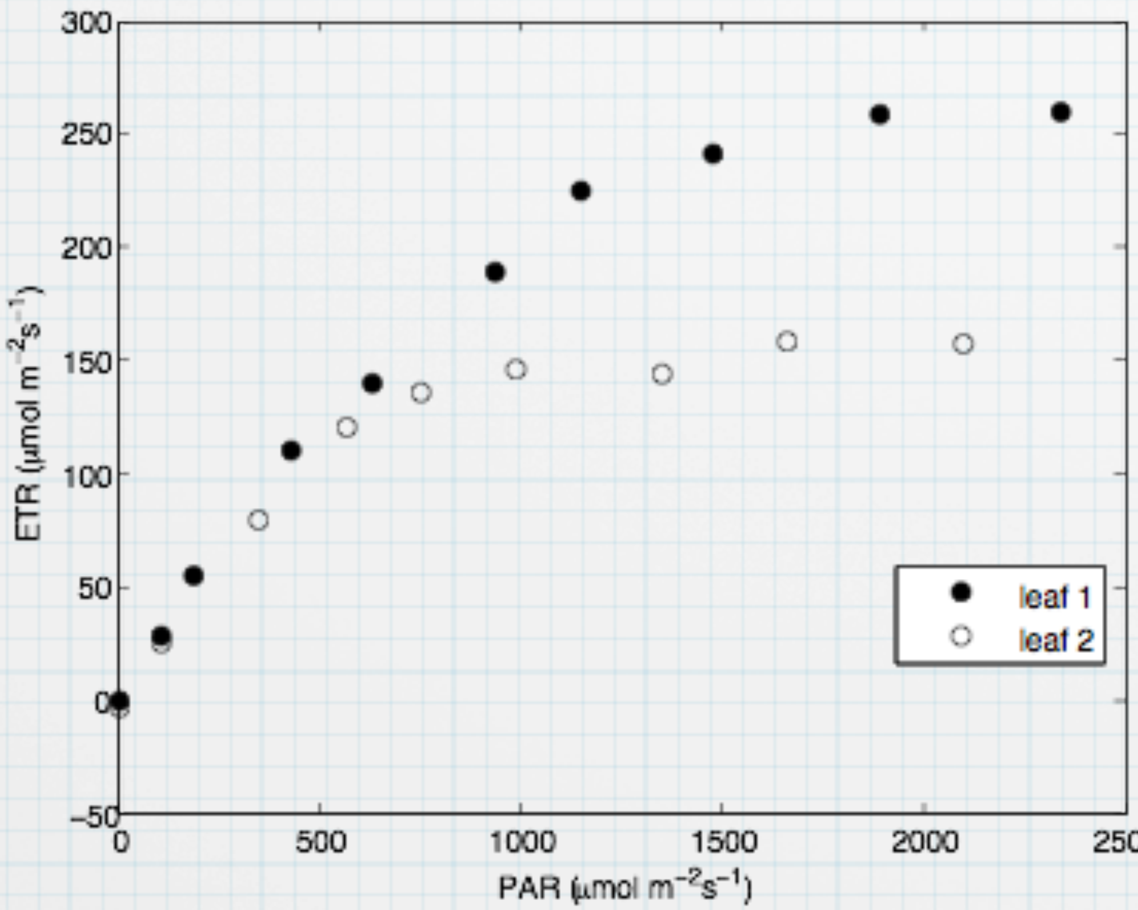


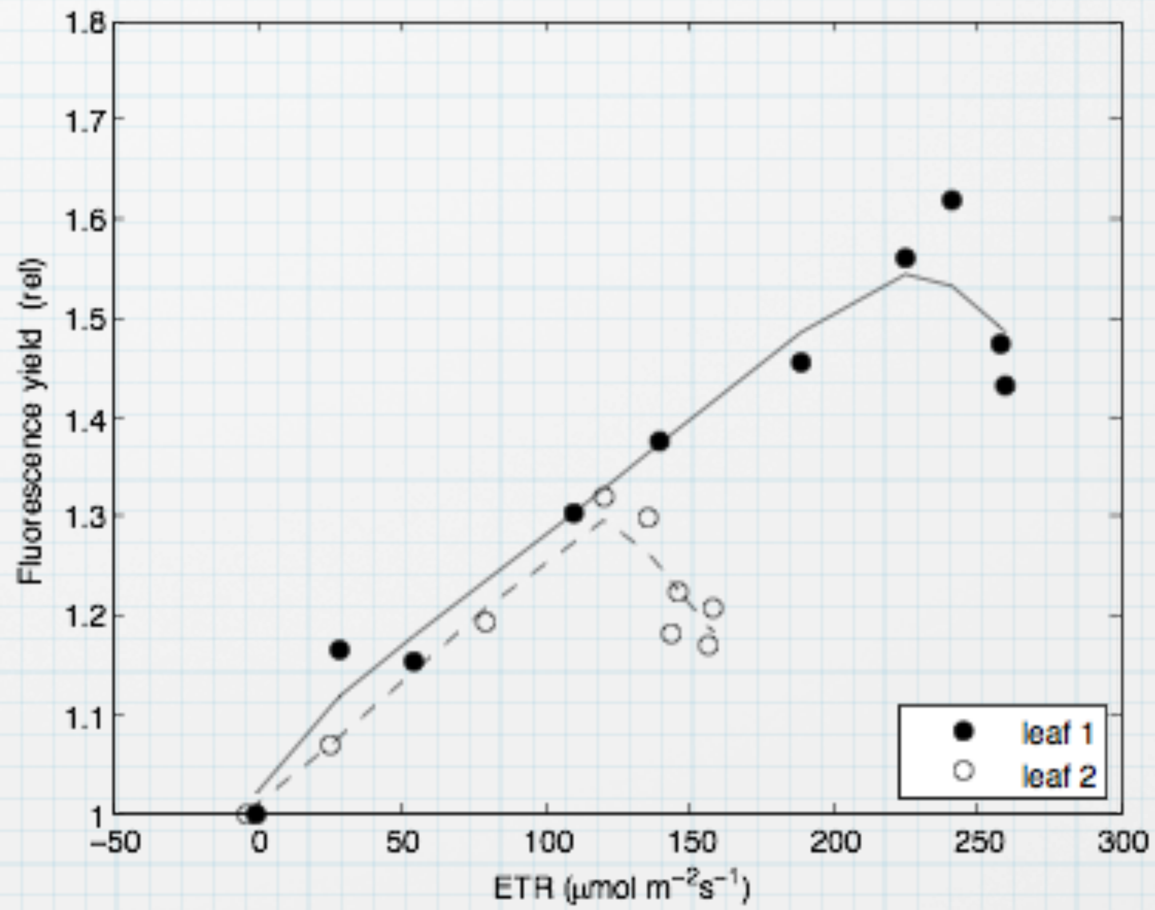
Final Thoughts:

- SIF is turning out to be surprisingly useful:
  - Seems to be proportional to GPP;
  - Indicates drought;
  - Indicates beginning and end of growing season.
- It is also a hot topic in fundamental research on photosynthesis.
- Fluorescence is a product of photosynthesis which can be modeled and measured over the globe. If we model SIF correctly does it mean that we have modeled GPP correctly?
- We have come up with a new way to use MODIS data to obtain a metric, the NIRv, which we consider to be the NIR refection from the vegetation of a mixed scene. It is approximated as NIRv =NIRt * NDVI and it correlates remarkably well with SIF and GPP.



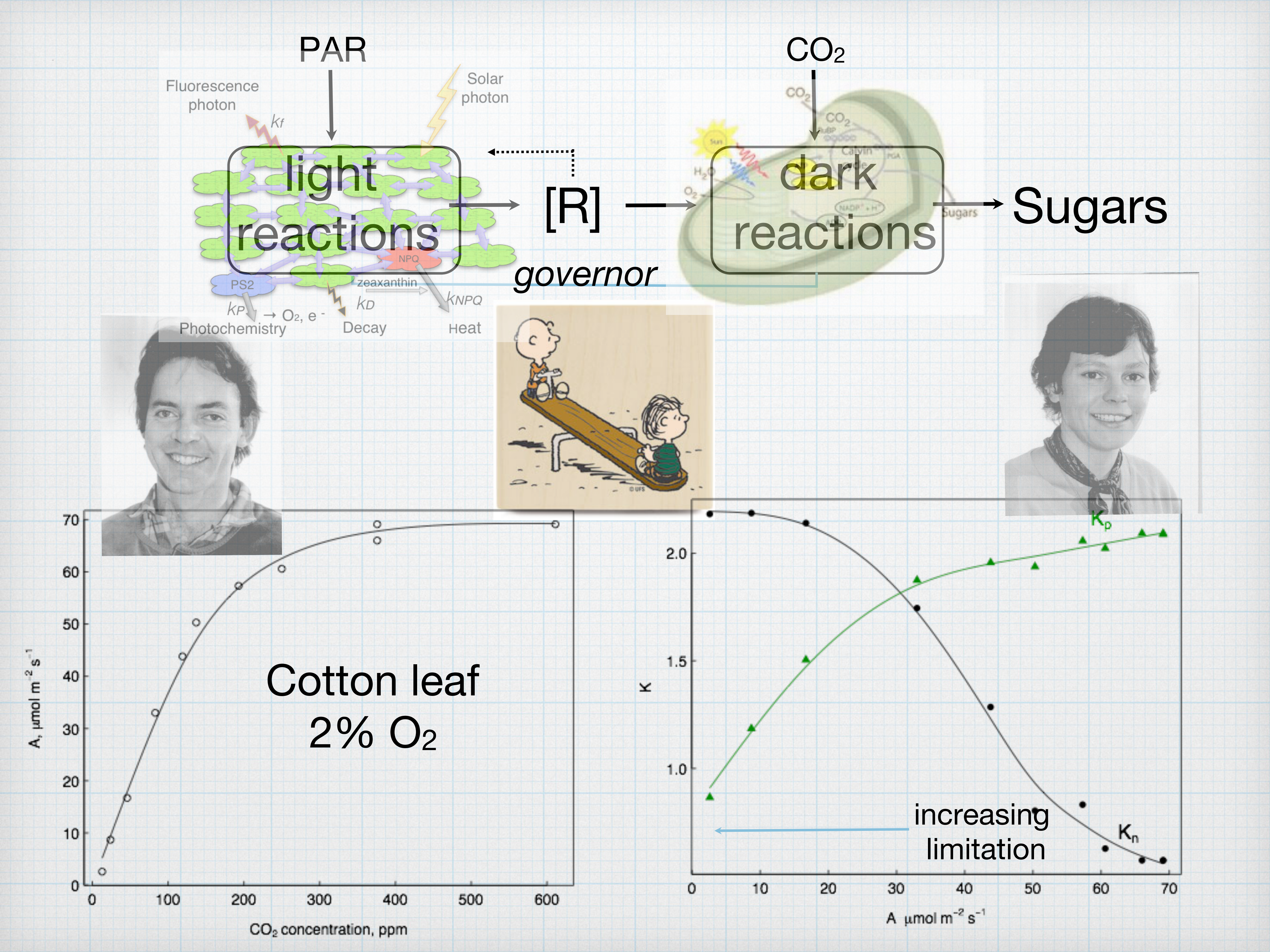
Fluorescence *vs.* the electron transport rate (ETR)



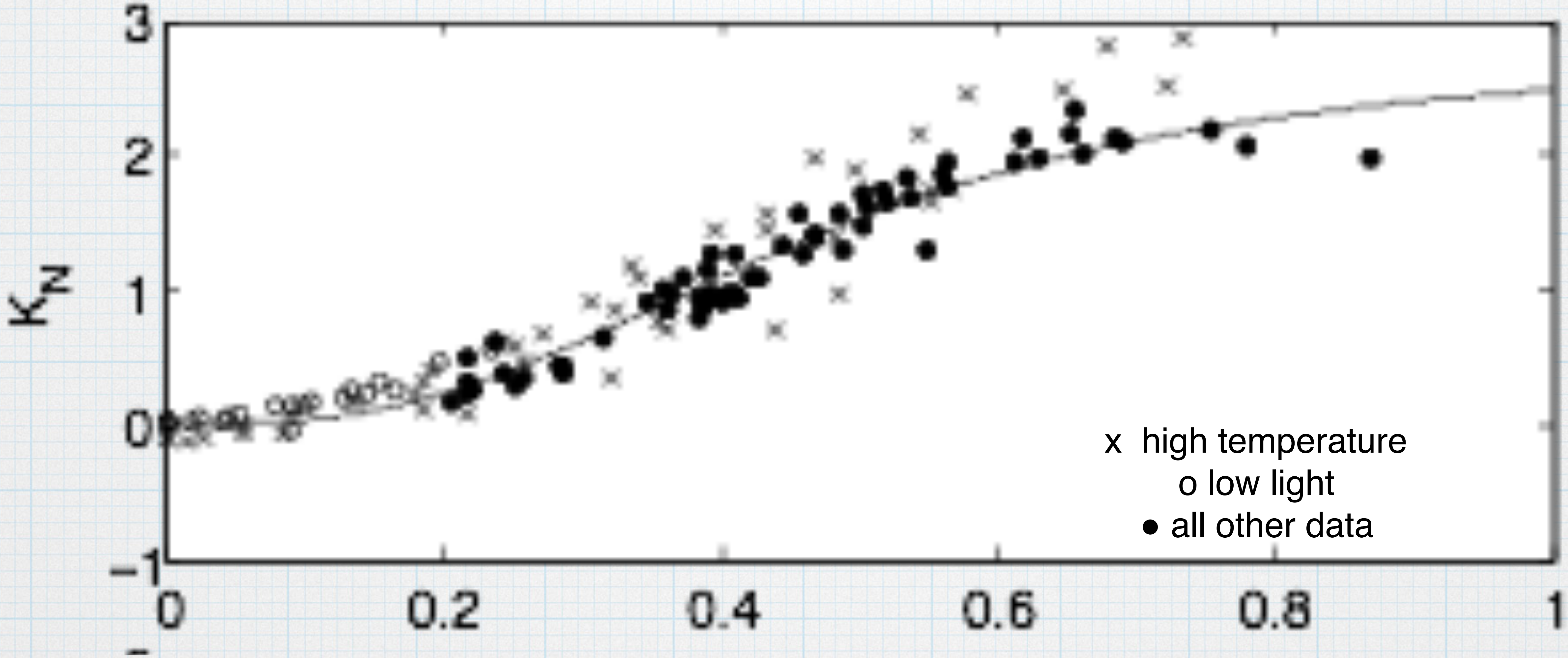


Summary

- Studies of the mechanisms controlling fluorescence provide a good basis for predicting the yield of solar induced fluorescence (SIF).
- Feedback mechanisms appear to keep fluorescence yield fairly constant.
- Stress (cold, drought, heat) generally tends to reduce fluorescence.
- Observations of SIF generally show larger changes than predicted based on physiological parameterizations. Seems like structure also plays a role


PAR
CO2
Fluorescence photon
Solar photon
kf
light reactions
[R]
dark reactions
Sugars
governor
PS2
NPQ
zeaxanthin
kP
→ O2, e-
kD
kNPQ
Photochemistry
Decay
Heat
Calvin cycle
Cotton leaf
2% O2
A, µmol m-2 s-1
CO2 concentration, ppm
K
Kp
Kn
increasing limitation
A µmol m-2 s-1

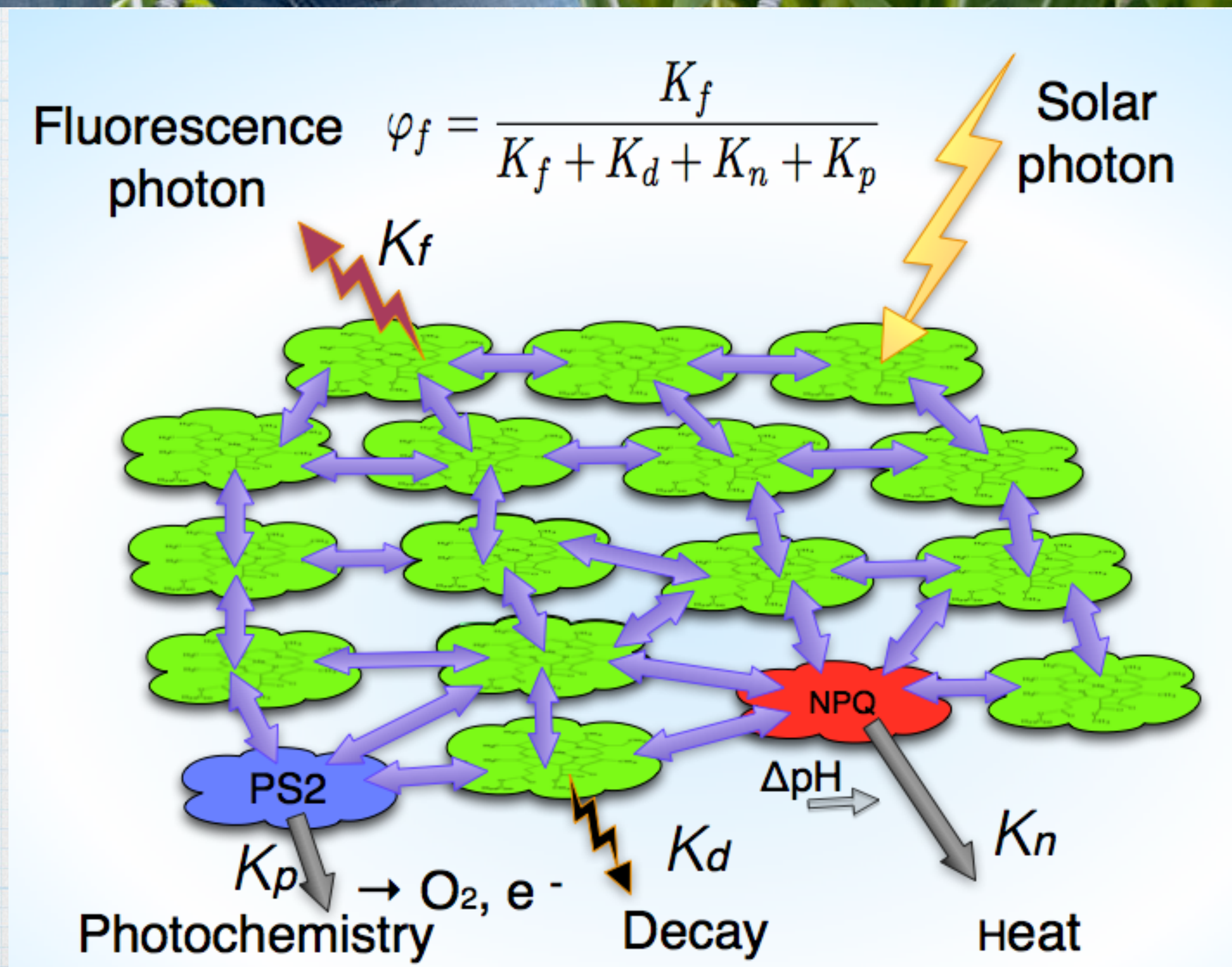
Finding and empirical expression for K_N



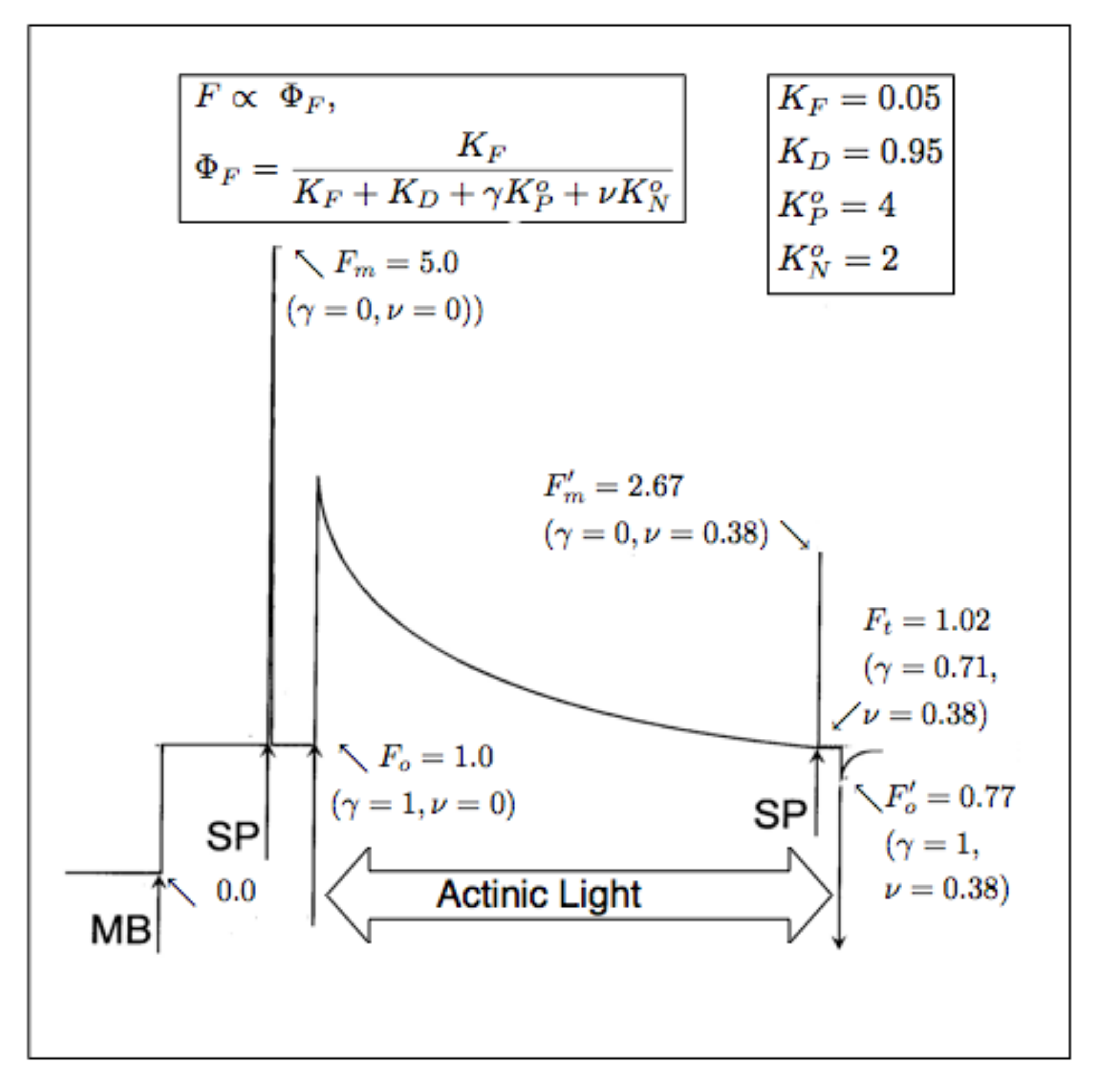
X (Feedback Factor)

$$K_N = \nu K_N^o \quad \text{with} \quad \nu = \frac{(1+\beta)x^\alpha}{\beta + x^\alpha}$$

Tol, C., Berry, J. A., Campbell, P. K. E., Campbell, P., & Rascher, U. (2014). Models of fluorescence and photosynthesis for interpreting measurements of solar-induced chlorophyll fluorescence. Journal of Geophysical Research-Biogeosciences, 119(12), 2312–2327. http://doi.org/10.1002/2014JG002713

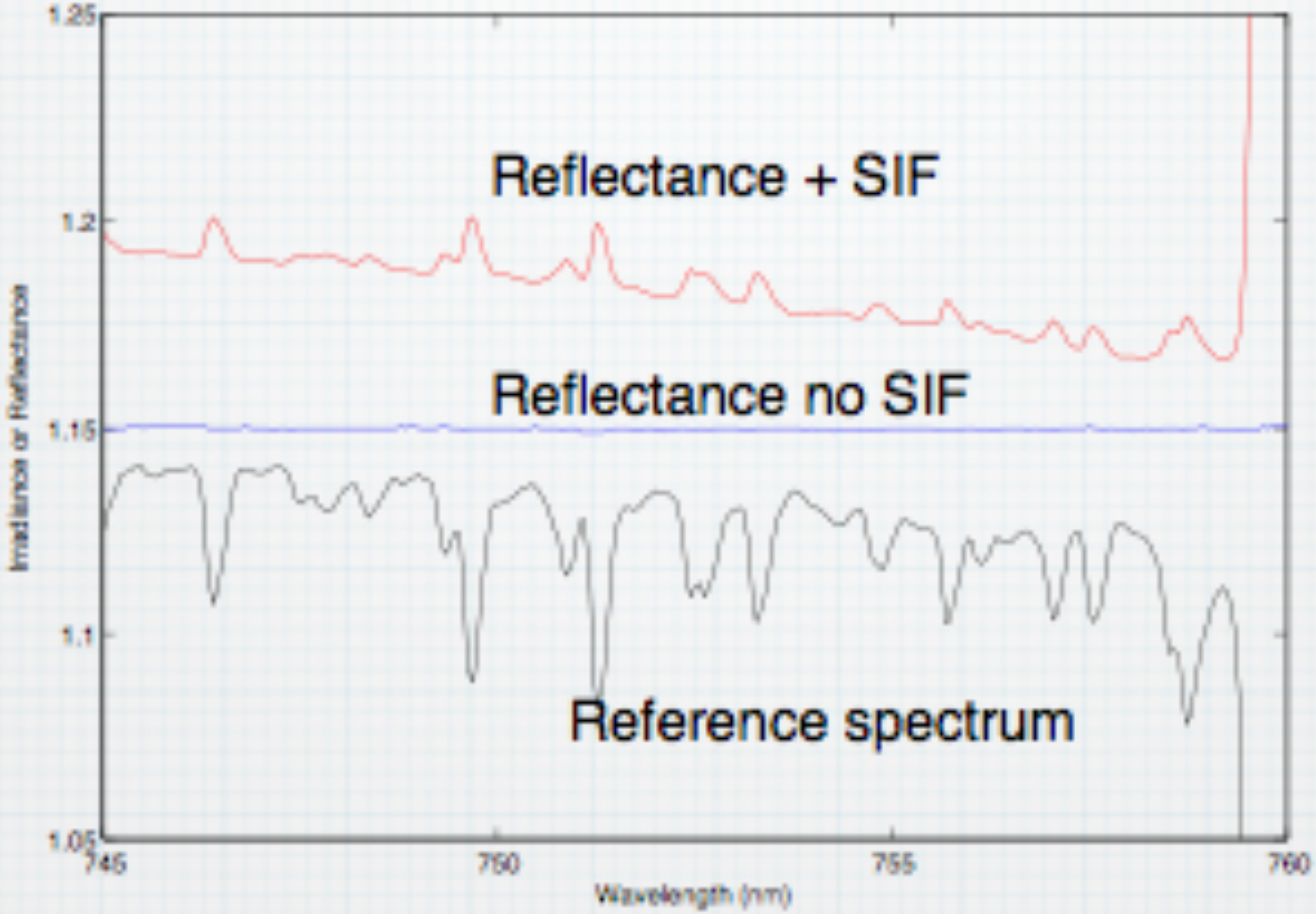

Fluorescence photon
$\varphi_f = \frac{K_f}{K_f + K_d + K_n + K_p}$
Solar photon
K_f
NPQ
PS2
ΔpH
K_p
$\rightarrow O_2, e^-$
Photochemistry
K_d
Decay
K_n
Heat

Relating PAM levels to absolute yields



Tol, C., Berry, J. A., Campbell, P. K. E., Campbell, P., & Rascher, U. (2014). Models of fluorescence and photosynthesis for interpreting measurements of solar-induced chlorophyll fluorescence. Journal of Geophysical Research-Biogeosciences, 119(12), 2312–2327. http://doi.org/10.1002/2014JG002713

Digging out Solar Induced Fluorescence (SIF)



Schlau-Cohen, G. S., & Berry, J. (2015). Photosynthetic fluorescence, from molecule to planet. Physics Today, 68(9), 66–67. http://doi.org/10.1063/PT.3.2924

Comparison of SIF Capable Satellites

Instrument	Status*	Coverage	Footprint (km)	Revisit time	Spectral Range (nm)	FWHM (nm)	SNR	SIF pixel Quality***
FOLIAGE	F	N/S Amer.	[Very Good] 2.4x4.8	[Excellent] 2-3 hrs	[Excellent] 490-790	[Very Good] 0.30	[Excellent]	[Excellent]
FLEX[1]	F	56S-75N	[Excellent] 0.3x0.3	[Poor] 19 d	[Excellent] 500-780	[Very Good] 0.3-2	[Very Good]	?
TROPOMI[2]	S	Global	[Good] 7x7	[Very Good] 1 d	[Very Good] 660-800	[Poor] 0.5	[Excellent]	[Very Good]
GOME-2[3]	0 2007-	Global	[Poor] 40x80	[Very Good] 1.5 d	[Excellent] 270-800	[Poor] 0.5	[Excellent]	[Very Good]
TEMPO[4]	S	CONUS	[Very Good] 4x5	[Excellent] 1 hr	[Very Good] 520-740	[Poor] 0.6	[Very Good]	[Very Good]
OCO-2[5]	0 2014-	Global**	[Very Good] 2x2	[Poor] 16 d	[Poor] 755 -775	[Excellent] 0.05	[Good]	[Very Good]
GOSAT[6]	0 2009-	Global**	[Good] 10x10	[Good] 3 d	[Poor] 755 -775	[Excellent] 0.03	[Poor]	[Fair]
Sentinel 4[7]	S	Europe	[Good] 8x8	[Excellent] 1 hr	[Poor] 755 -775	[Very Good] 0.12	[Good]	[Good]
GCPM[8]	F	US	[Very Good] 4x4	[Excellent] 1 hr	[Poor] 756-760	[Very Good] 0.10	[Fair]	[Good]
CarbonSat[9]	F	Global	[Very Good] 2x2	[Fair] 5 d	[Fair] 747 -773	[Very Good] 0.10	[Poor]	[Fair]

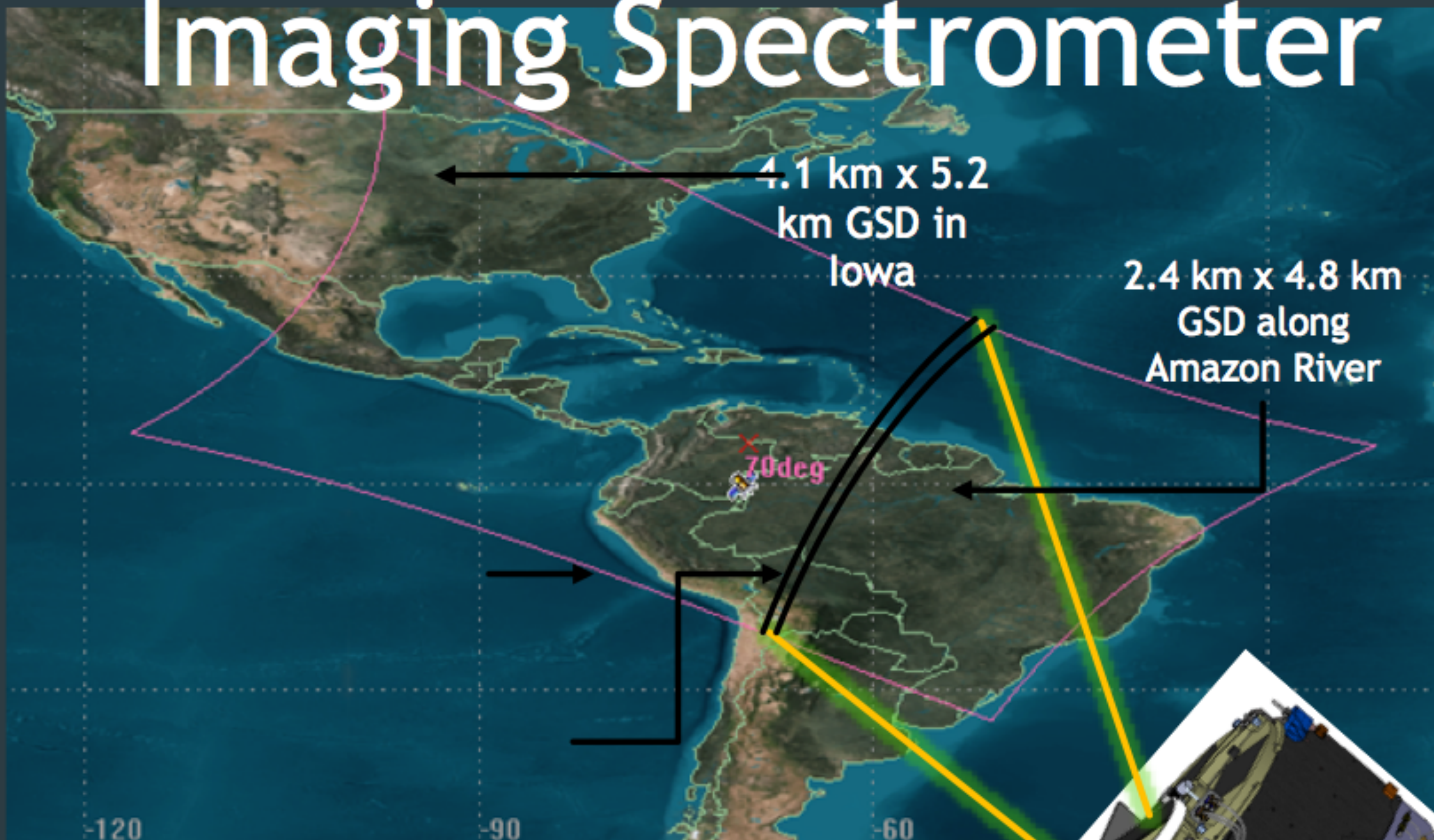
●: Excellent; ◒: Very Good; ○: Good; ◓: Fair; ●: Poor

[1]Rascher [2007]; [2] Guanter et al. [2015]; [3] Joiner et al. [2013]; [4] Joiner, unpublished; [5]Frankenberg et al. [2014]; [6] Joiner et al. [2011, 2012] ; [7] Miejer et al. [2014]; [8] Key et al. [2012]; [9] Buchwitz et al. [2013]

F: in formulation (not yet selected) | S: selected for launch | 0: in orbit ** Global in extent, but sparse coverage (not complete) * Far-red SIF only*

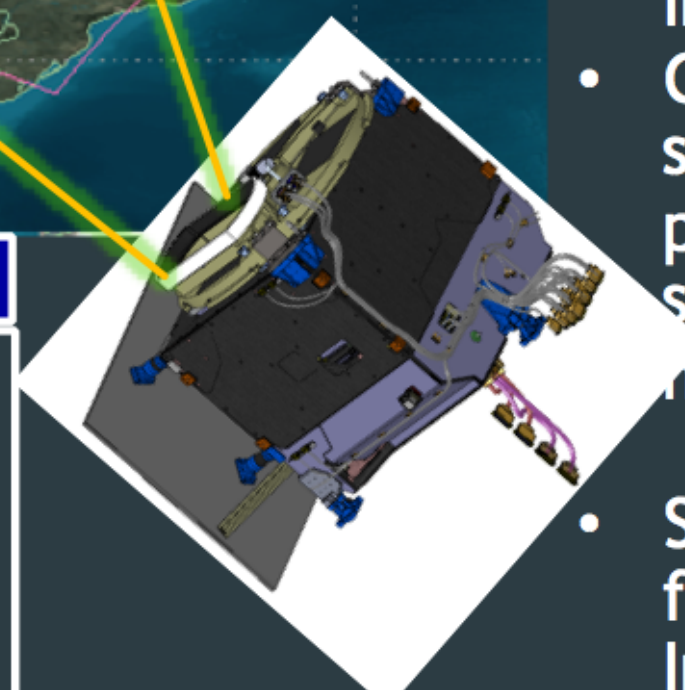
FOLIAGE

Geostationary: Stop-and-Stare Imaging Spectrometer



Performance Parameters

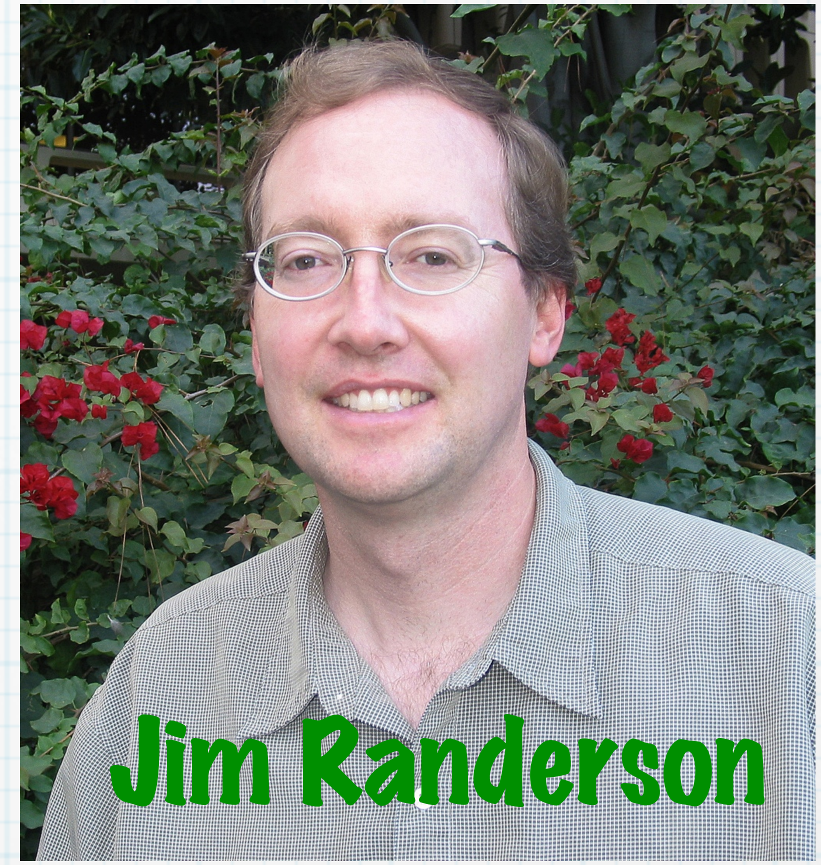
- 4.7 seconds per image and step
- 1521 images per 120 minute SE-NW scan Daily solar calibration.
- Can focus in on selected areas for intensive study.
- 490-780 nm spectral range 0.3 nm FWHH signal to noise >1000 (in stop-n-stare mode)
- Instrument optimized for solar-induced fluorescence measurements.



- Coverage – most of the highly productive regions of the Americas - including Amazon and agricultural areas.
- First dedicated, measuremen of solar-induced fluorescence (SIF, both red and far-red) ar the Photochemical Reflectan Index (PRI).
- Goals – direct measurement seasonal and diurnal photosynthesis; detection of stress, and improvement of models.
- Synergistic parameters deriv from GOES-R Advanced Basel Imager
- More chances to see betwee the clouds.

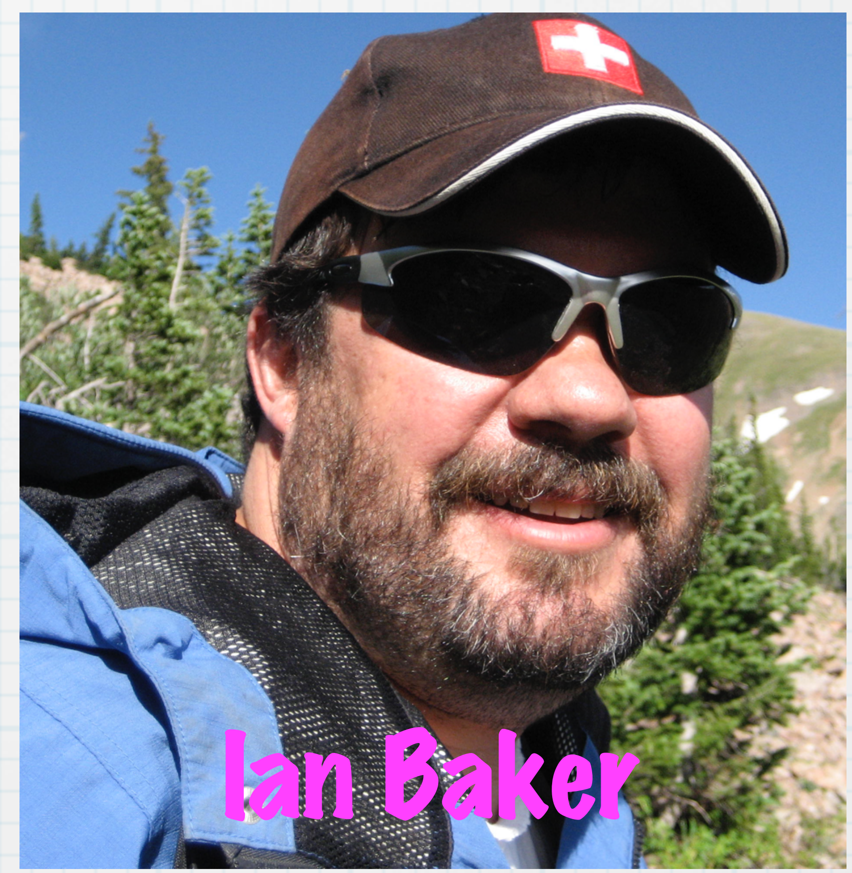

Greg Asner

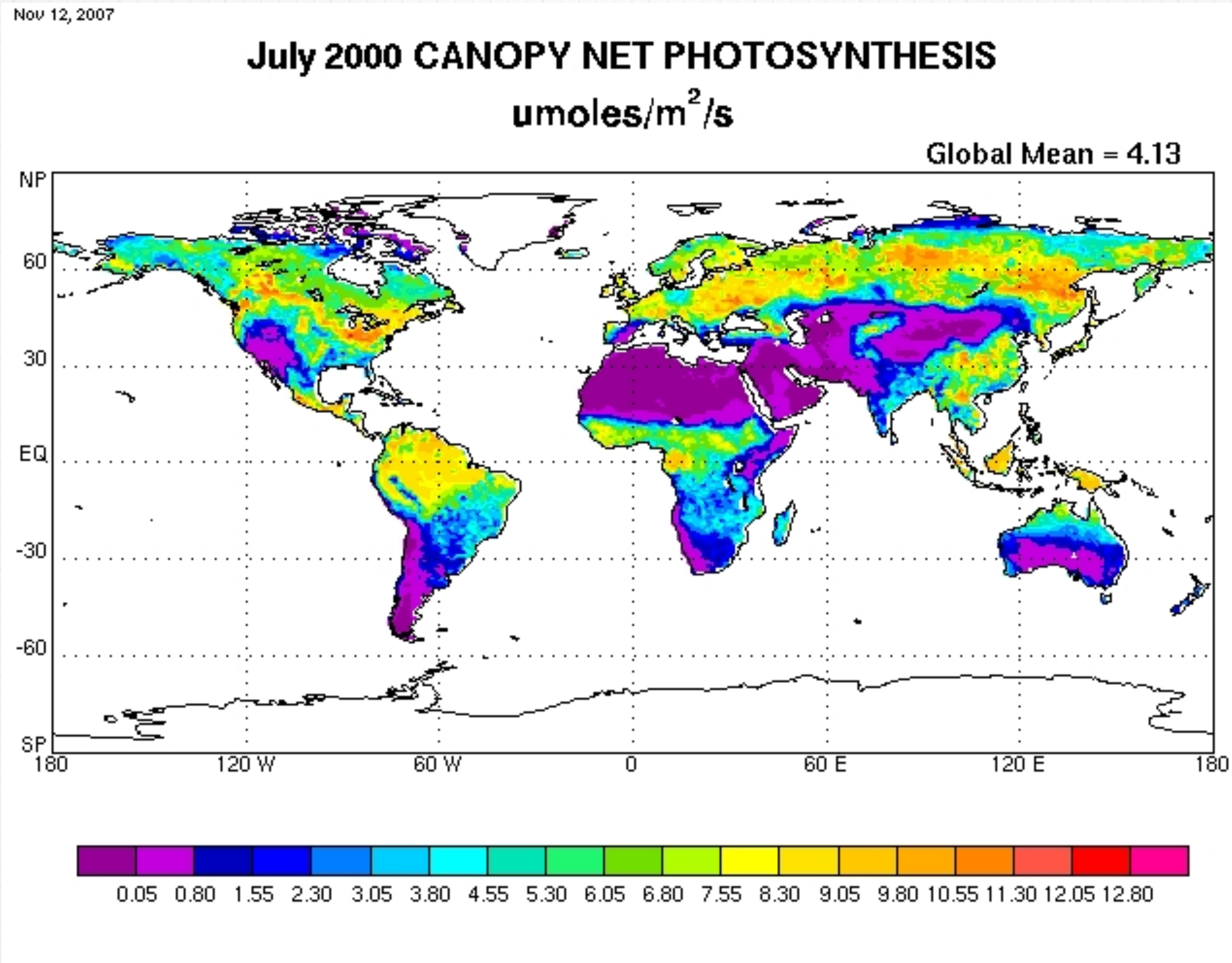

Scott Denning


Jim Randerson


Ruth de Freis


Chris Still


Ian Baker


Nov 12, 2007
July 2000 CANOPY NET PHOTOSYNTHESIS
umoles/m²/s
Global Mean = 4.13
NP
60
30
EQ
-30
-60
SP
180
120 W
60 W
0
60 E
120 E
180
0.05 0.80 1.55 2.30 3.05 3.80 4.55 5.30 6.05 6.80 7.55 8.30 9.05 9.80 10.55 11.30 12.05 12.80

To summarize:

Breakthroughs aren’t obvious until they happen.

The pieces that ultimately fit together are the key to breakthroughs; we need to be *looking* for them, and we need *cultivate* them.

In light of the Decadal Survey, I’d like to make the point that the NASA centers are a tremendous resource for

this “scientific potential energy”

flipping the switches of the universe

That's how we got here. Now, where are we going?

Several speakers have already mentioned fluorescence

Key discoveries:

Plascyk, J. A. (1975). The MK II Fraunhofer Line Discriminator (FLD-II) for Airborne and Orbital Remote Sensing of Solar-Stimulated Luminescence. Optical Engineering, 14(4), 339–0. http://doi.org/10.1117/12.7971842

Perkin-Elmer & Wollops

Guanter, L., Alonso, L., Gómez-Chova, L., Amorós-López, J., Vila, J., & Moreno, J. (2007). Estimation of solar-induced vegetation fluorescence from space measurements. Geophysical Research Letters, 34(8), L08401. http://doi.org/10.1029/2007GL029289

ESA

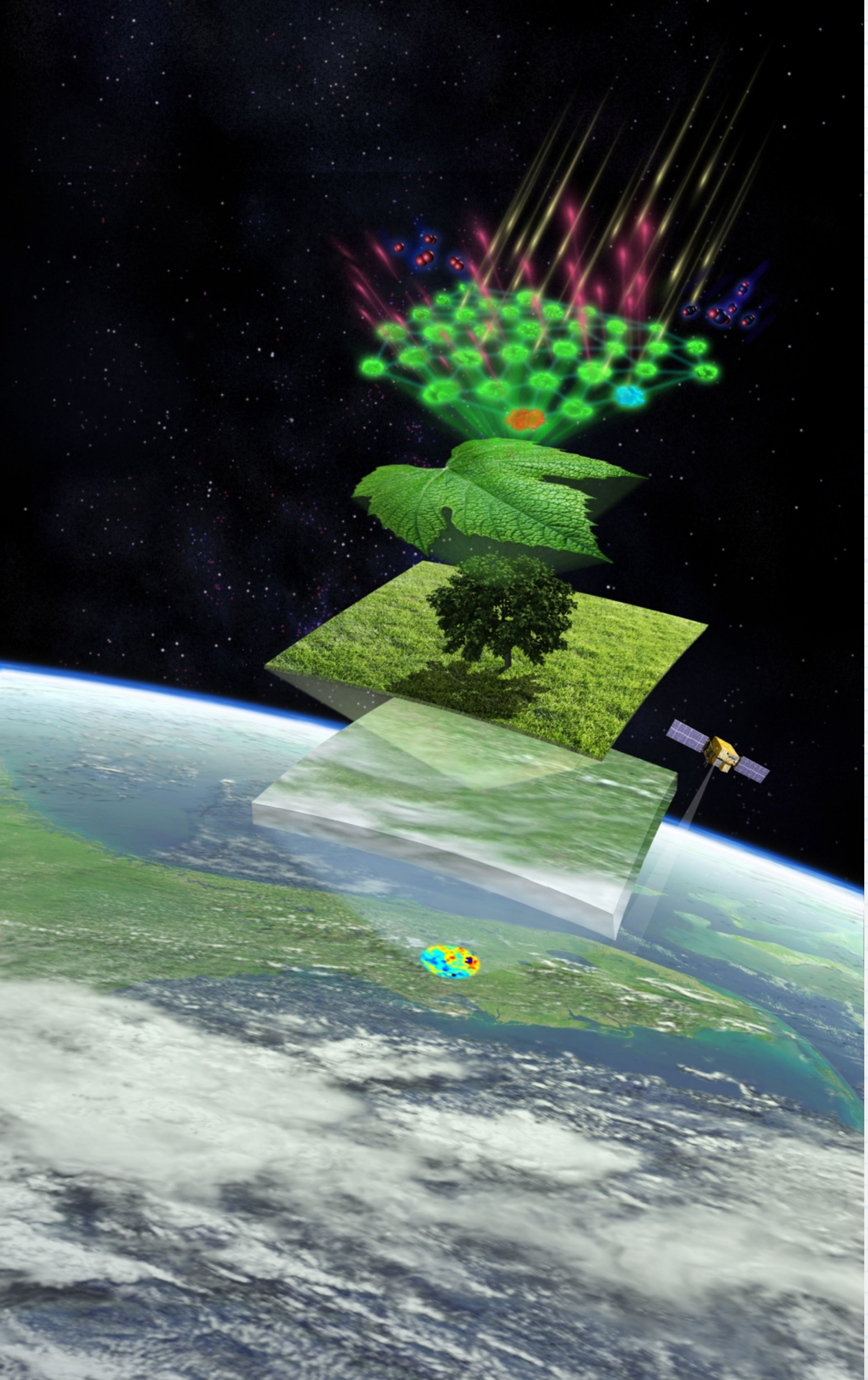
Frankenberg, C., Butz, A., & Toon, G. C. (2011). Disentangling chlorophyll fluorescence from atmospheric scattering effects in O 2A-band spectra of reflected sun-light. GEOPHYSICAL RESEARCH LETTERS, 38(3), L03801. doi: 10.1029/2010GL045896

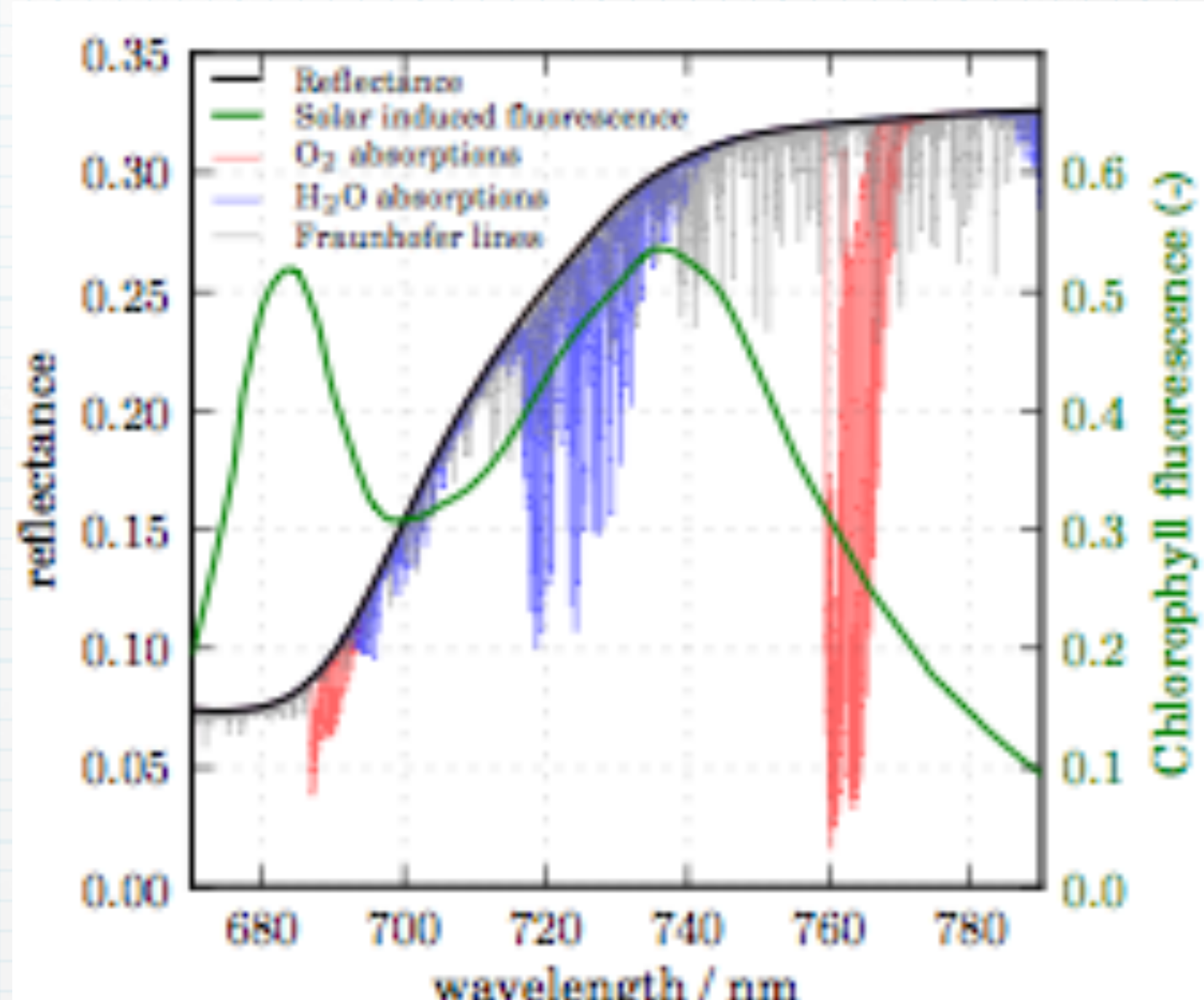
JPL

Joiner, J., Yoshida, Y., Vasilkov, A. P., Yoshida, Y., Corp, L. A., & Middleton, E. M. (2011). First observations of global and seasonal terrestrial chlorophyll fluorescence from space. Biogeosciences, 8(3), 637–651. doi:10.5194/bg-8-637-2011

GSFC

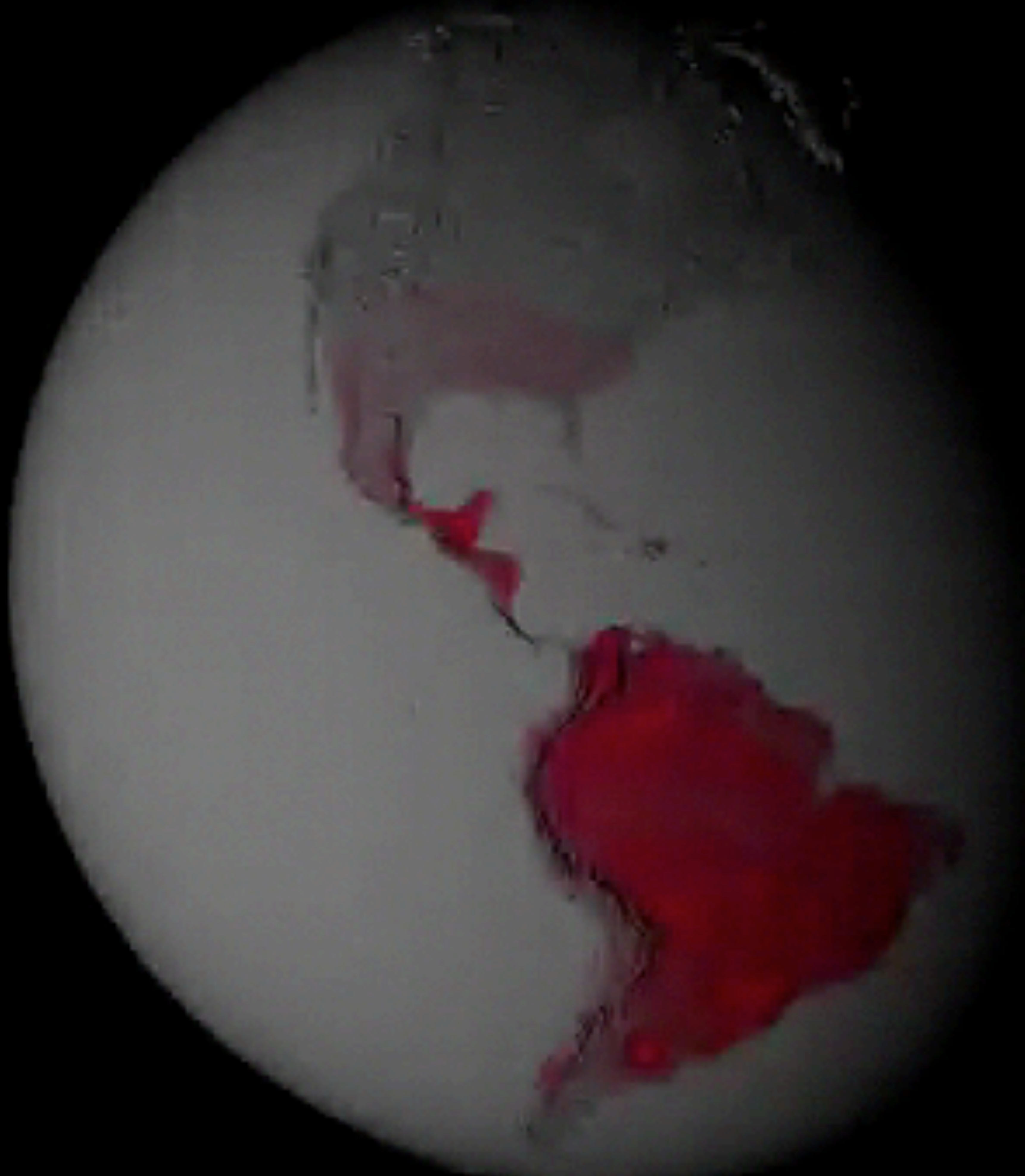
- Fluorescence from terrestrial plants is difficult to measure





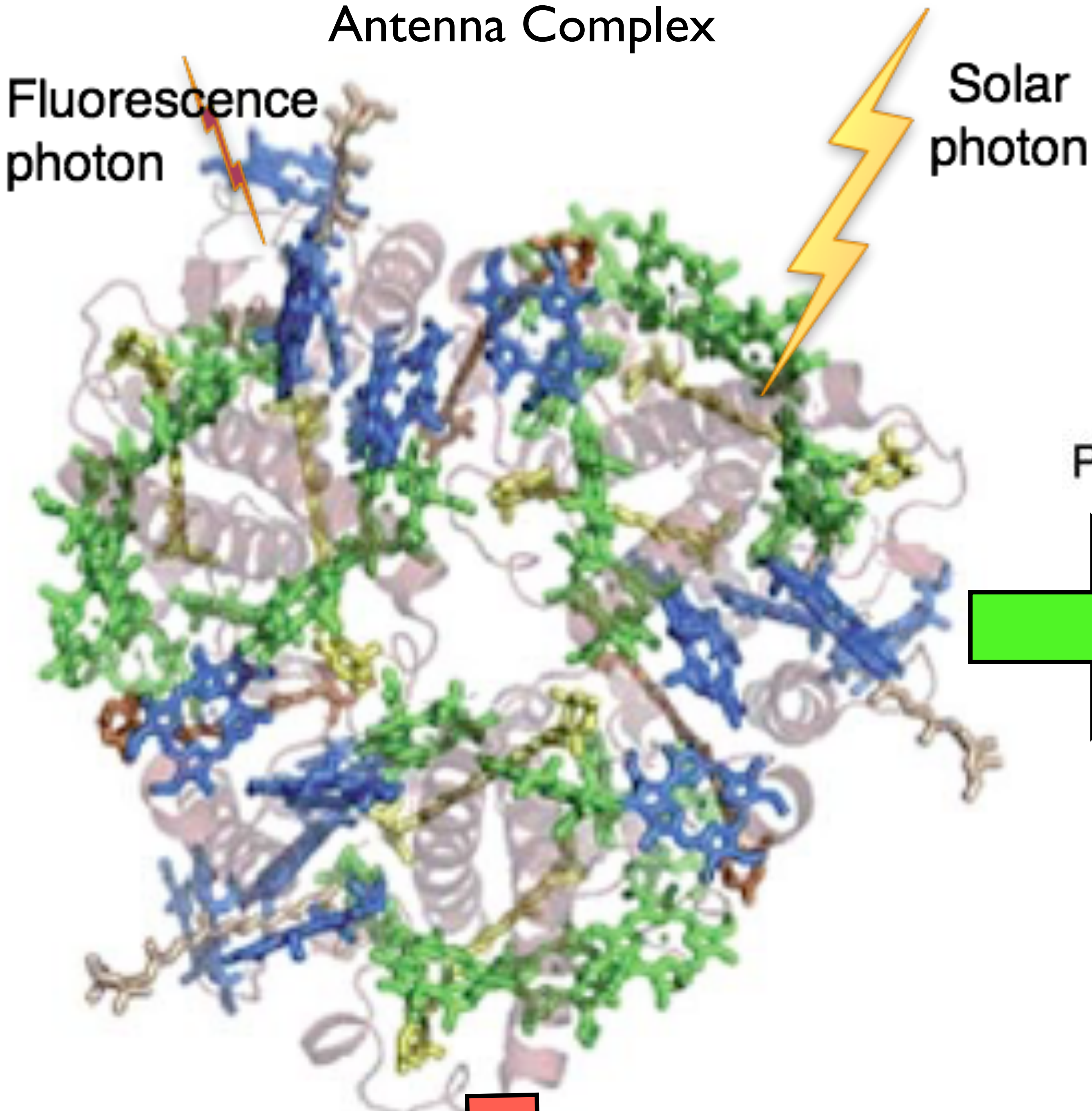
- In-filling of lines in the solar spectrum can be used to distinguish fluorescence from reflected light.

- It takes a special high resolution spectrometer. So far it has been accomplished with 5 satellites

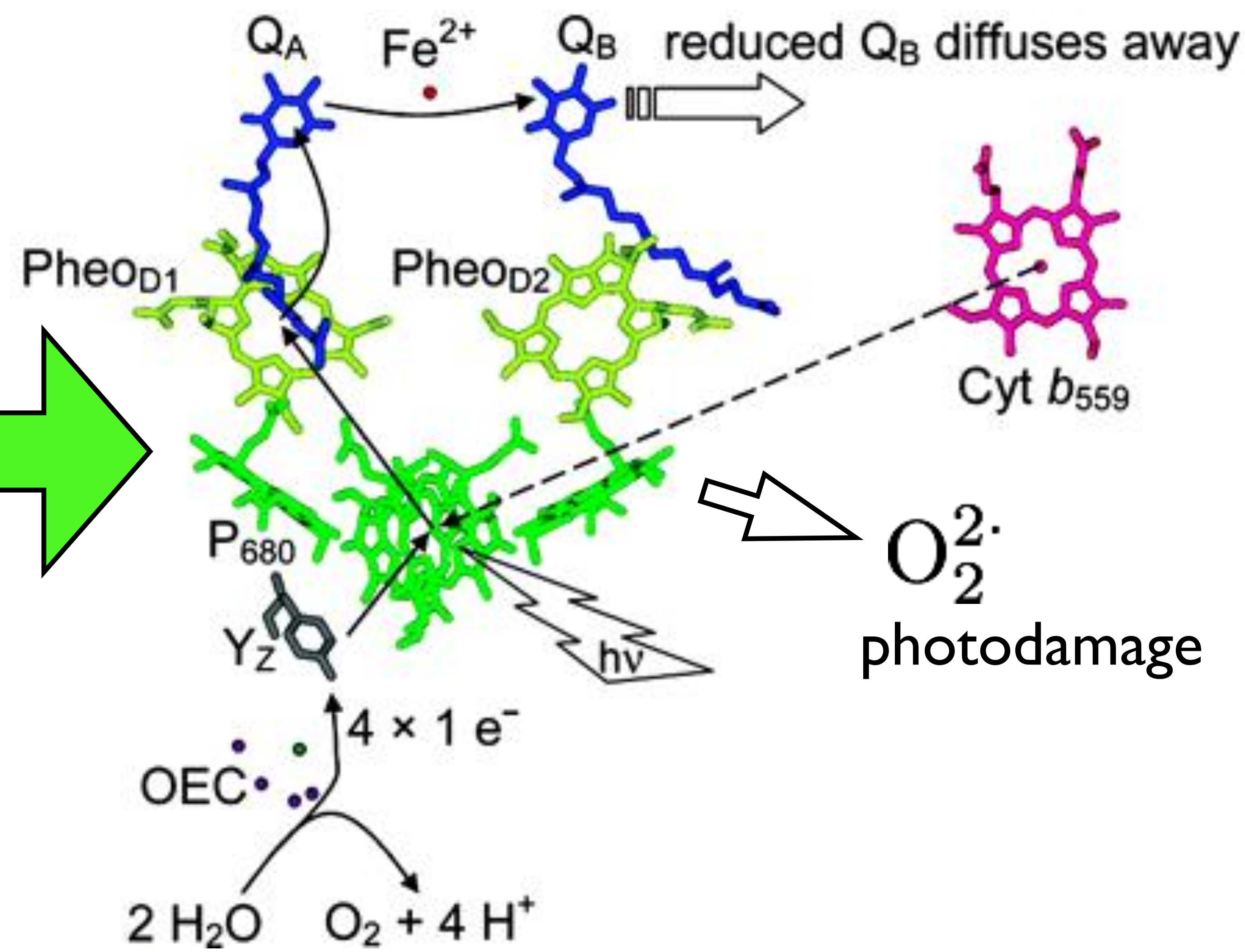


Fluorescence in Photosynthesis Research

Antenna Complex



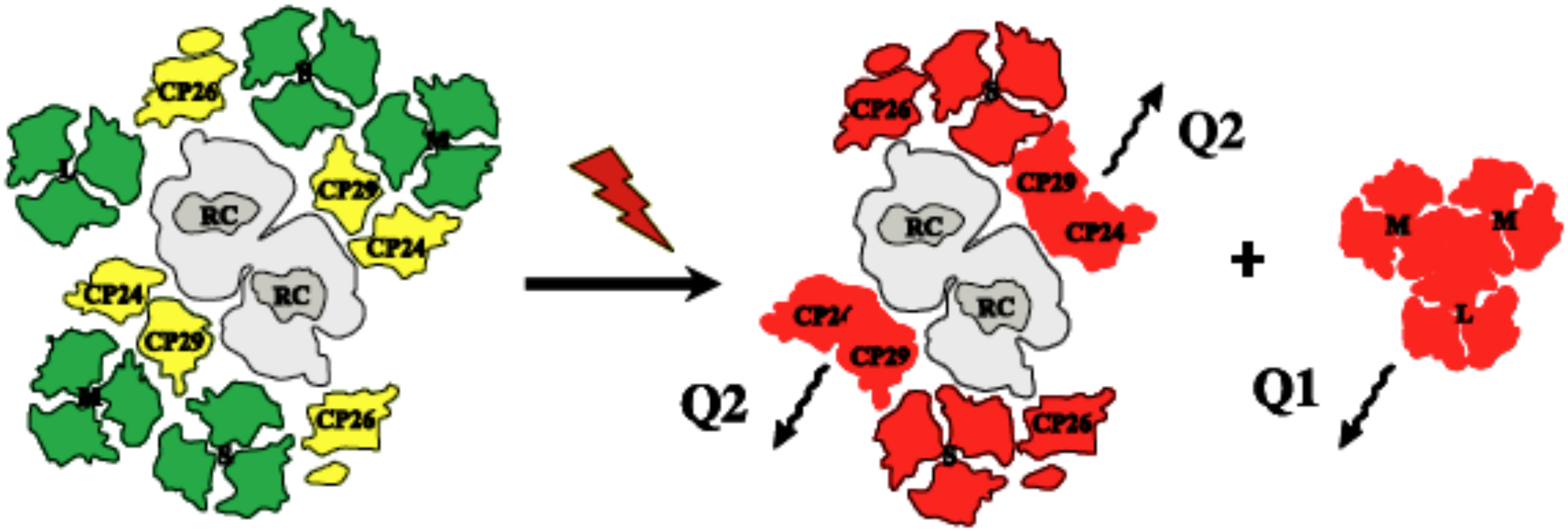
PS-II Reaction Center

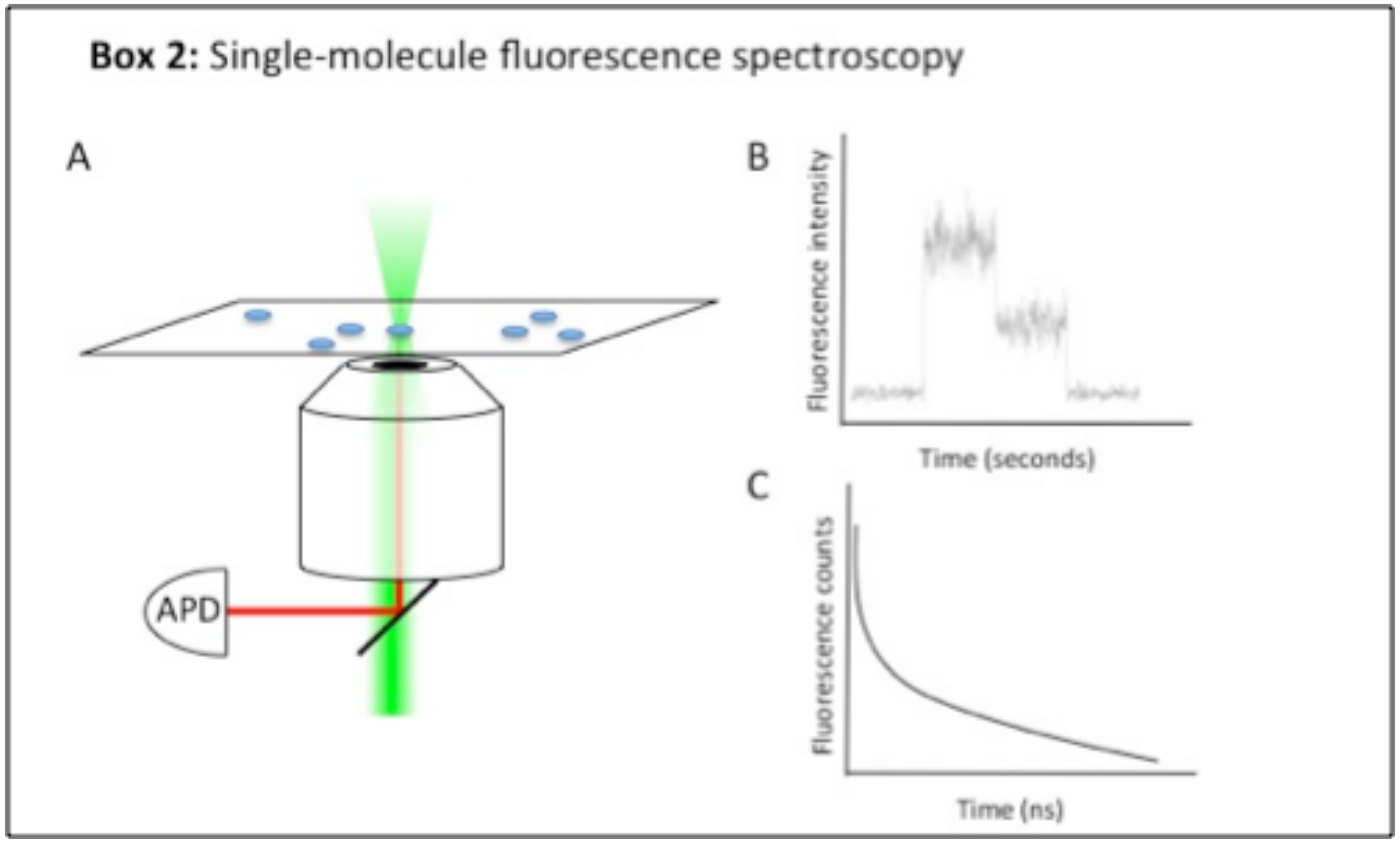


Non-photochemical Quenching

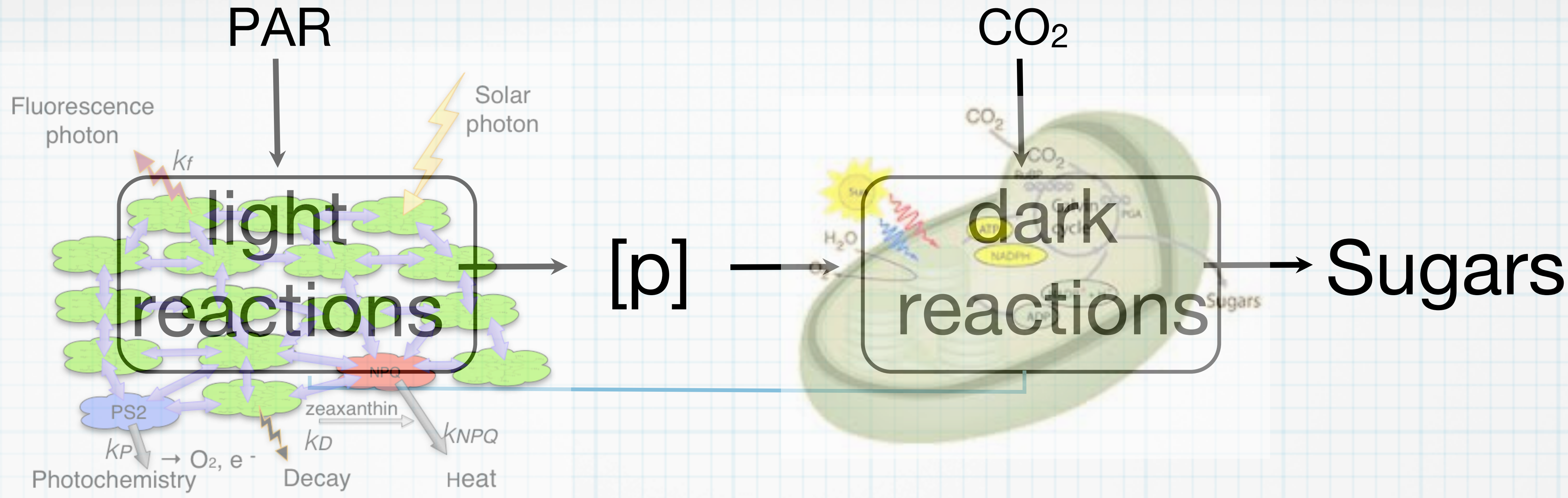
Fleming, G. R., Schlau-Cohen, G. S., Amarnath, K., & Zaks, J. (2012). Design principles of photosynthetic light-harvesting. Faraday Discussions, 155, 27. http://doi.org/10.1039/c1fd00078k

Non Photochemical Quenching

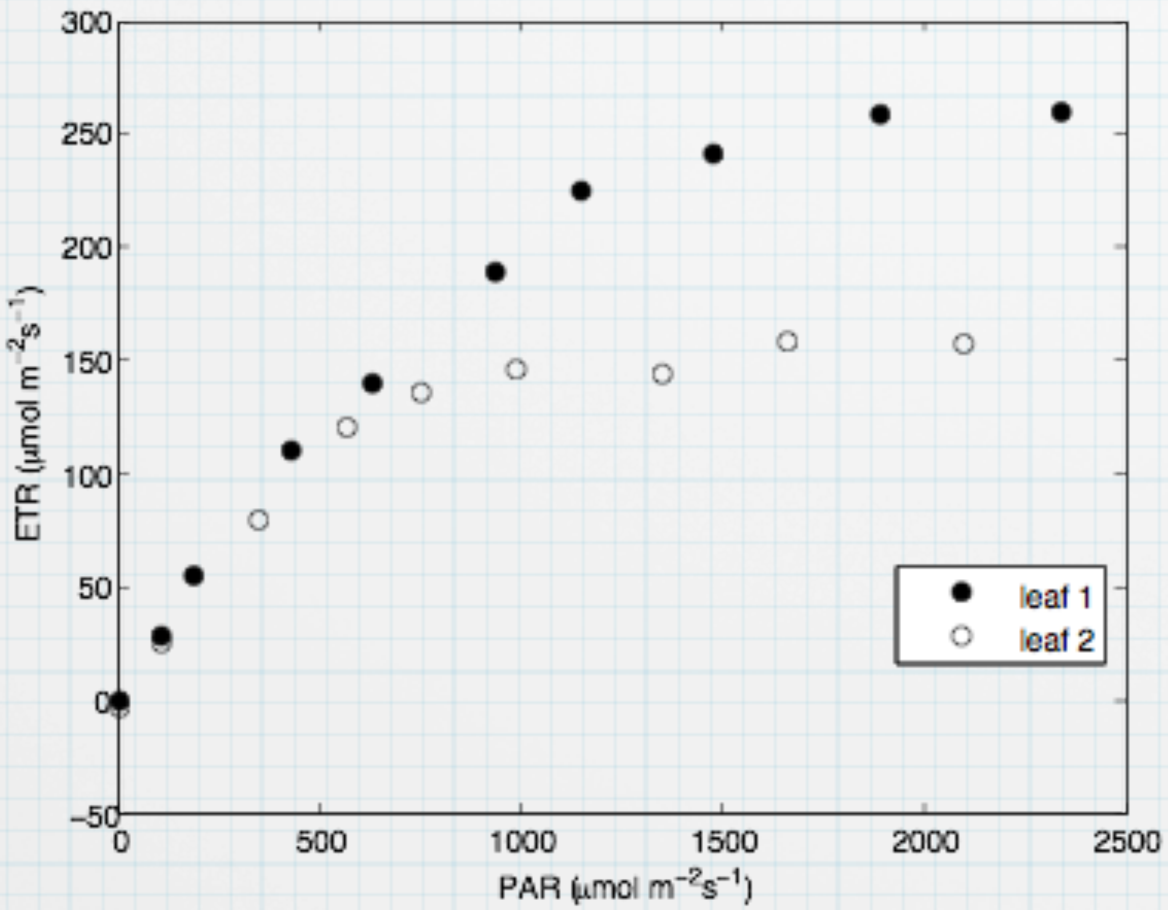


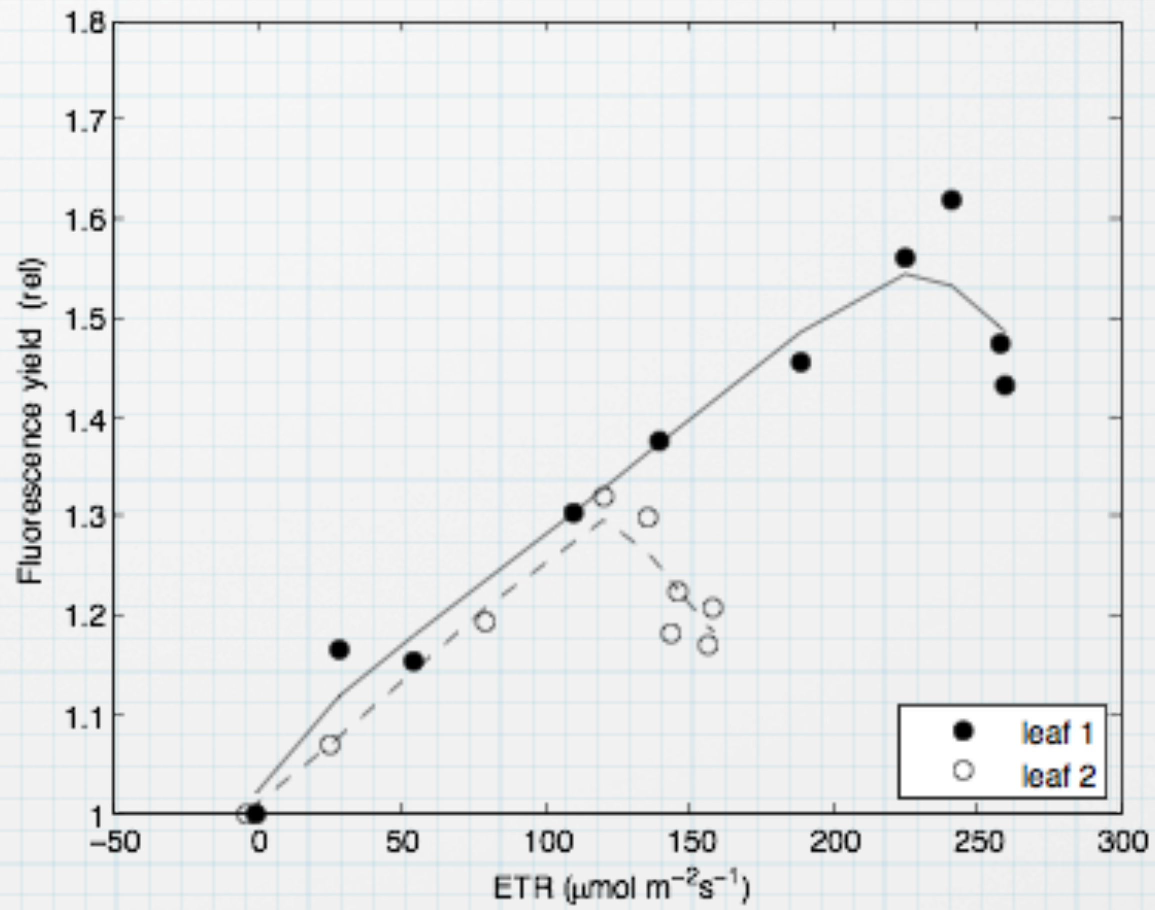


Schlau-Cohen, G. S., Bockenhauer, S., Wang, Q., & Moerner, W. E. (2014). Single-molecule spectroscopy of photosynthetic proteins in solution: exploration of structure–function relationships. Chemical Science, 5(8), 2933. http://doi.org/10.1039/c4sc00582a

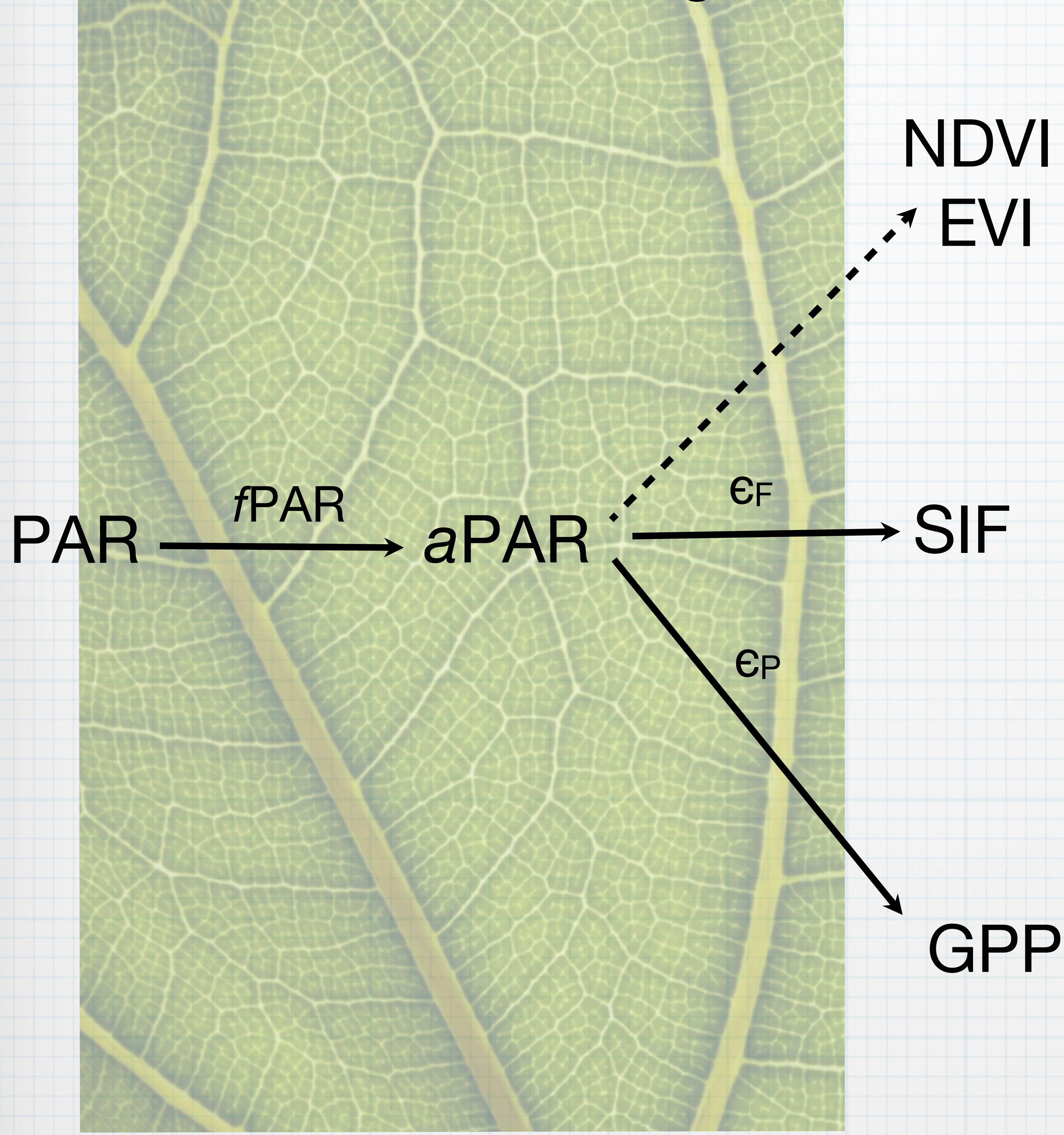


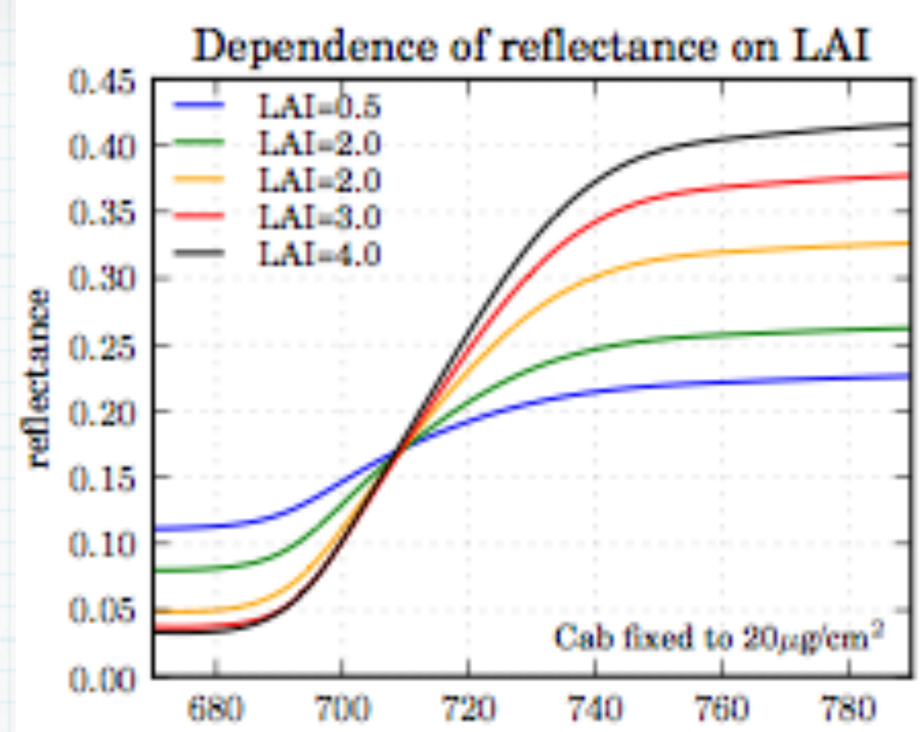
Fluorescence *vs.* the electron transport rate (ETR)

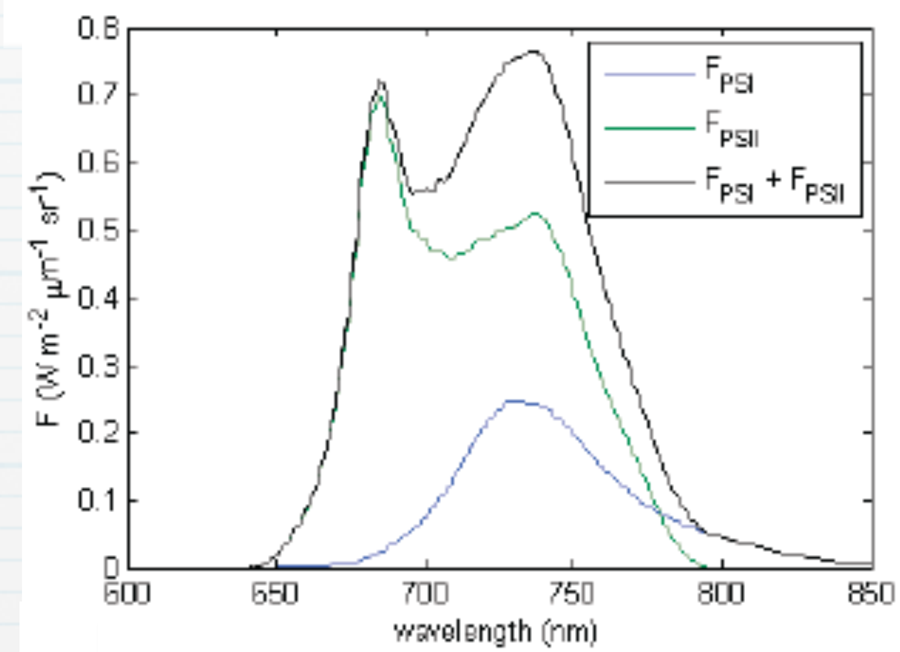


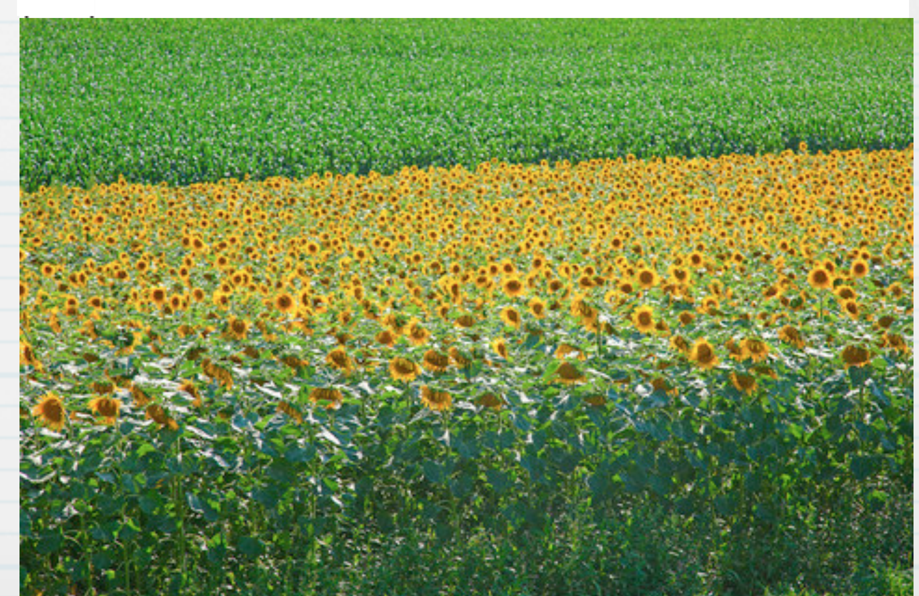


GPP, SIF & Veg. Indices









GPP and Solar Induced Fluorescence (SIF)

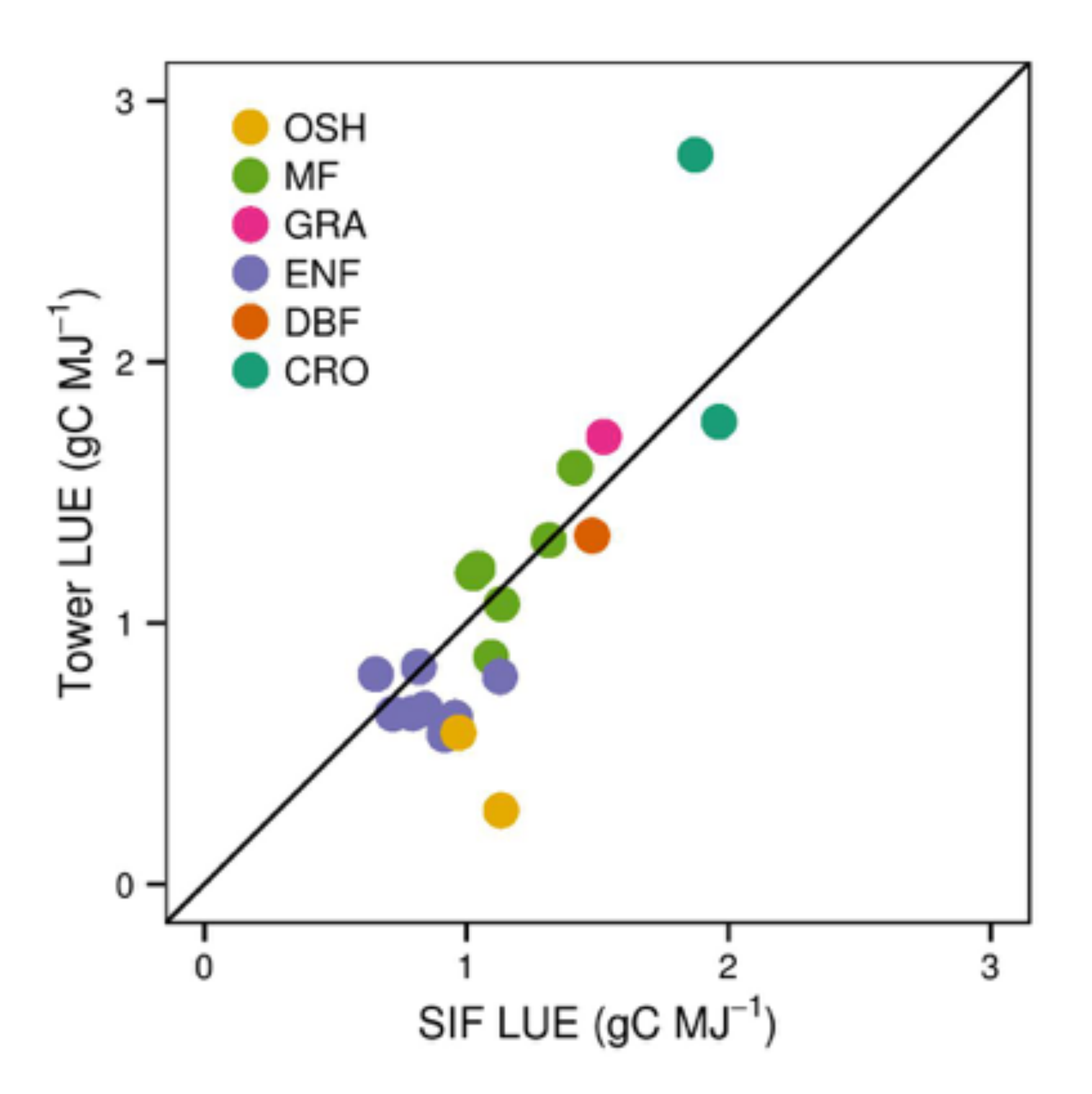
$$aPAR = f(\mathrm{NDVI}) \times \mathrm{PAR}$$

$$\mathrm{GPP} = a\mathrm{PAR} \times \epsilon_P$$

$$\mathrm{SIF} = a\mathrm{PAR} \times \epsilon_F$$

$$\mathrm{GPP} = \mathrm{SIF} \times \frac{\epsilon_P}{\epsilon_F}$$

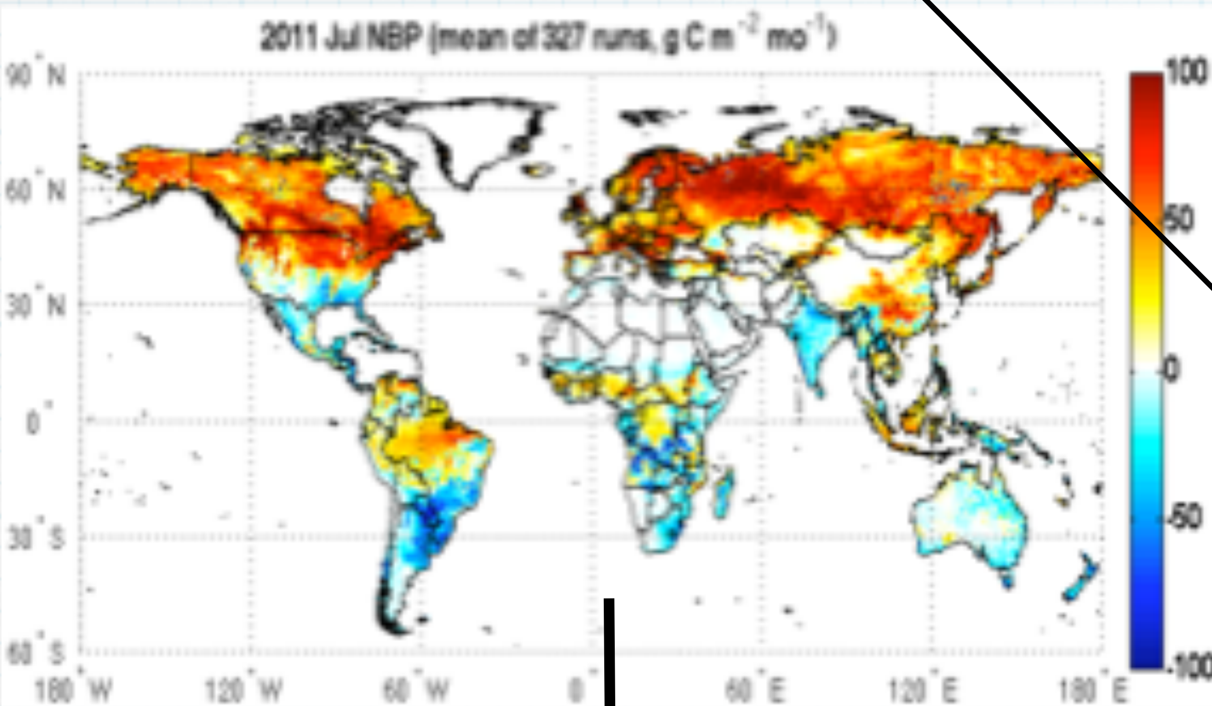
ε_P *vs.* ε_F at Flux Towers



Grayson Badgley, John Kimball et al.

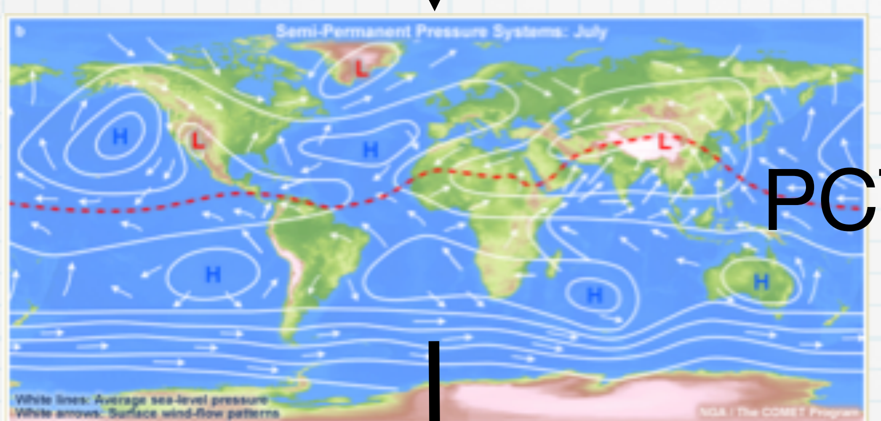
CASA, carbon cycle model

G. James Collatz, Joanna Joiner, Stephan R Kawa et al.

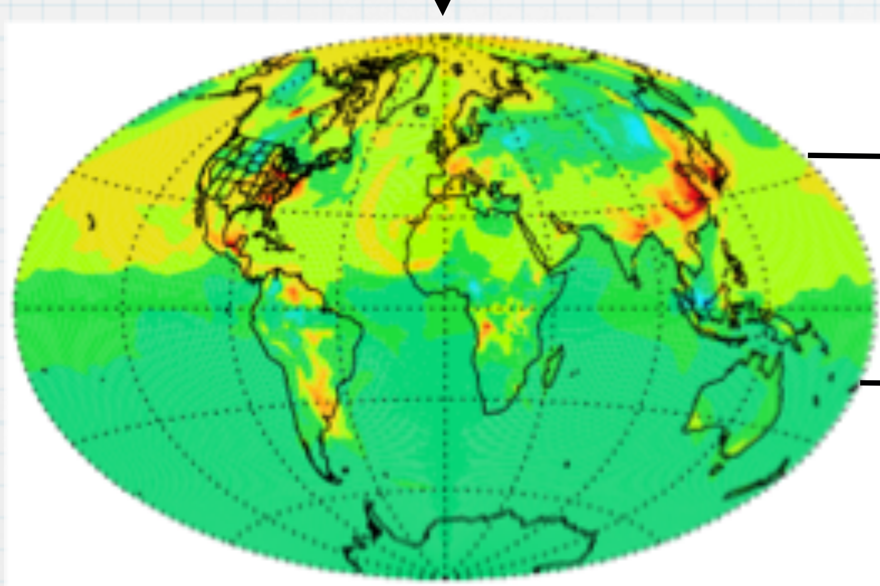


$$\begin{cases} \text{NPP} = \text{PAR} \cdot \text{FPAR} \cdot \text{LUE} \\ \qquad \text{where} \;\; \text{LUE} = f(\text{T}, \text{P}/\text{PET}) \\ \\ \text{NPP} = k \cdot \text{SIF} \end{cases}$$

$$\text{where}: \quad k = \frac{\overline{\text{NPP}_{max}}}{\overline{\text{SIF}_{max}}}$$

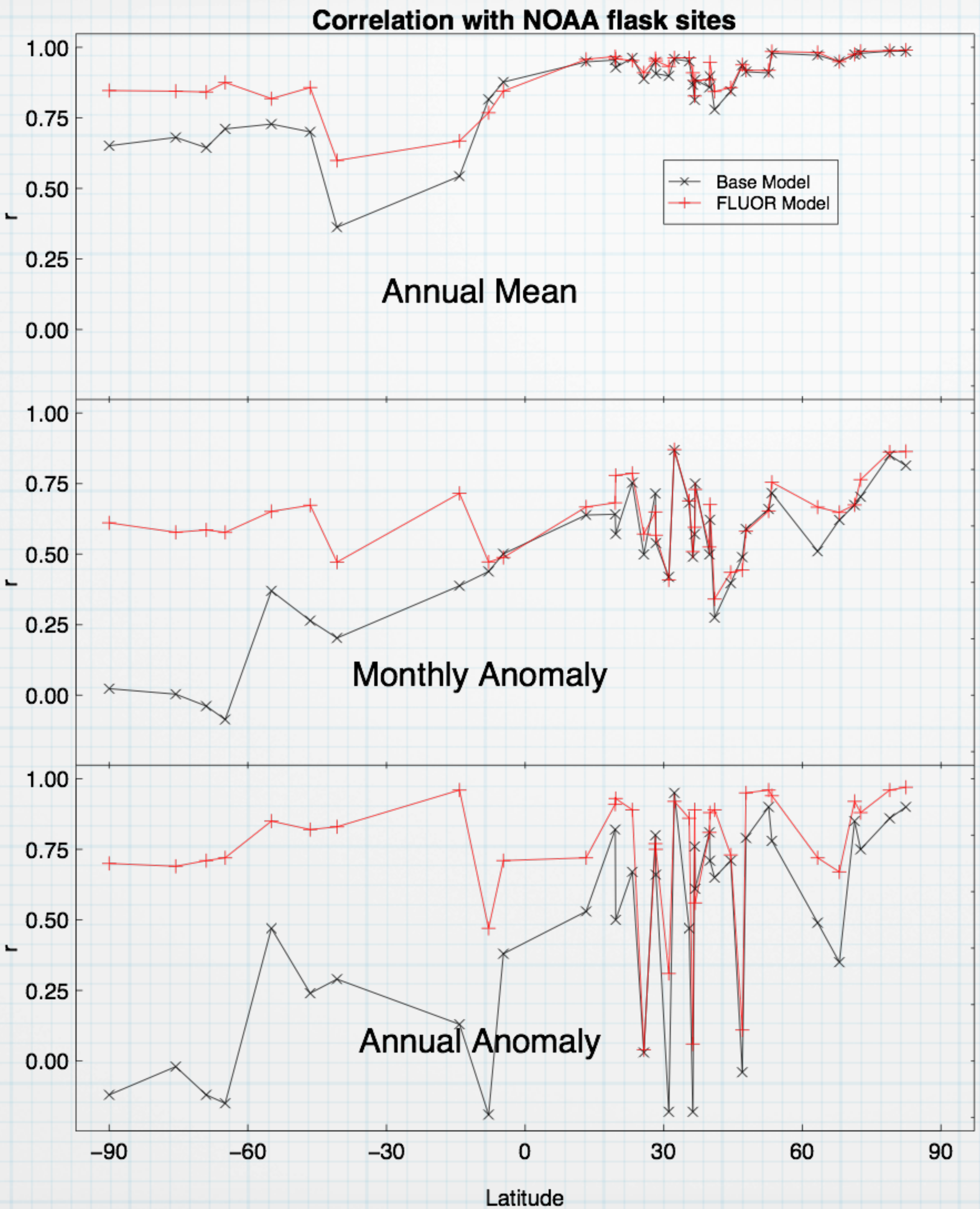


PCTM, atmos. transport model



Baseline model $[CO2]_{i,j}$

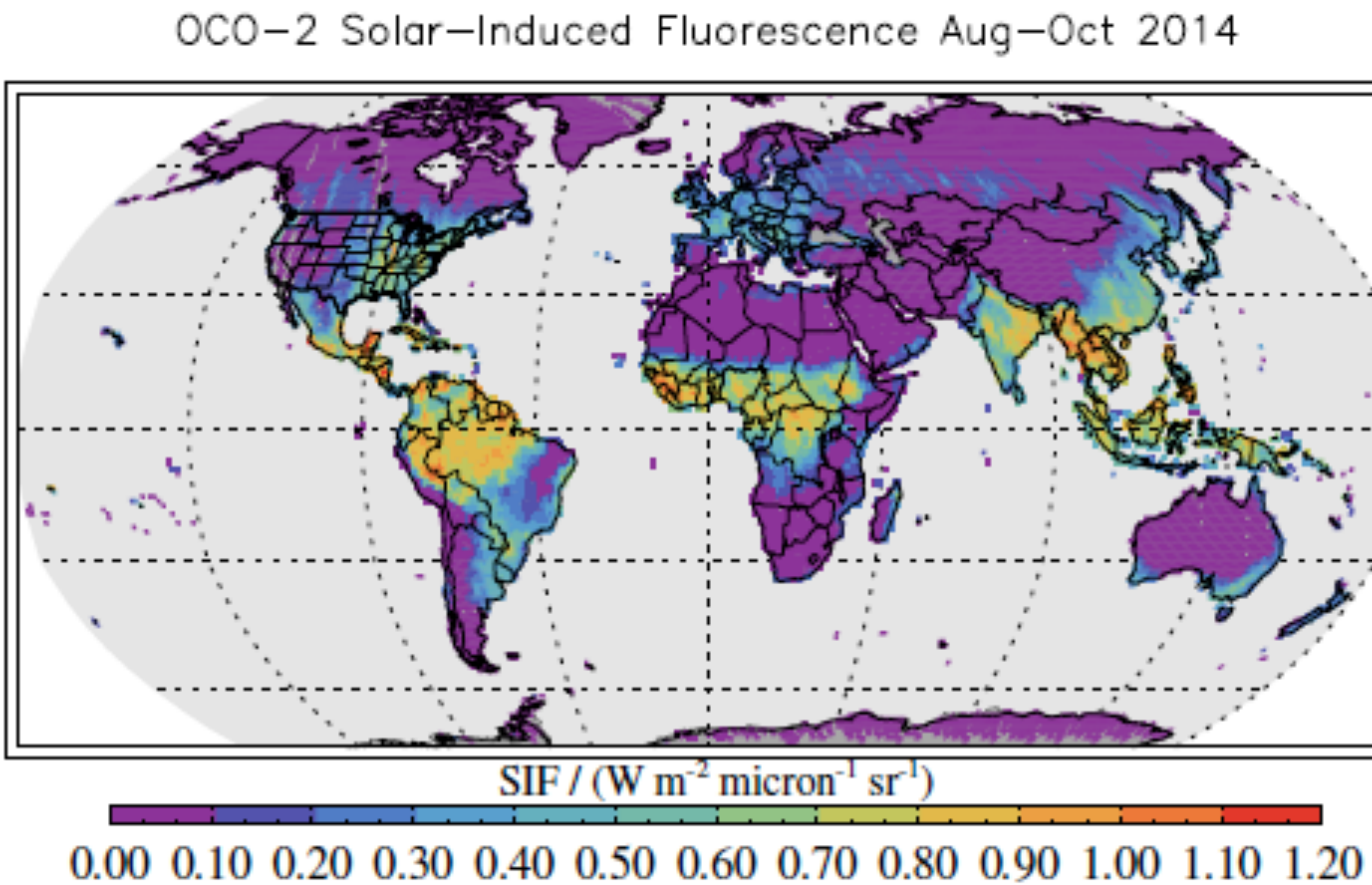
Flour. model $[CO2]_{i,j}$



Correlation with NOAA flask sites
Base Model
FLUOR Model
Annual Mean
Monthly Anomaly
Annual Anomaly
r
1.00
0.75
0.50
0.25
0.00
-90
-60
-30
0
30
60
90
Latitude

Jim Collatz

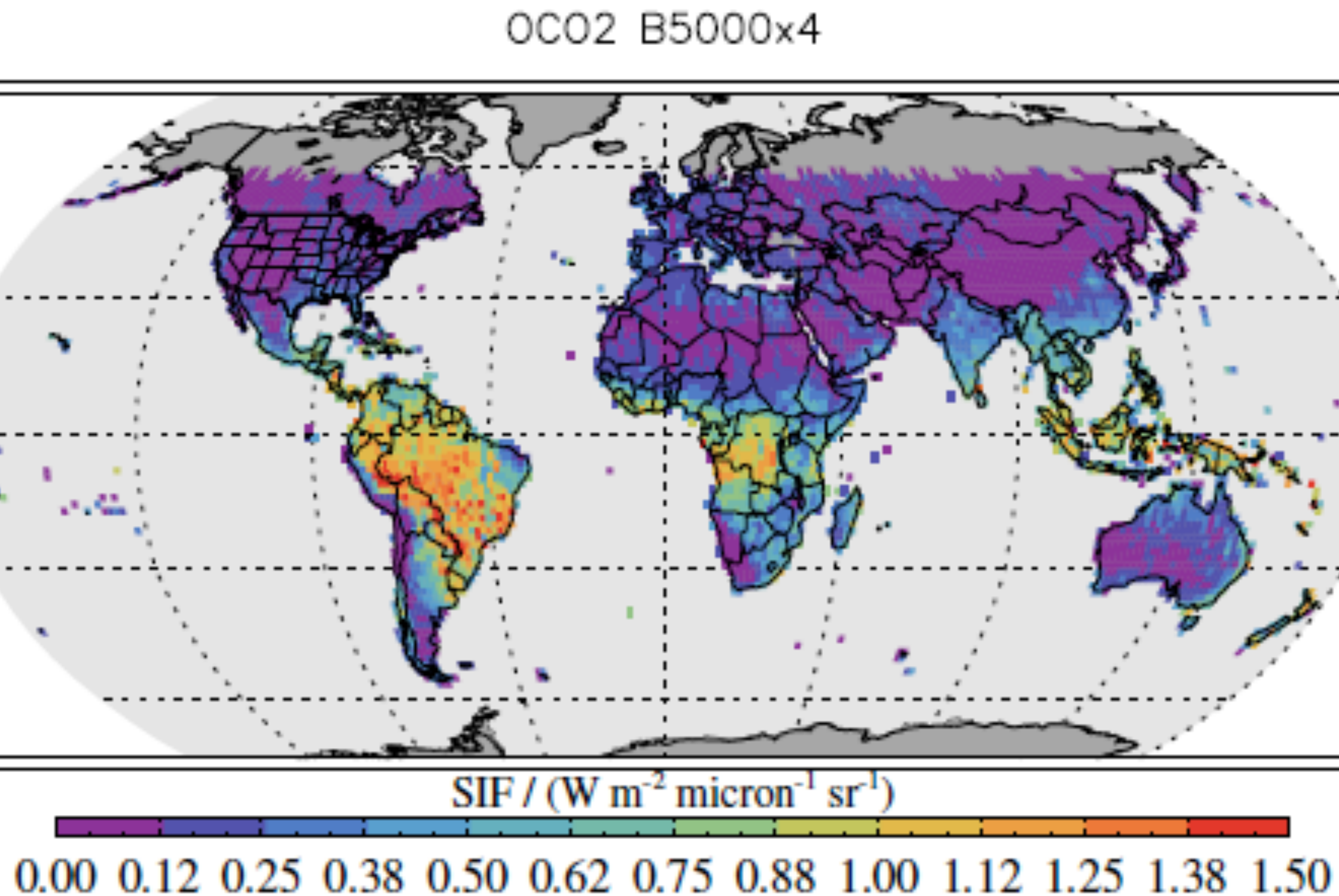
3–month OCO–2 average (all modes)



still tentative. . .

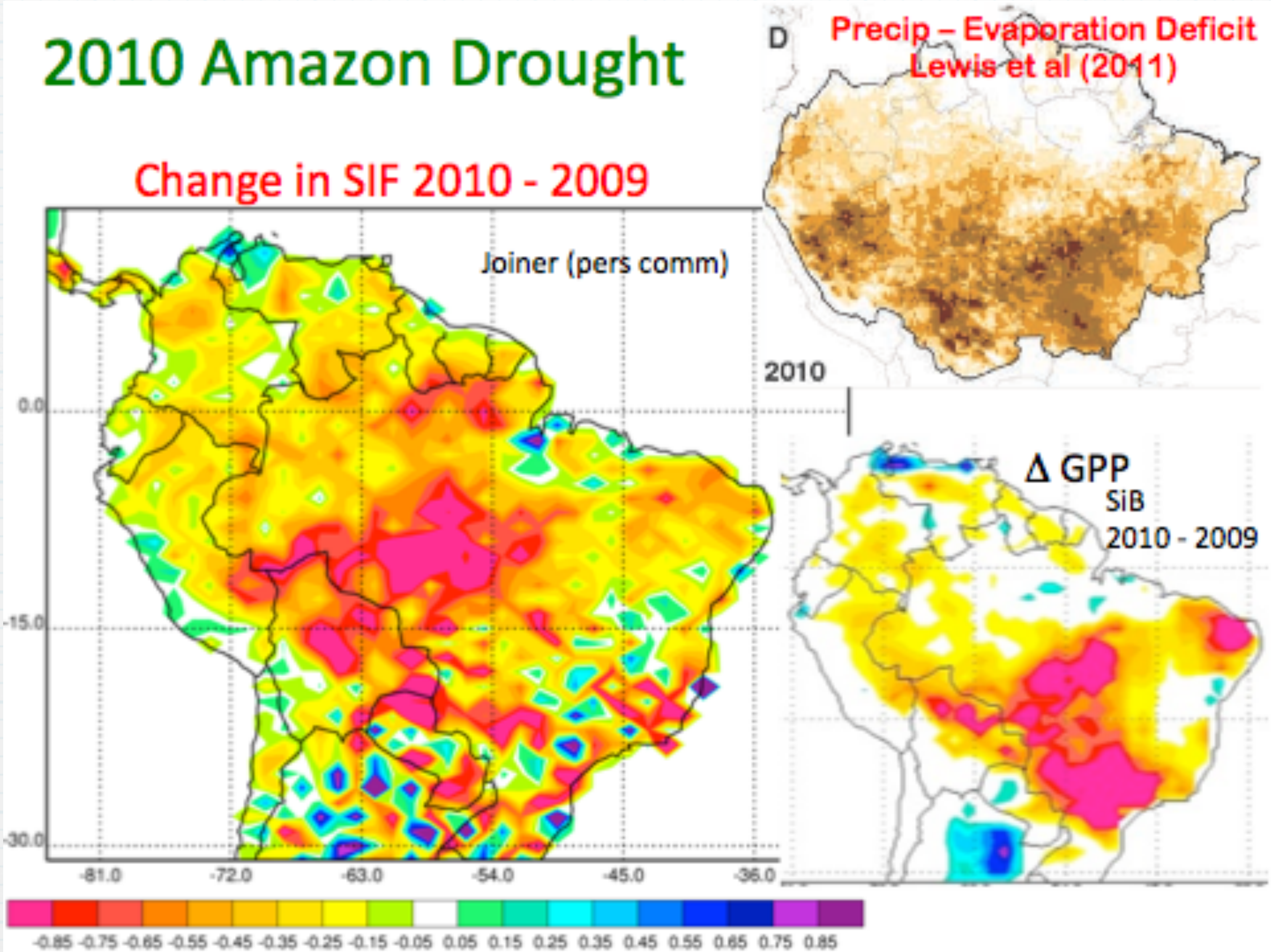
Christian Frankenberg

Latest B5000 dataset (Nov / Dec. 2014)

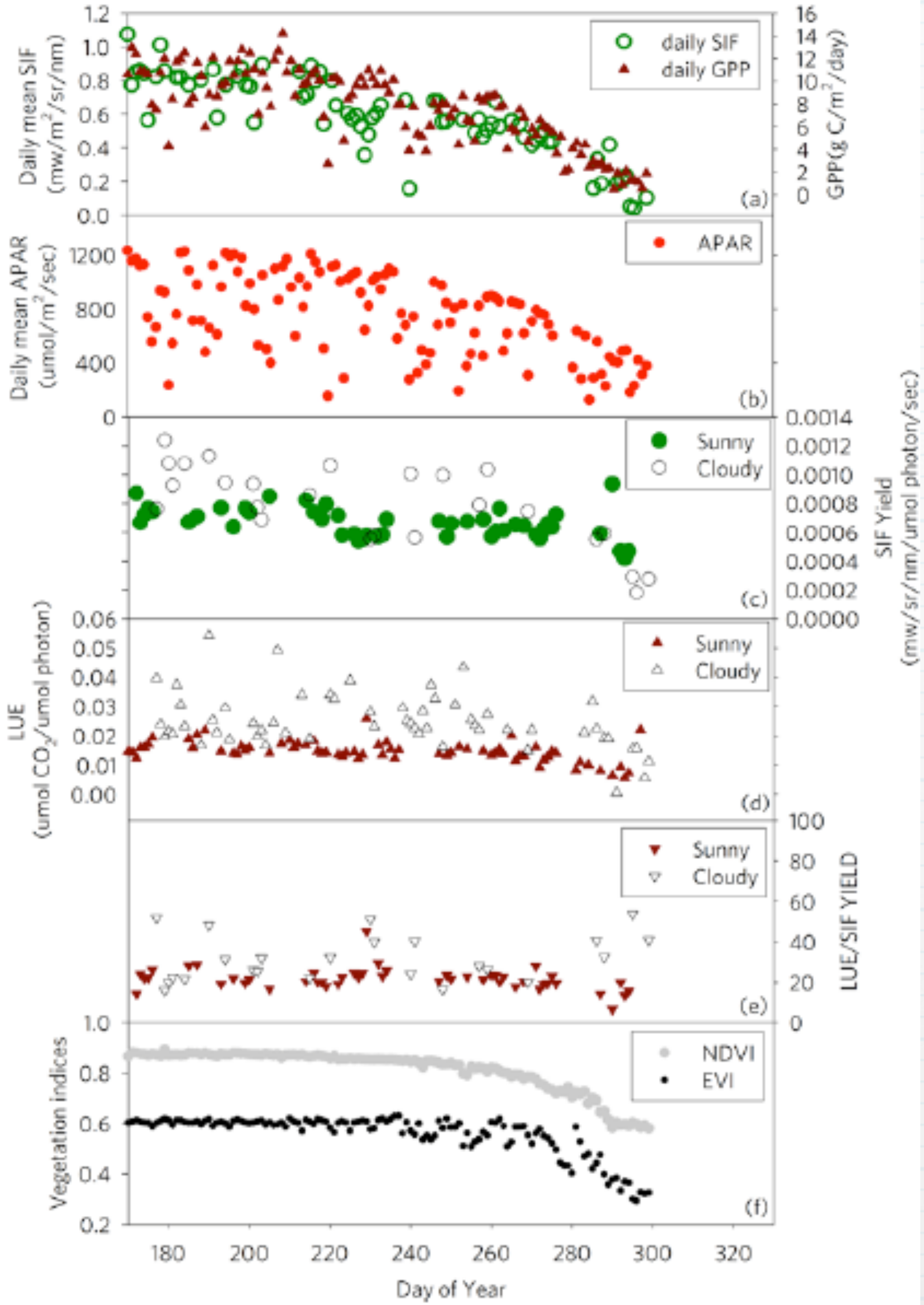


still tentative. . .

Fluorescence Responds to Drought

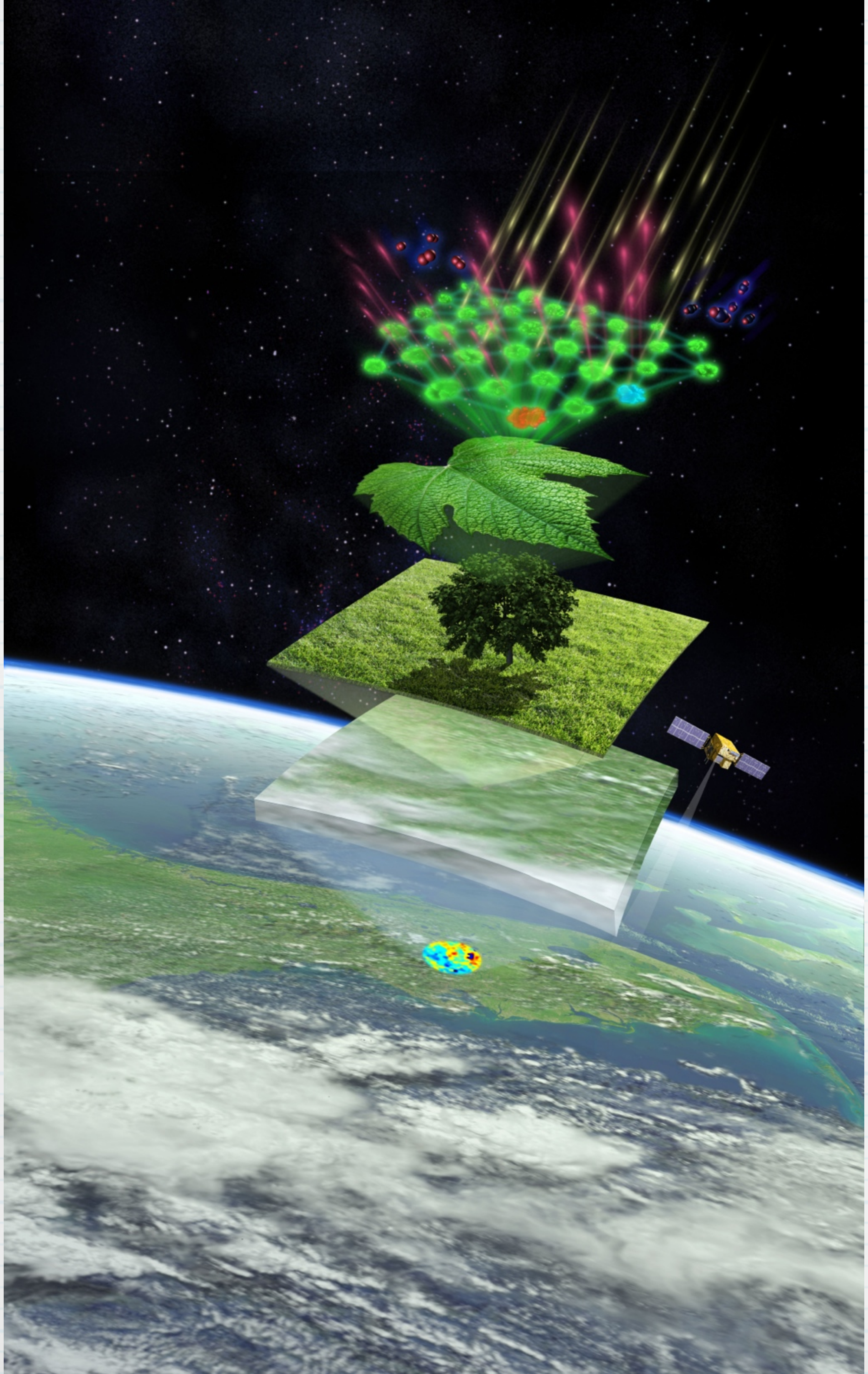


Ian Baker, Joanna Joiner & Scott Denning



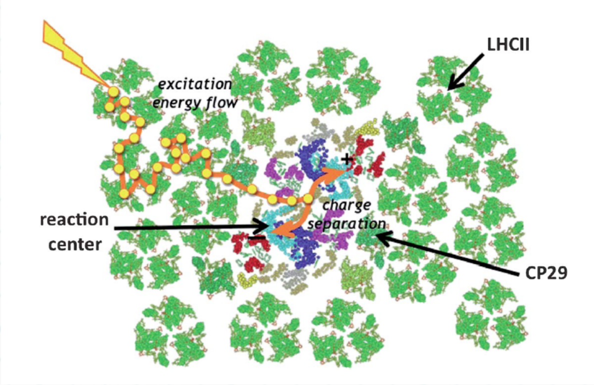
Studies of fluorescence (SIF) at HF flux tower.

Yang, X., Tang, J., Mustard, J. F., Lee, J.-E., Rossini, M., Joiner, J., et al. (2015). Solar-induced chlorophyll fluorescence correlates with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous forest. Geophysical Research Letters, n/a–n/a. http://doi.org/10.1002/2015GL063201

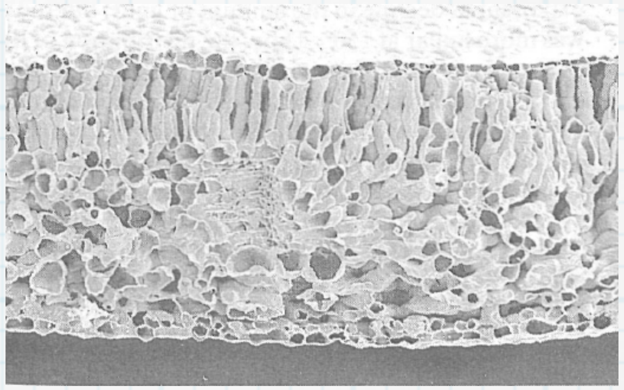


SIF

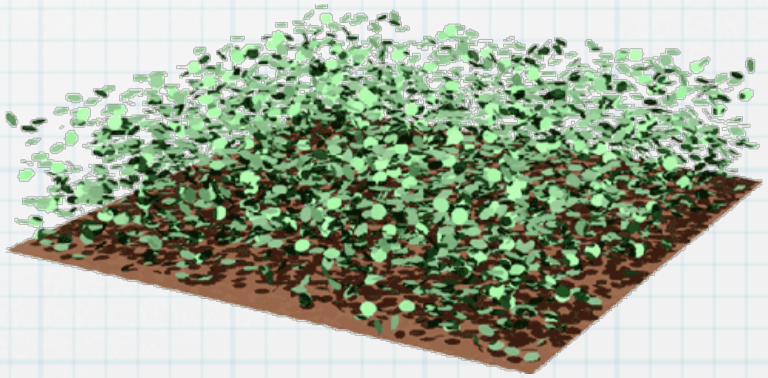
We need to consider hierarchy of scales



chloroplast membrane

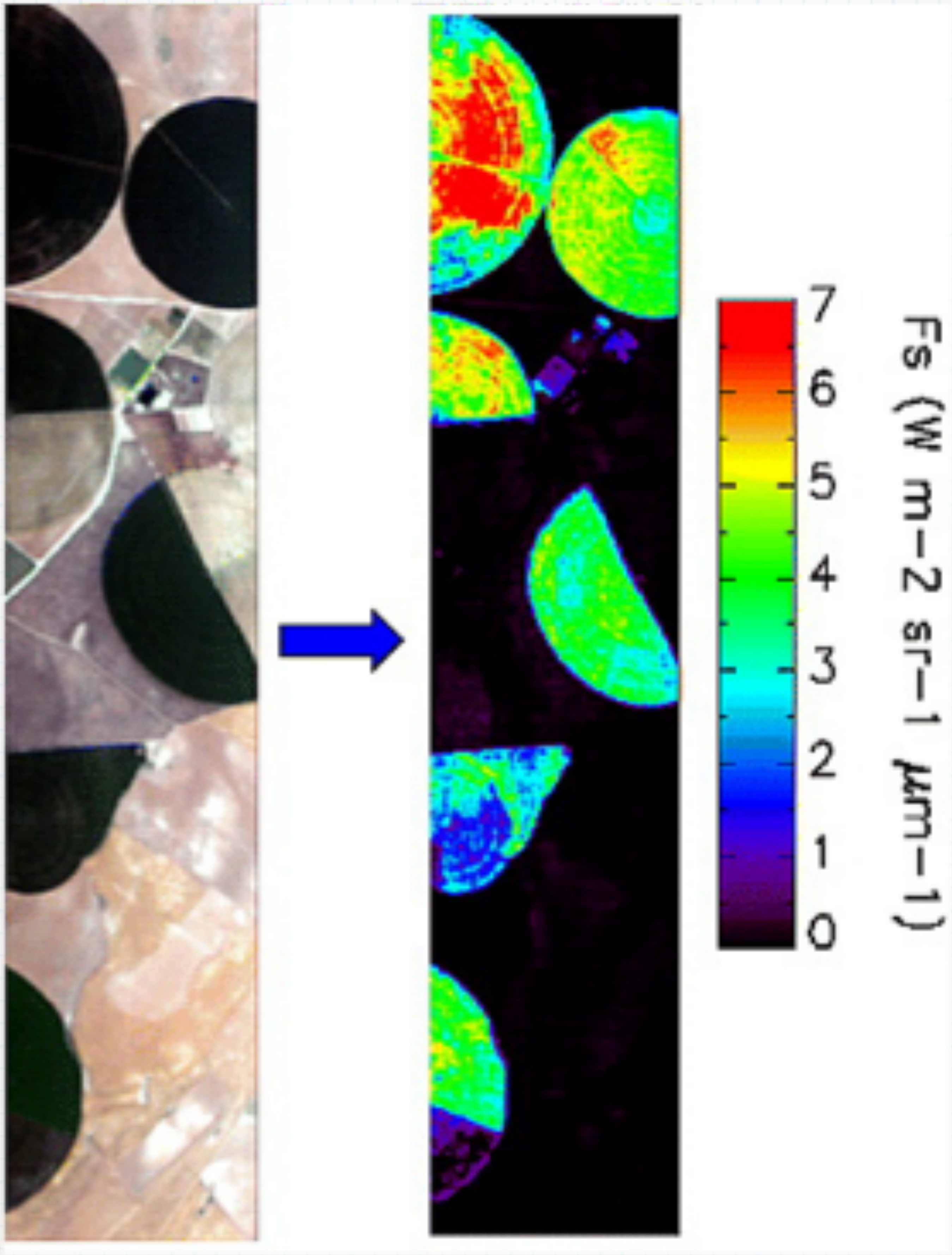


leaf



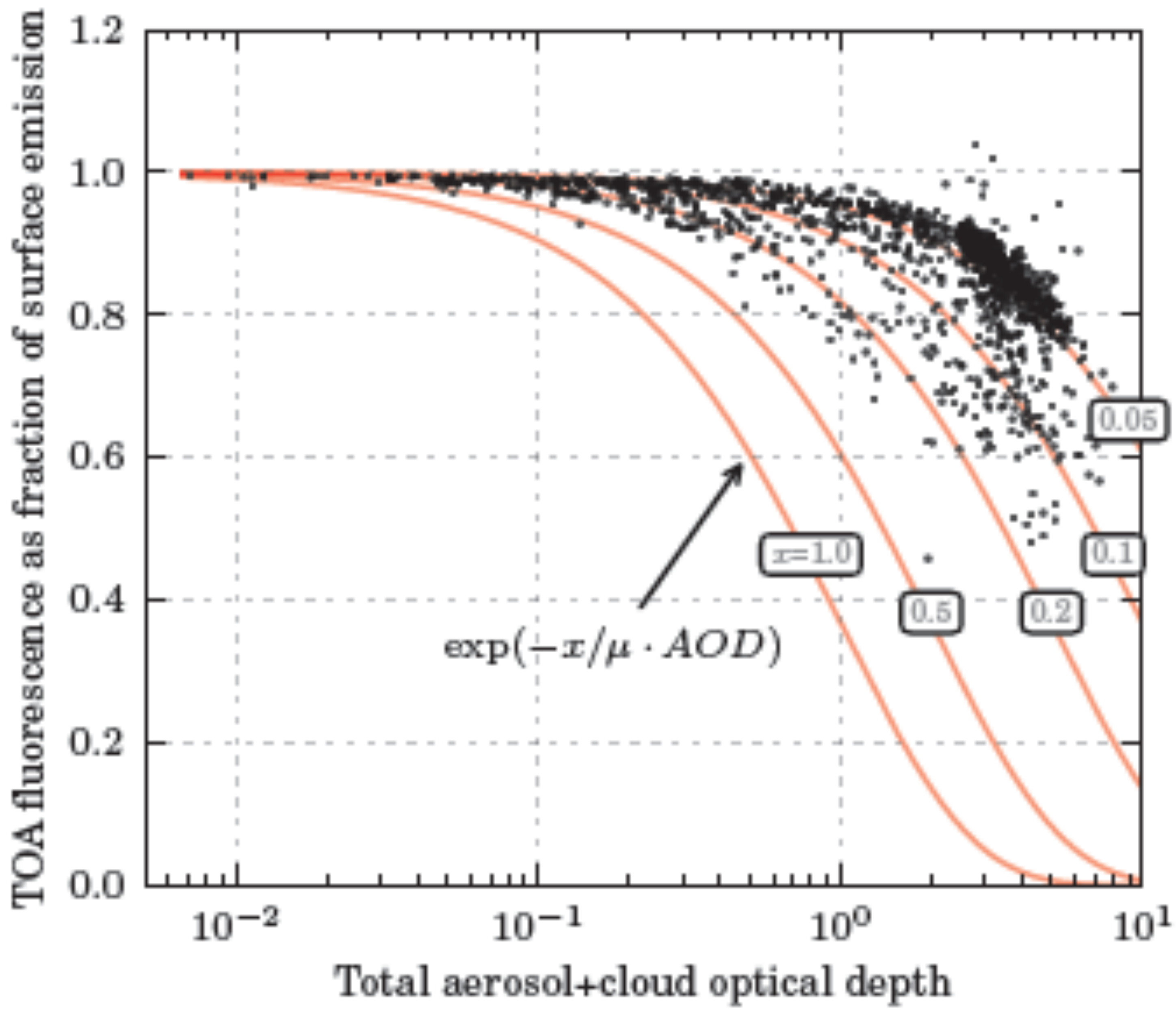
canopy

but understanding the mechanism is a critical first step.

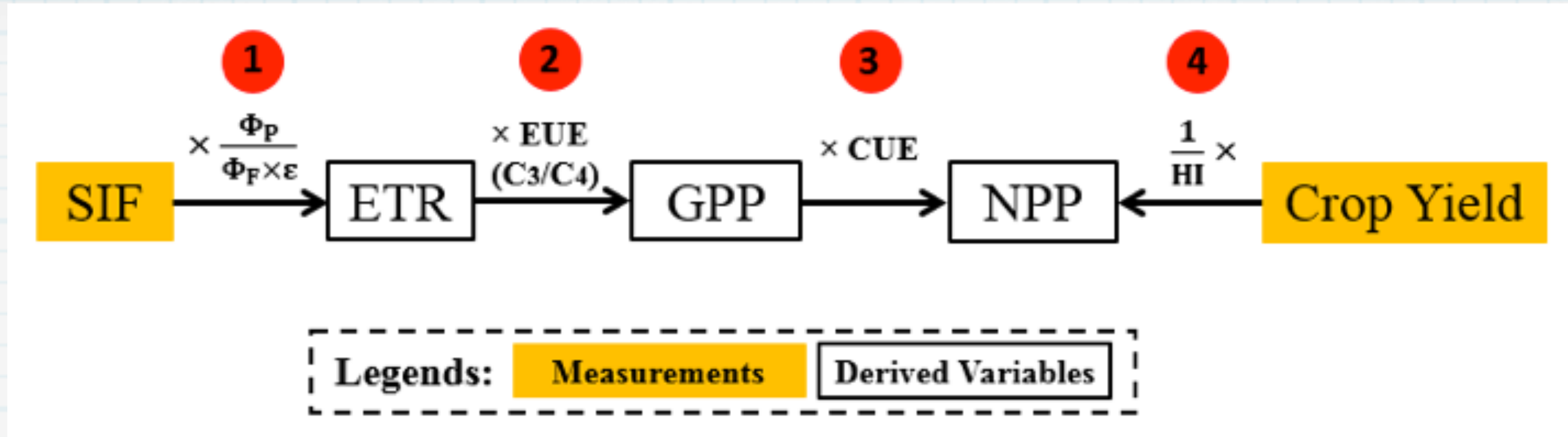


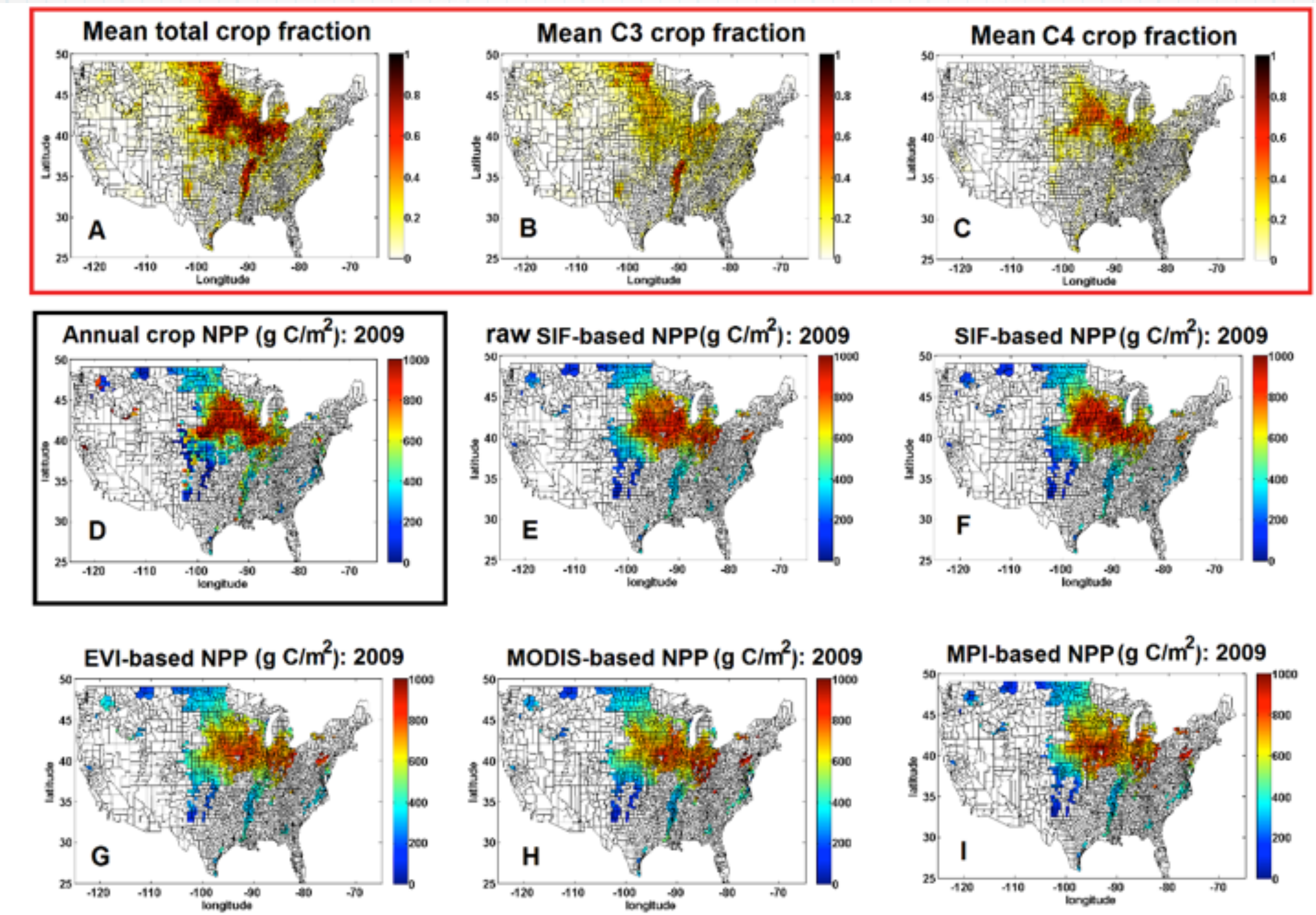
Fs (W m-2 sr-1 μm-1)
0
1
2
3
4
5
6
7

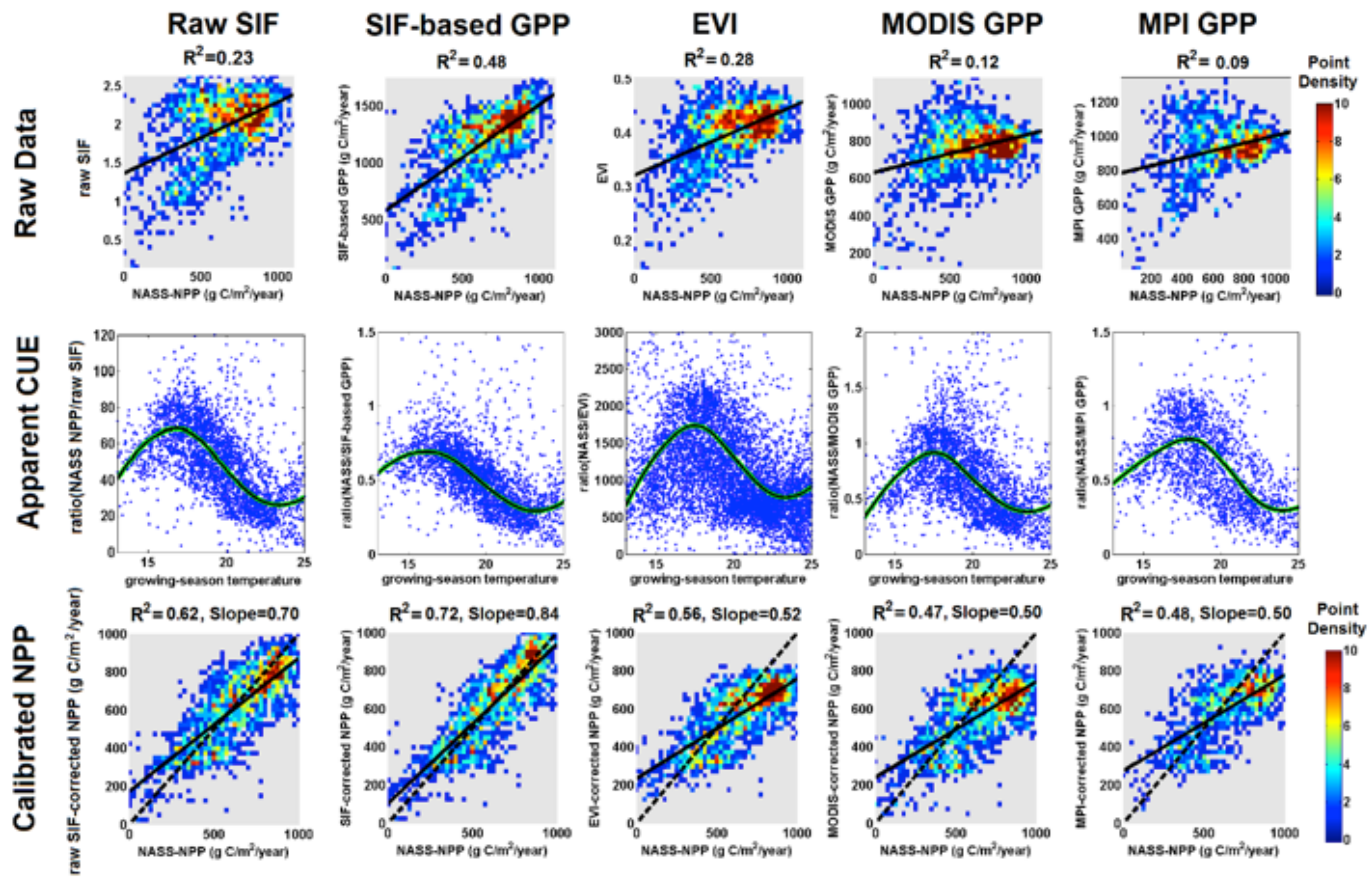
The scattering impact, added advantage of fluorescence (esp. in tropics)



Frankenberg et al, AMT (2012)


1
2
3
4
× Φ_P / (Φ_F×ε)
× EUE (C3/C4)
× CUE
1/HI ×
SIF
ETR
GPP
NPP
Crop Yield
Legends:
Measurements
Derived Variables


Mean total crop fraction
Mean C3 crop fraction
Mean C4 crop fraction
A
B
C
Annual crop NPP (g C/m2): 2009
raw SIF-based NPP(g C/m2): 2009
SIF-based NPP(g C/m2): 2009
D
E
F
EVI-based NPP (g C/m2): 2009
MODIS-based NPP (g C/m2): 2009
MPI-based NPP (g C/m2): 2009
G
H
I
Latitude
Longitude
latitude
longitude


Raw SIF
SIF-based GPP
EVI
MODIS GPP
MPI GPP
Raw Data
Apparent CUE
Calibrated NPP
R²=0.23
R²= 0.48
R²= 0.28
R²= 0.12
R²= 0.09
Point Density
raw SIF
SIF-based GPP (g C/m²/year)
EVI
MODIS GPP (g C/m²/year)
MPI GPP (g C/m²/year)
NASS-NPP (g C/m²/year)
ratio(NASS NPP/raw SIF)
ratio(NASS/SIF-based GPP)
ratio(NASS/EVI)
ratio(NASS/MODIS GPP)
ratio(NASS/MPI GPP)
growing-season temperature
R²=0.62, Slope=0.70
R²=0.72, Slope=0.84
R²=0.56, Slope=0.52
R²=0.47, Slope=0.50
R²=0.48, Slope=0.50
raw SIF-corrected NPP (g C/m²/year)
SIF-corrected NPP (g C/m²/year)
EVI-corrected NPP (g C/m²/year)
MODIS-corrected NPP (g C/m²/year)
MPI-corrected NPP (g C/m²/year)

$$\left(2+1.5\beta/\alpha\right)V_c\left[V_{G_{max}}\left(1-V_c/\alpha\right)+\frac{V_{N_{max}}}{1+K_I/I}\right] = V_{G_{max}}\left(1-V_c/\alpha\right.$$

$$V_c^2\left(-\frac{V_{G_{max}}}{\alpha}\left(2+1.5\beta/\alpha\right)\right)+V_c\left(\left(2+1.5\beta/\alpha\right)\left(V_{G_{max}}+\frac{V_{N_{max}}}{1+K_I/I}\right)+\frac{V_{G_{max}}}{\alpha}\right.$$

x b.s by $\frac{(1+K_I/I)}{-V_{G_{max}}}$

$$-V_{G_{max}}\frac{V_{N_{max}}}{1+K_I/I}\ 0$$

$$\frac{V_c^2}{\alpha^2}\left(2\alpha+1.5\beta\right)\left(1+K_I/I\right)-\frac{V_c}{\alpha}\left[\left(2\alpha+1.5\beta\right)\left(1+K_I/I\right)+\frac{V_{N_{max}}}{V_{G_{max}}}\right)+\ldots$$

$$+\ldots = 0$$

$$+V_{N_{max}}$$

$$\frac{V_c^2}{\alpha^2}\left(2\alpha+1.5\beta\right)\left(1+K_I/I\right)-\frac{V_c}{\alpha}\left[\left(2\alpha+1.5\beta\right)\left(1+\frac{K_I}{I}+\frac{V_{N_{max}}}{V_{G_{max}}}\right)+V_{N_{max}}\right.$$

$$+V_{N_{max}}$$

$$V_0 = \frac{\beta}{\alpha}V_c$$

$$\frac{V_c}{\alpha} = \frac{\left[\left(2\alpha+1.5\beta\right)\left(1+\frac{K_I}{I}+\frac{V_{N_{max}}}{V_{G_{max}}}\right)+V_{N_{max}}\right] \pm \sqrt{\{\ \}^2-4\left(2\alpha+1.5\beta\right)(1+\ldots}}{2\left(2\alpha+1.5\beta\right)\left(1+K_I/I\right)}$$

1302 $I \equiv I$, $K_I \equiv I1$, $V_{N_{MAX}} \equiv N$, $V_{G_{max}} \equiv P\emptyset$

P 1629x

$\alpha \equiv VG$, $\beta \equiv V\emptyset$

N 146x 6

remember change 130, 140, 270

$V_c \equiv WG$, $V_0 \equiv W\emptyset$

130 I = 2000
135 I1 = 1000
140 P = 430
145 N = 39