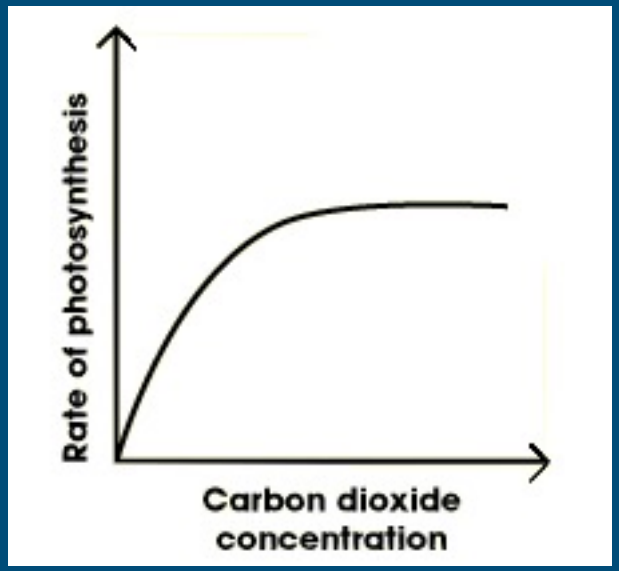
The historic effect of CO_2 on global photosynthesis

Trevor F. Keenan
Asst. Professor, UC Berkeley
Faculty Scientist, Lawrence Berkeley National Lab

Do we expect an effect of CO_2 on photosynthesis?

Do we expect an effect of CO_2 on photosynthesis?



Do we expect an effect of CO_2 on photosynthesis?

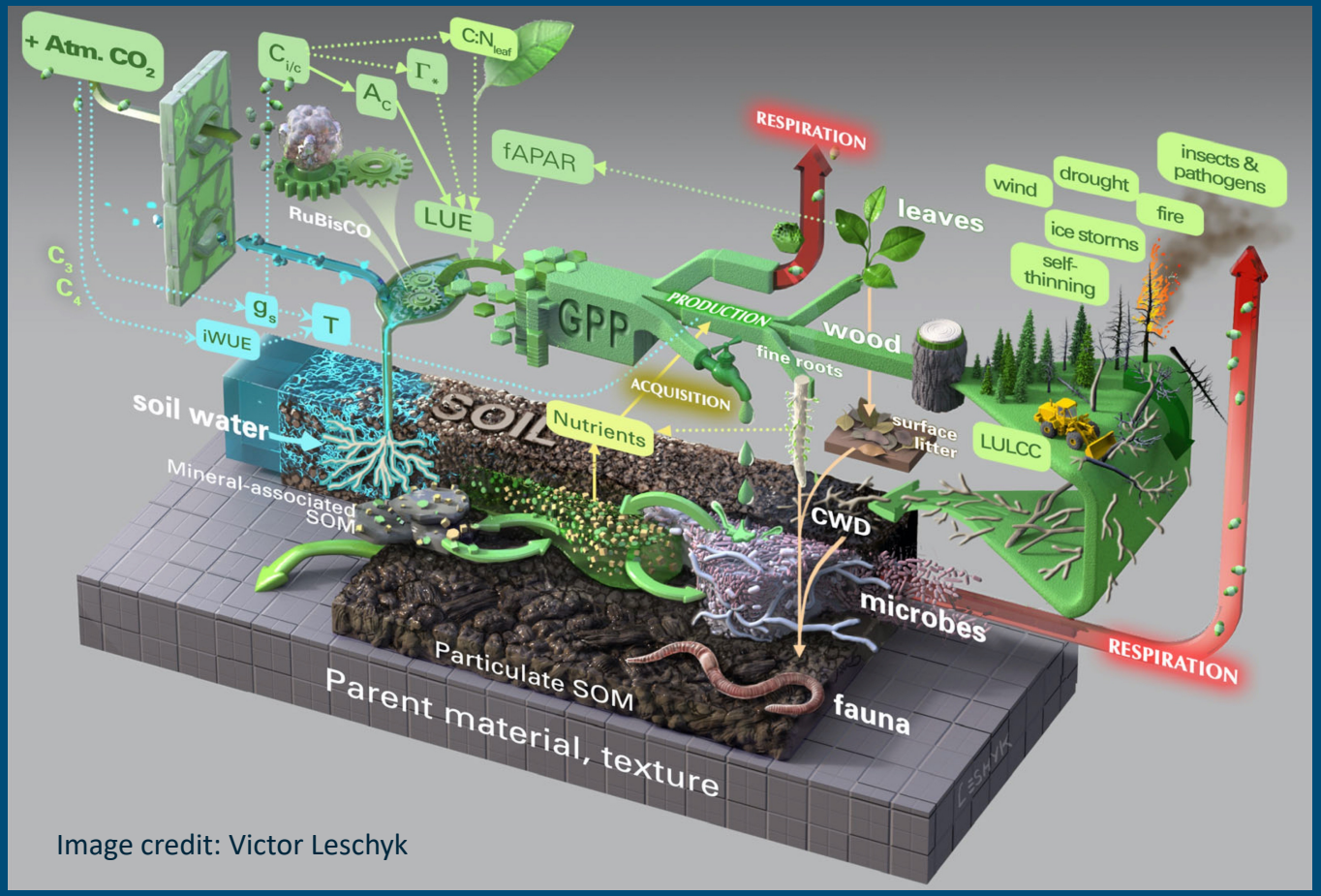
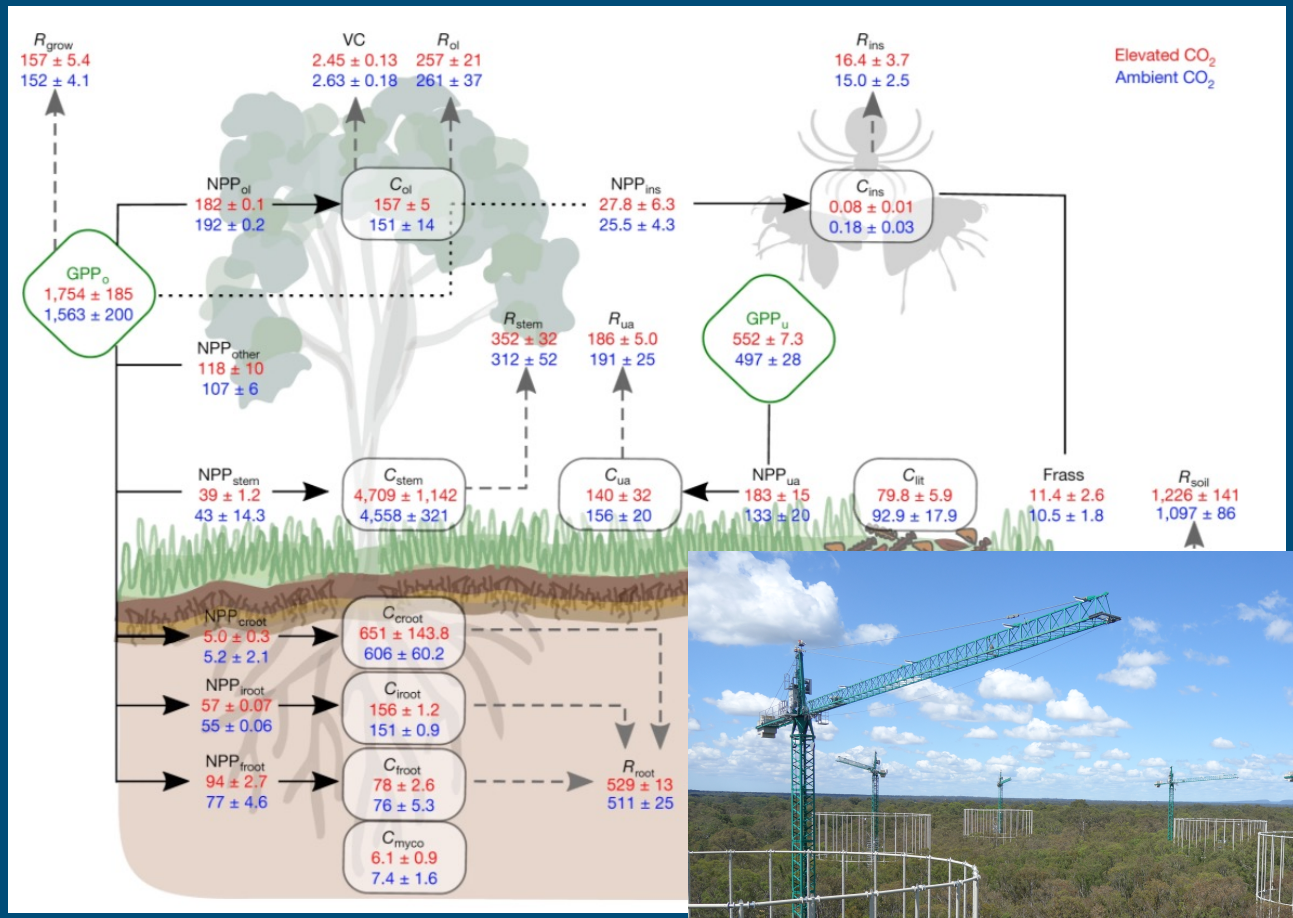


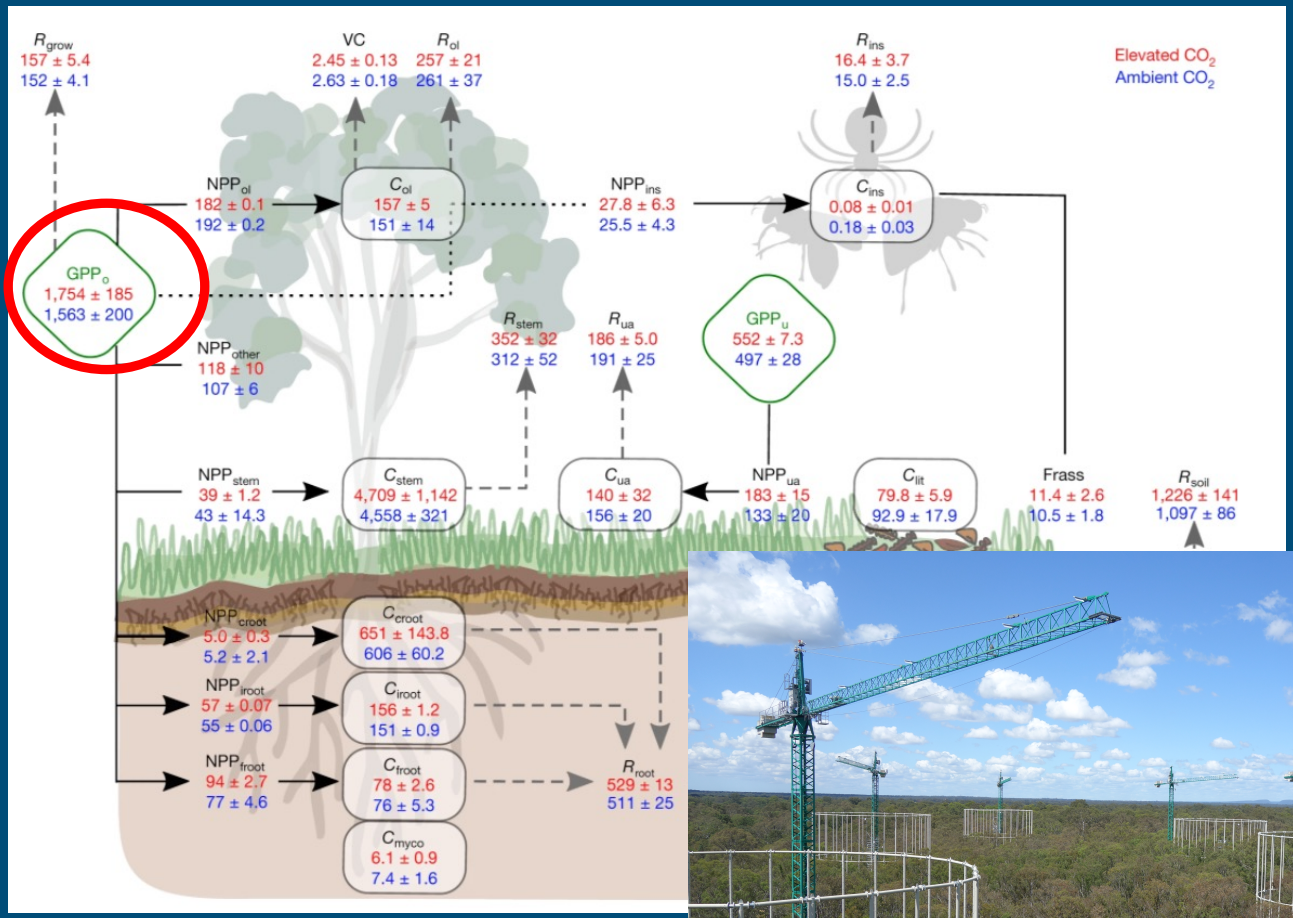
Image credit: Victor Leschyk



Jiang et al., 2020

12% GPP increase

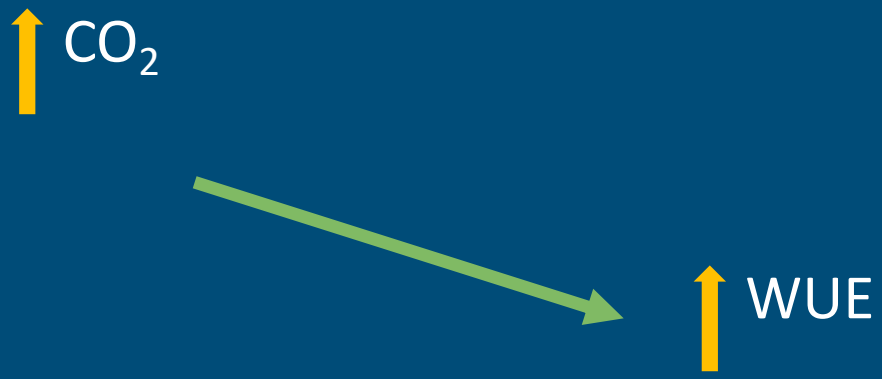
for a 35% increase in CO_2



Jiang et al., 2020

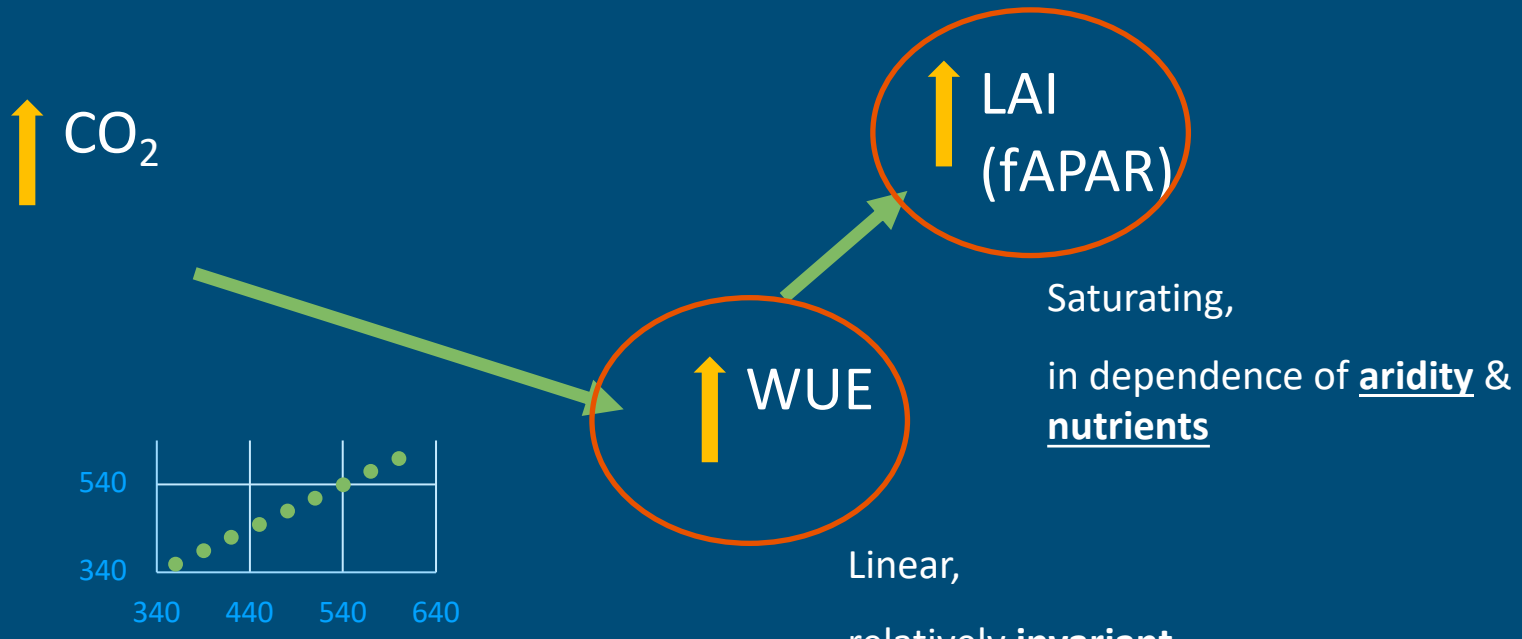
Expected effect of CO_2 on the carbon cycle

Expected effect of CO_2 on the carbon cycle

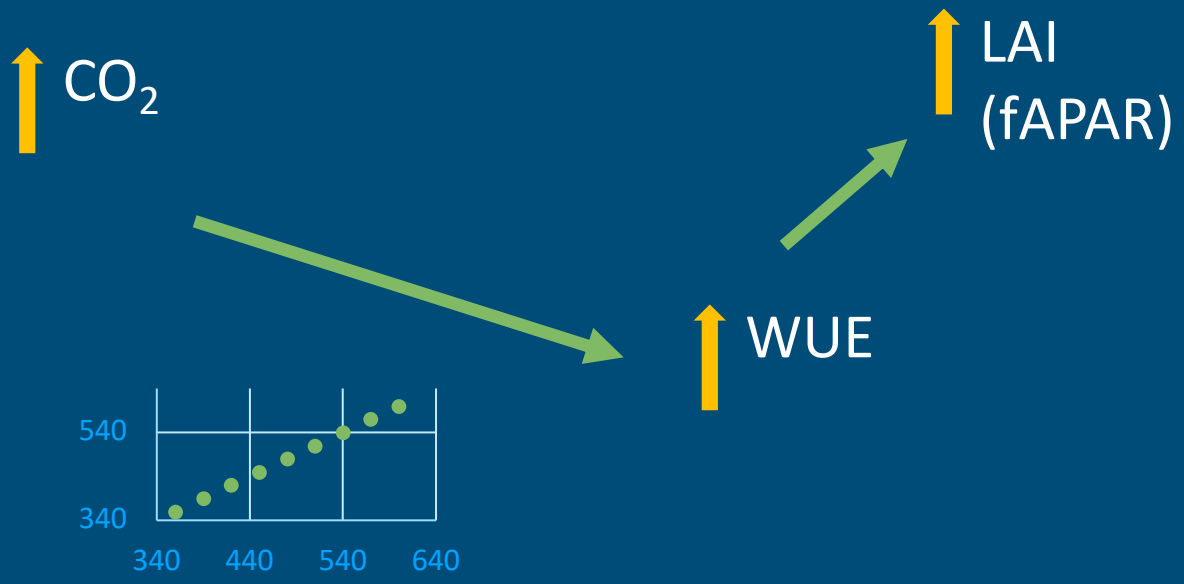


Expected effect of CO_2 on the carbon cycle

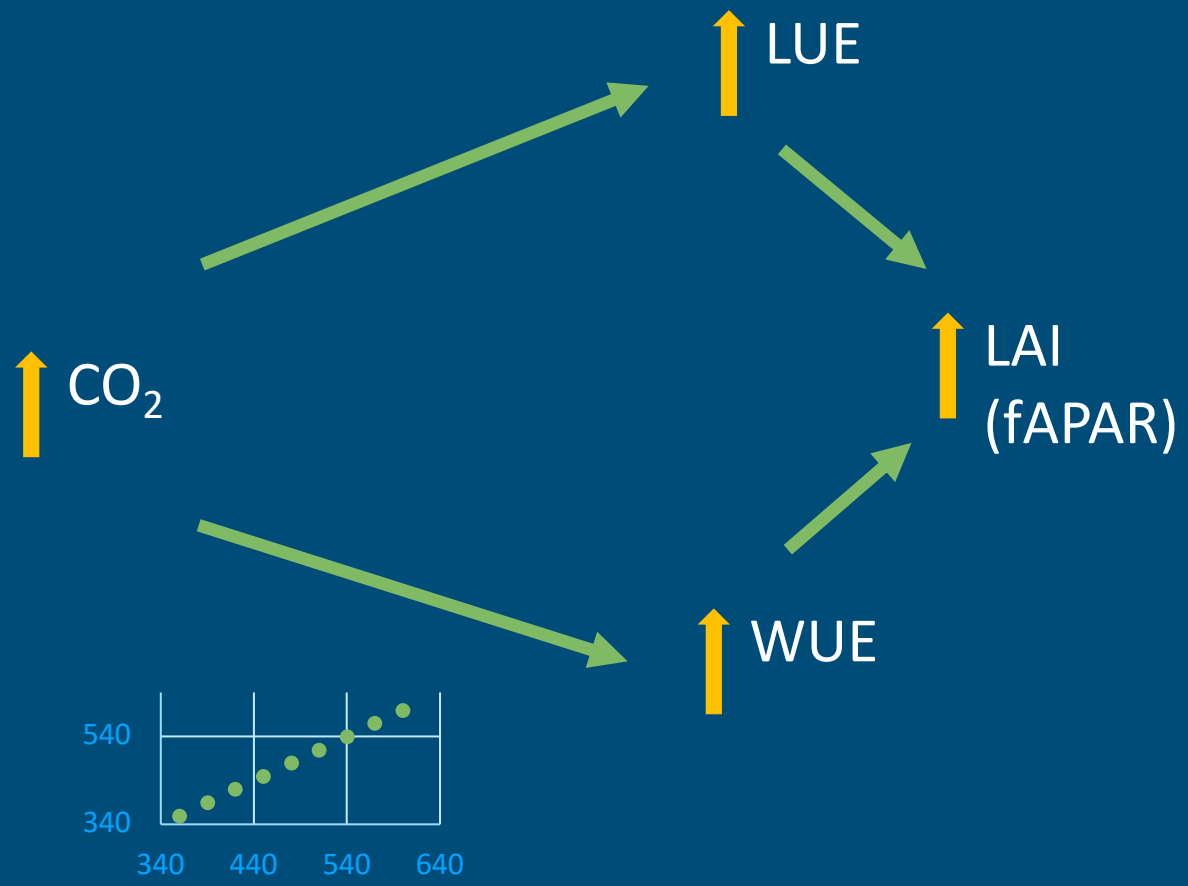
Expected effect of CO_2 on the carbon cycle



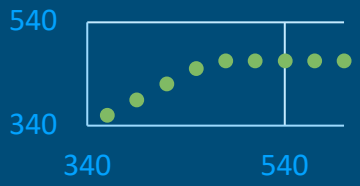
Expected effect of CO_2 on the carbon cycle



Expected effect of CO_2 on the carbon cycle



Expected effect of CO_2 on the carbon cycle



Saturating,

In dependence of **CO_2**

Modified by **temperature**

↑ LUE

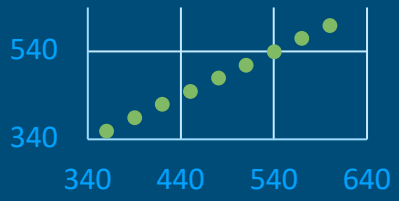
Saturating,

in dependence of **CO_2** & **nutrients**

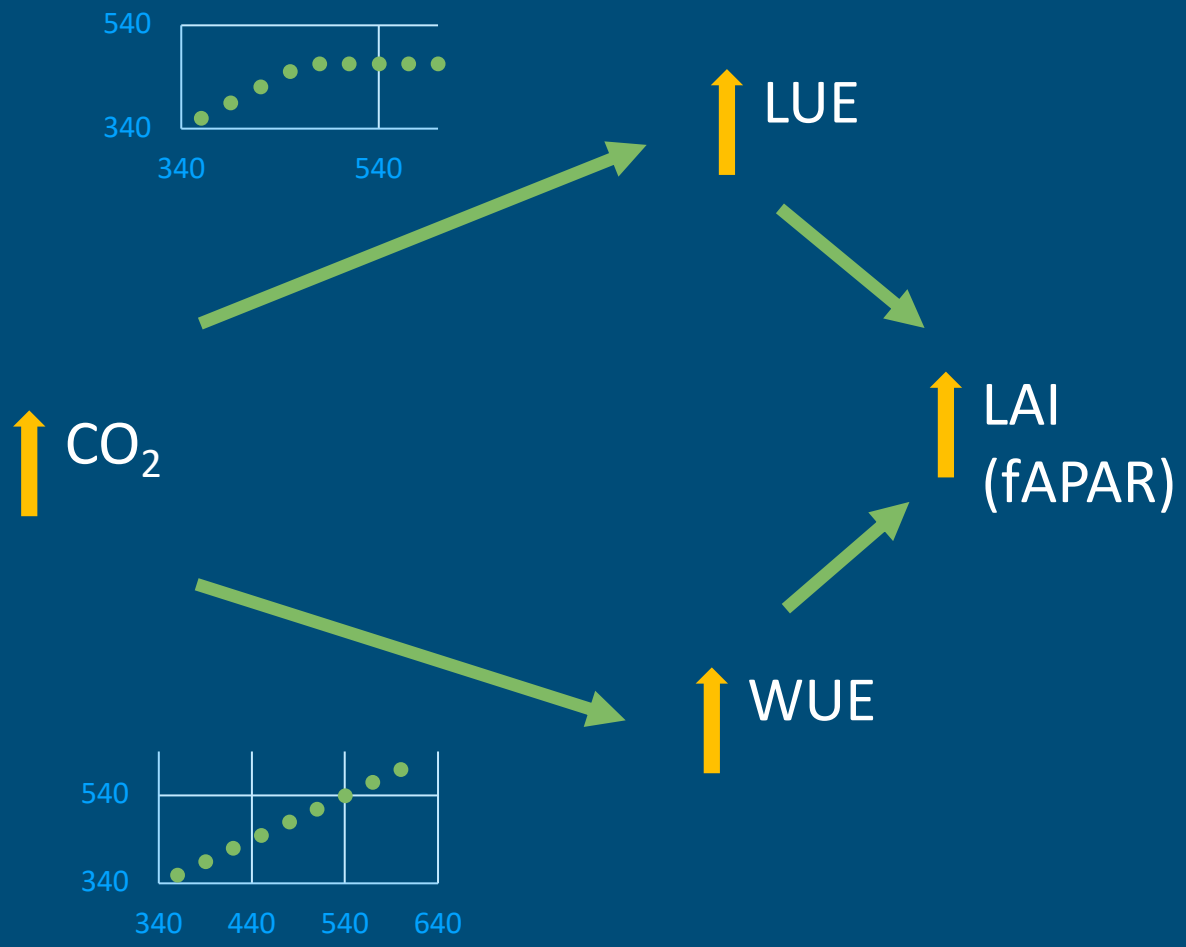
↑ LAI (fAPAR)

↑ CO_2

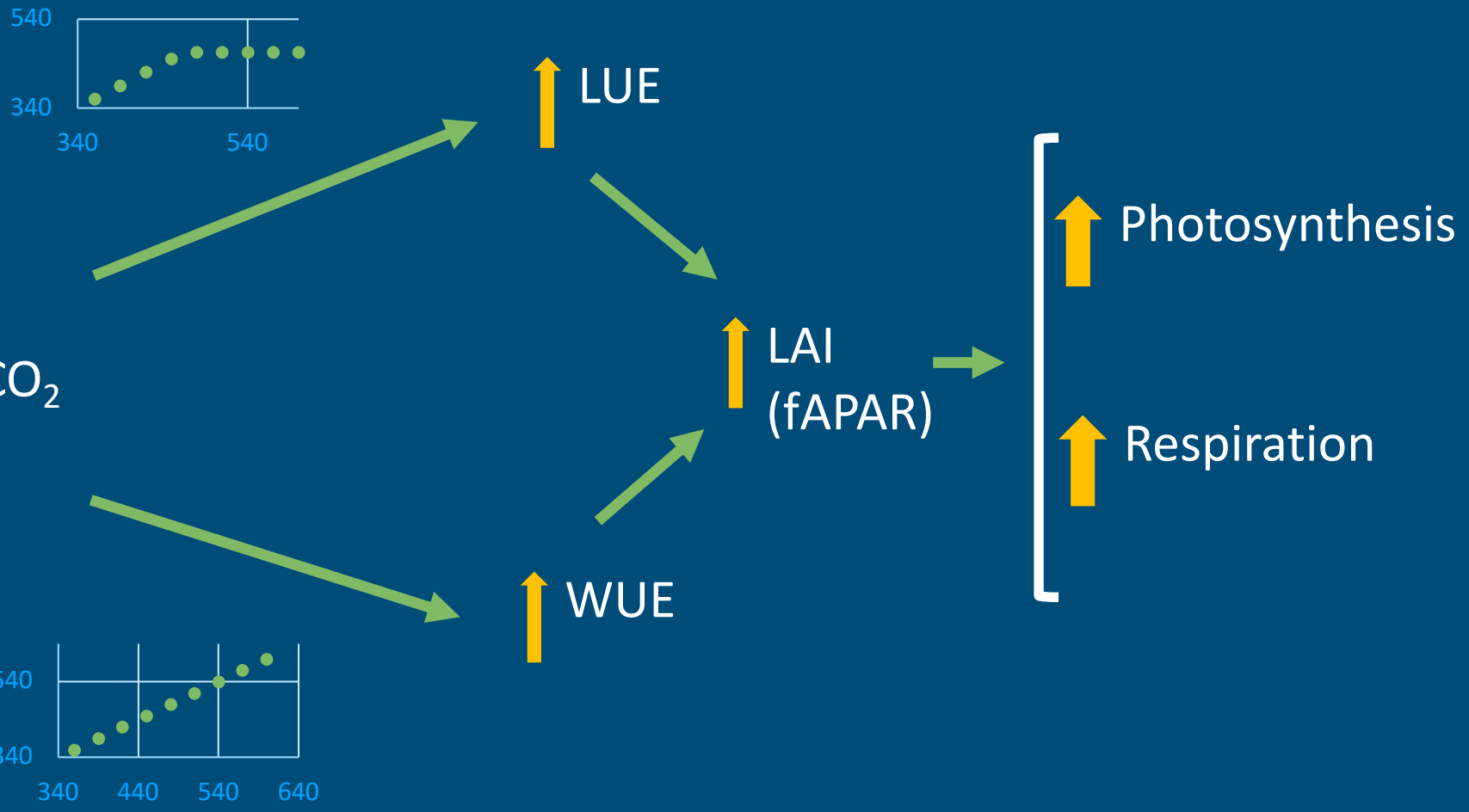
↑ WUE



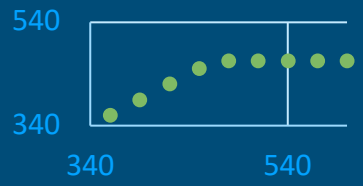
Expected effect of CO_2 on the carbon cycle

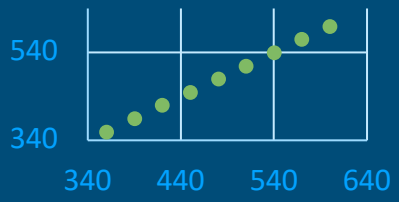


Expected effect of CO_2 on the carbon cycle

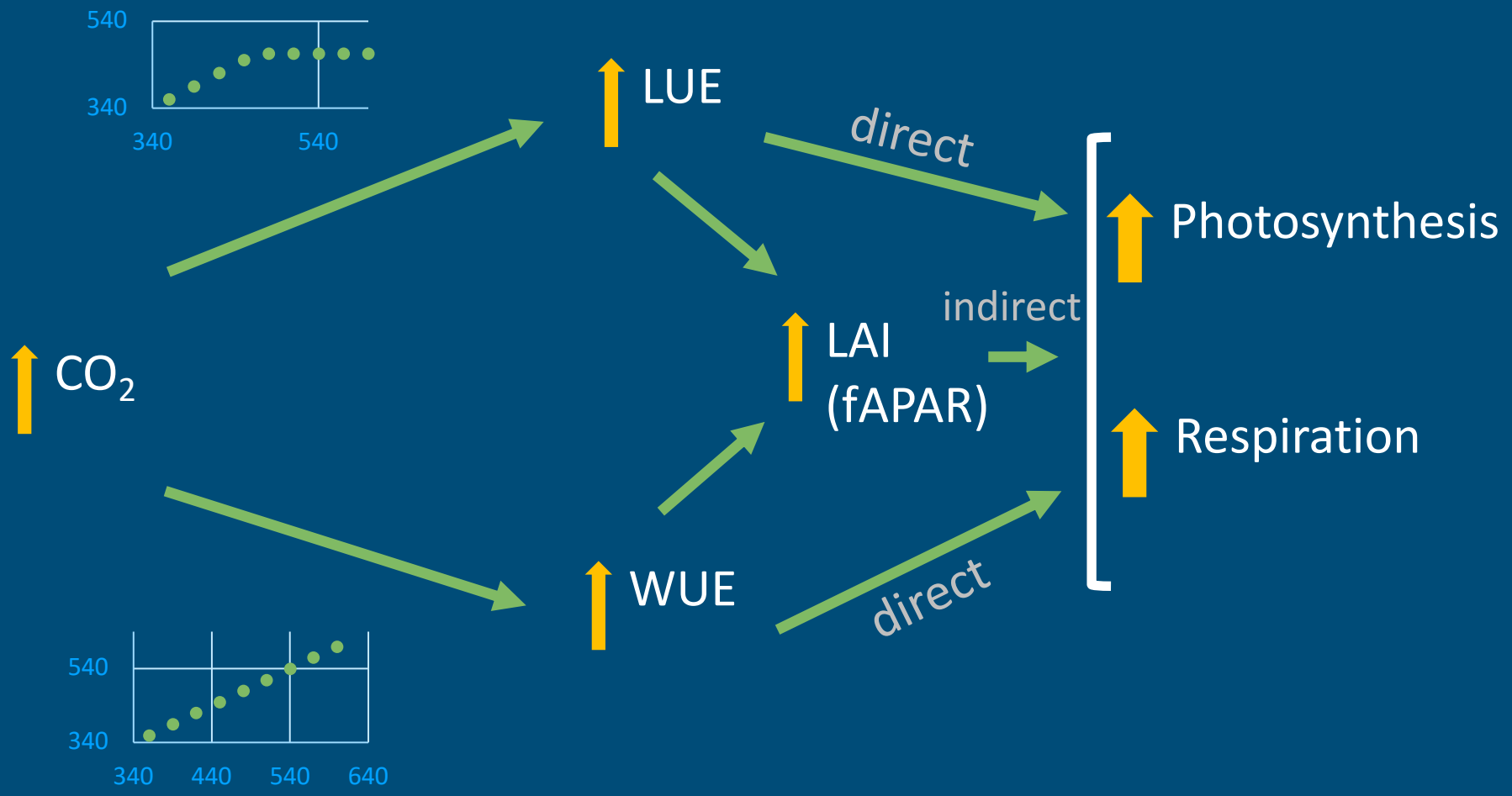


Expected effect of CO_2 on the carbon cycle

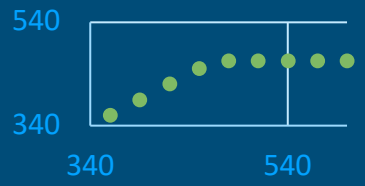




Expected effect of CO_2 on the carbon cycle



Expected effect of CO_2 on the carbon cycle



CO_2

LUE

WUE

LAI
(fAPAR)

direct

indirect

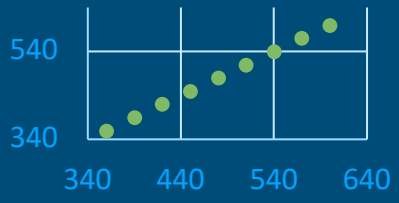
direct

CO_2, nutrient & temp. dependent pathway

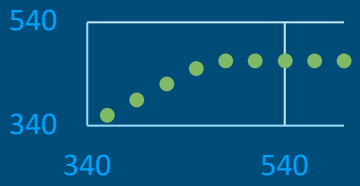
Photosynthesis

Respiration

Aridity & nutrient dependent pathway



Expected effect of CO_2 on the carbon cycle



CO_2

LUE

direct

LAI
(fAPAR)

indirect

WUE

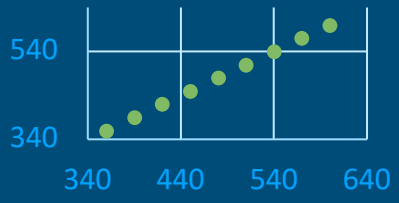
direct

CO_2, nutrient & temp. dependent pathway

Photosynthesis

/ ?

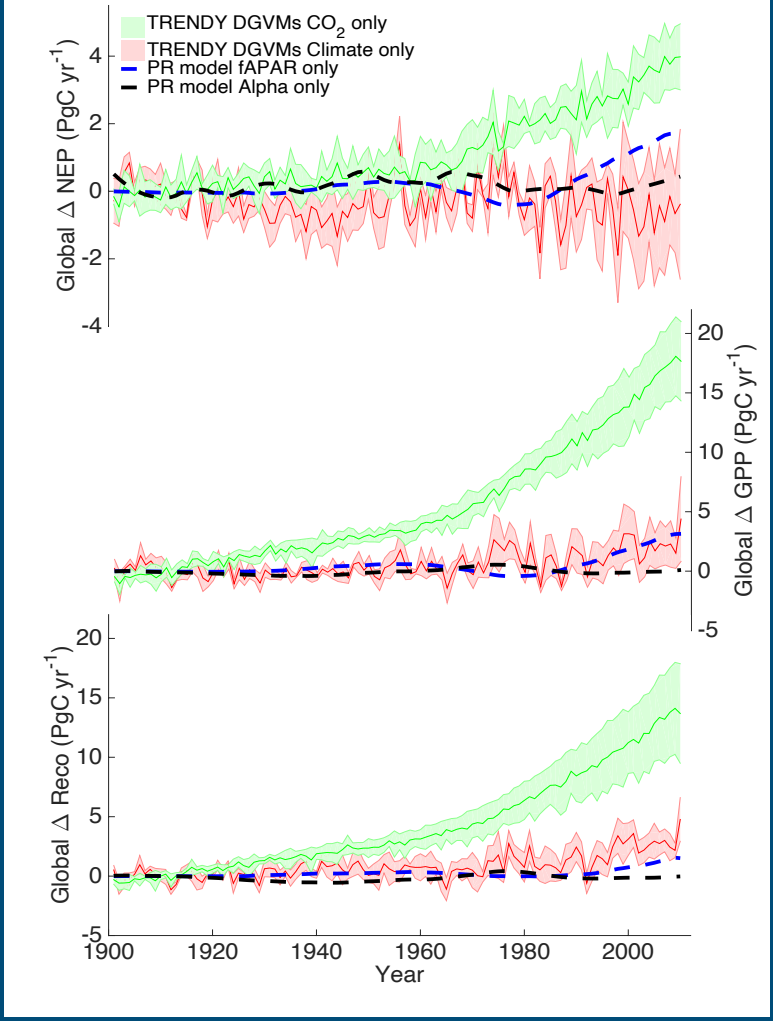
Respiration



Aridity & nutrient dependent pathway

CO_2 Fertilization magnitude?

CO_2 Fertilization magnitude?



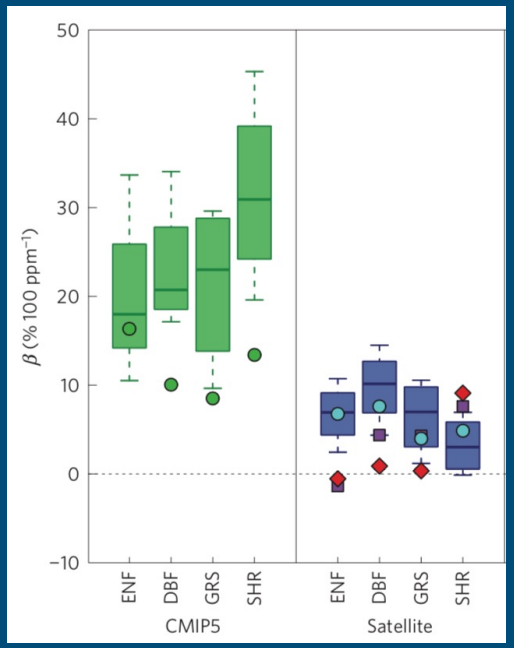
- CO_2 markedly increasing the net sink, photosynthesis and respiration.
- Vegetation greening a distant second.
- Warming increased both GPP and Respiration.
- No evidence for an increase in global water stress.

Keenan et al. (2016)

Nature Communications

CO_2 and light use efficiency

Big difference between satellite and DGVM estimated effect of CO_2 on photosynthesis

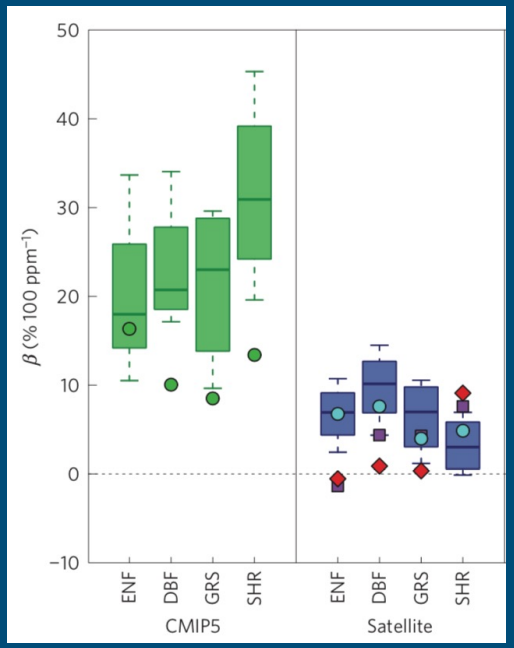


β = ∂(GPP)/∂(Ca),

Smith et al. (2016)

CO_2 and light use efficiency

Big difference between satellite and DGVM estimated effect of CO_2 on photosynthesis



β = ∂(GPP)/∂(Ca),

Smith et al. (2016)

<u>Current approaches</u> assume CO2 only effects fAPAR

e.g., MOD17:

GPP = u * fAPAR * PAR * f(T) * f(VPD)

But this **<u>only reflects the indirect effect of CO_2</u>**,

and the direct effect is much larger.

CO_2 and light use efficiency

Incorporating CO_2 effects in satellite based estimates

nature plants

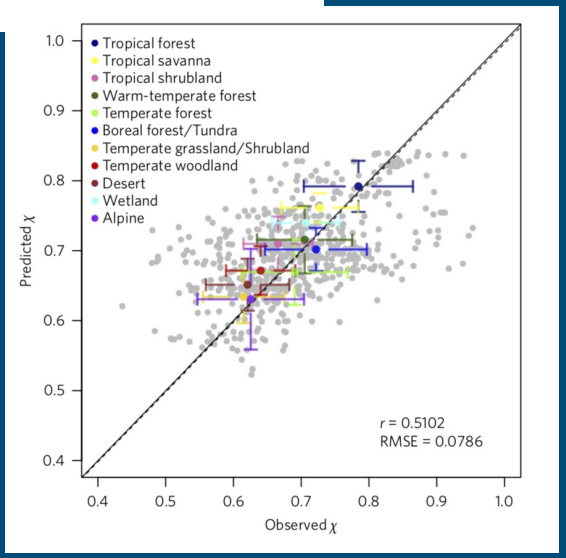
LETTERS

DOI: 10.1038/s41477-017-0006-8

Towards a universal model for carbon dioxide uptake by plants

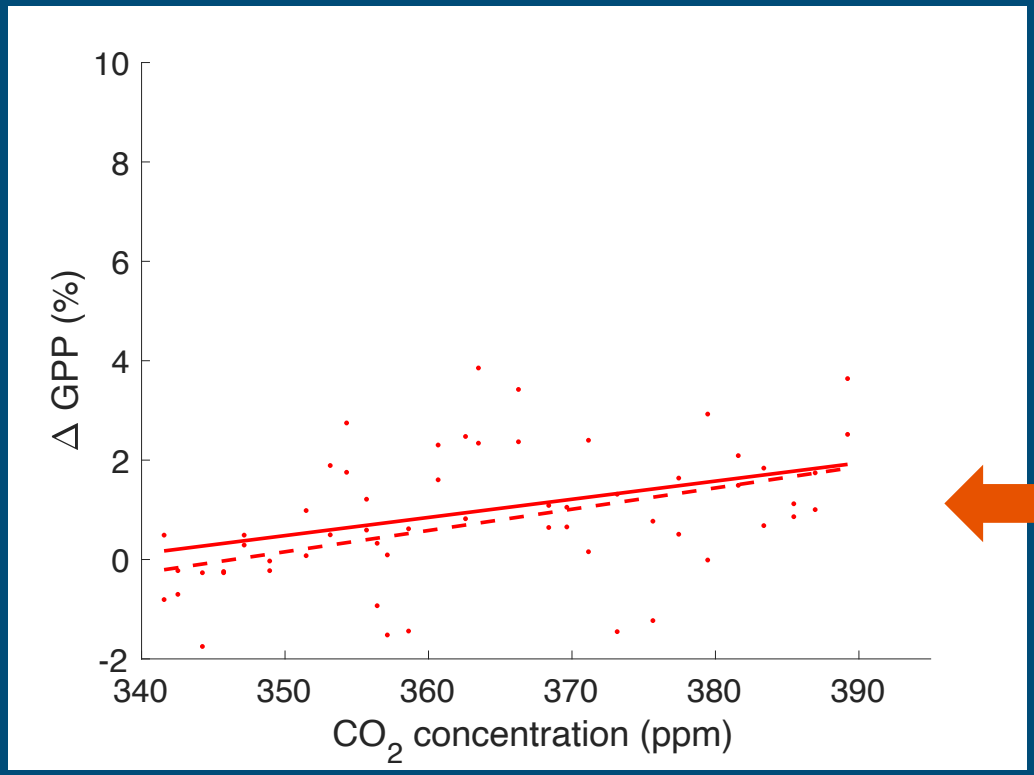
Han Wang[1,2,3*], I. Colin Prentice[1,2,4], Trevor F. Keenan[2,5], Tyler W. Davis[4,6], Ian J. Wright[2], William K. Cornwell[7], Bradley J. Evans[2,8] and Changhui Peng[1,9*]

Wang et al. 2017



Satellite GPP estimates predict low sensitivity of global GPP to CO2 (capturing mostly the greening effect)

Satellite GPP estimates predict low sensitivity of global GPP to CO2 (capturing mostly the greening effect)



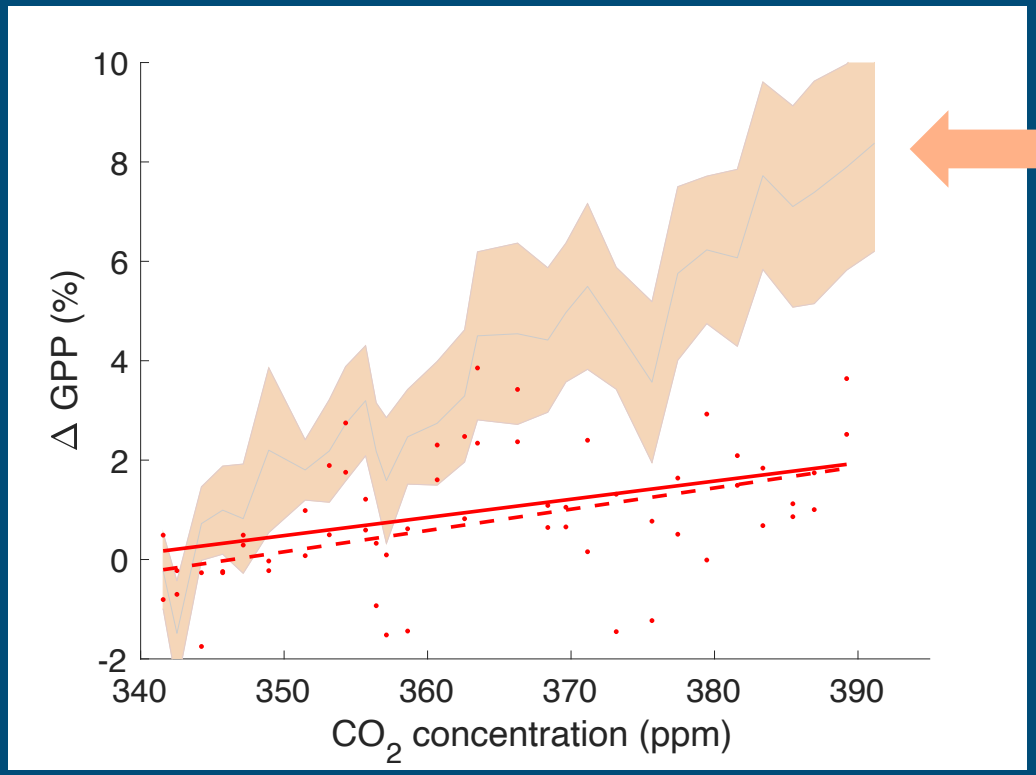
MODIS

or

Machine Learning / Empirical Upscaling

Keenan et al. (2020)

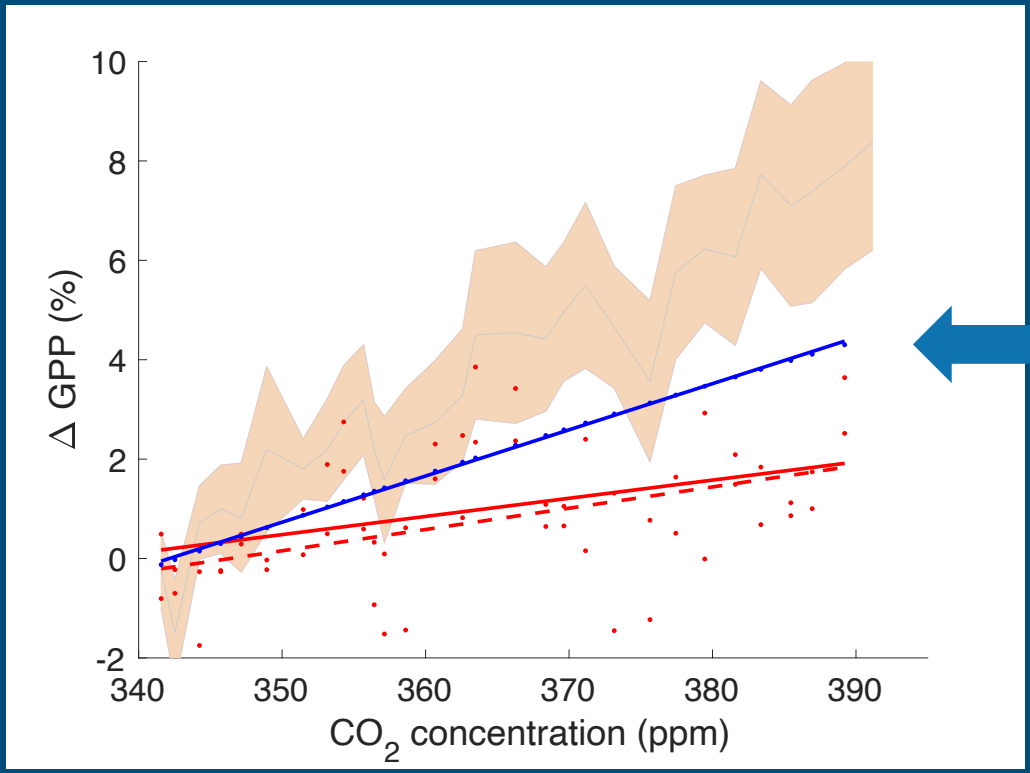
But DGVMs suggest the sensitivity should be higher



TRENDY models

Keenan et al. (2020)

The sensitivity of RuBisCO to CO2 is relatively large

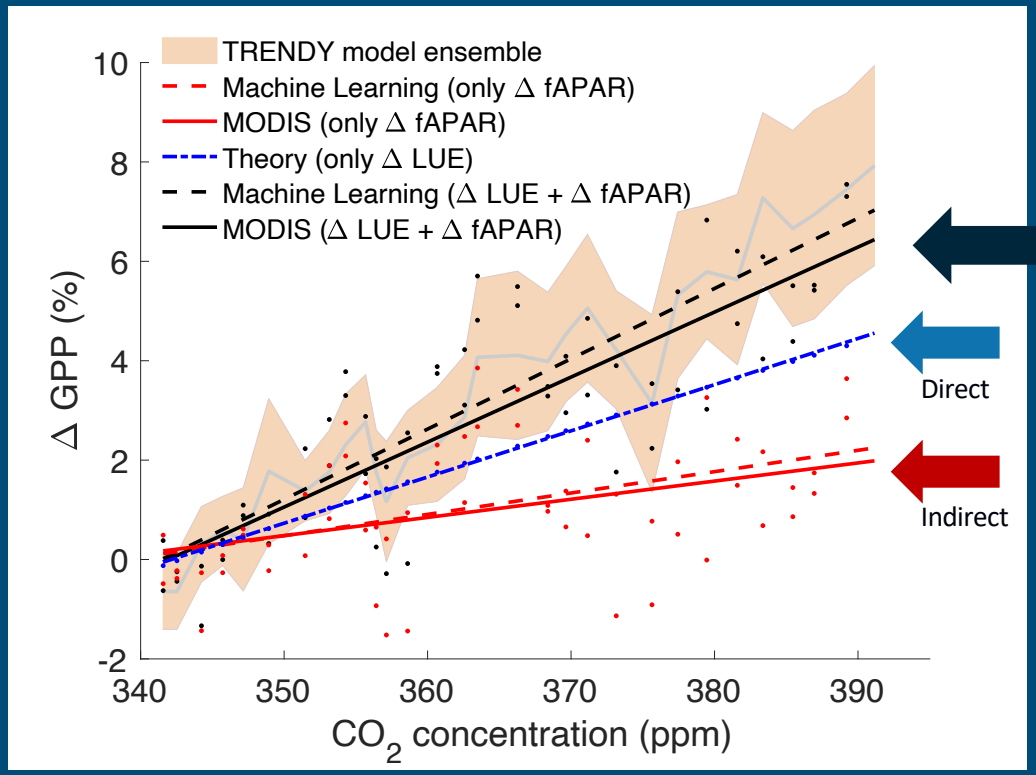


Theory

(pure direct effect)

Keenan et al. (2020)

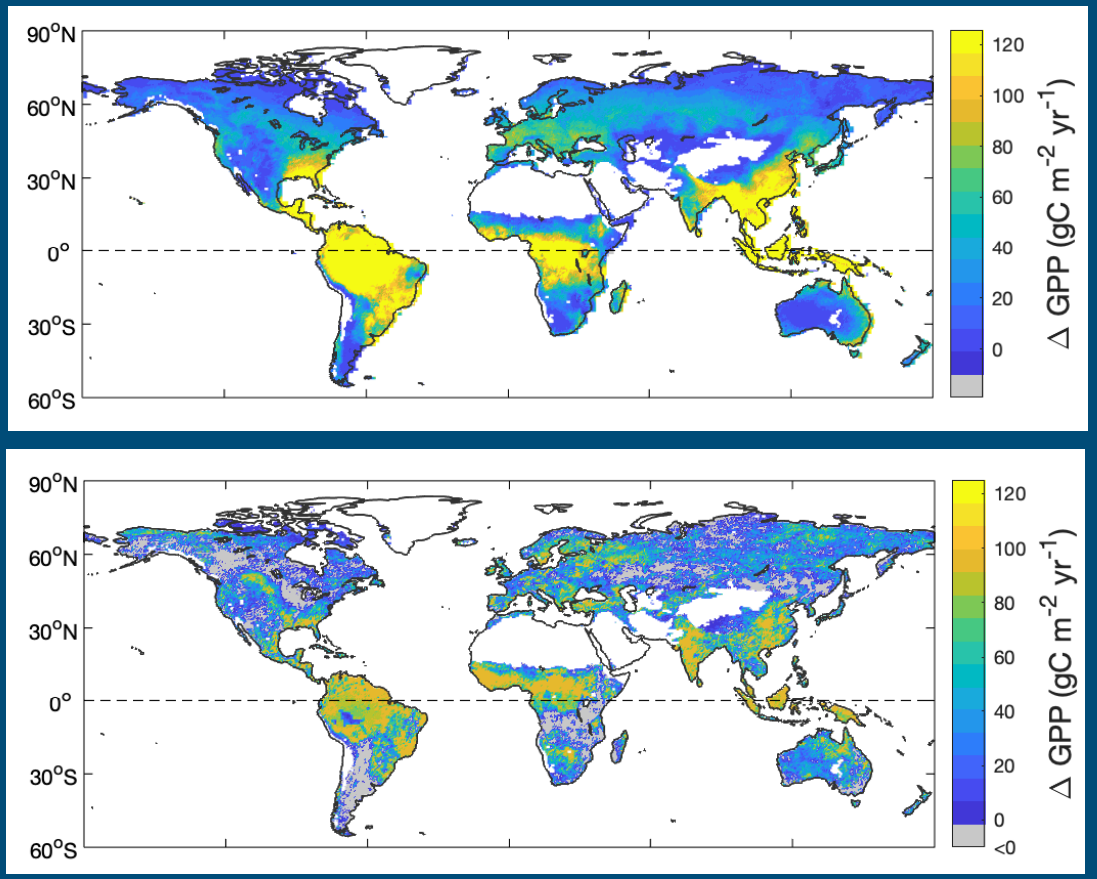
Adding RuBisCO sensitivity to remote sensing GPP estimates brings them roughly into line with DGVMs

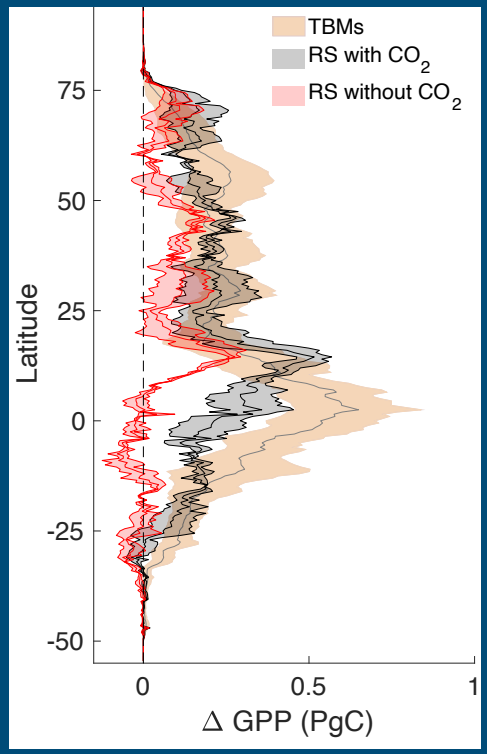


Keenan et al. (2020)

CO_2 and light use efficiency

General convergence in satellite and DGVM sensitivity

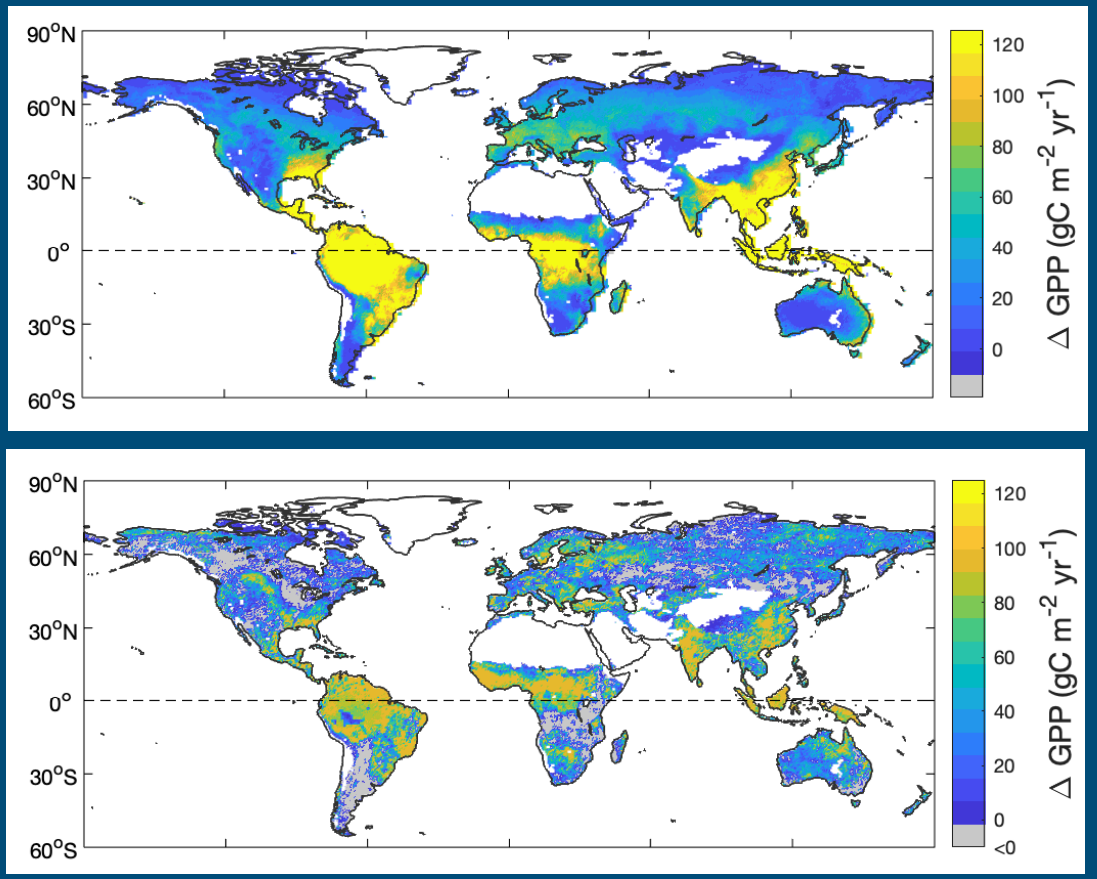


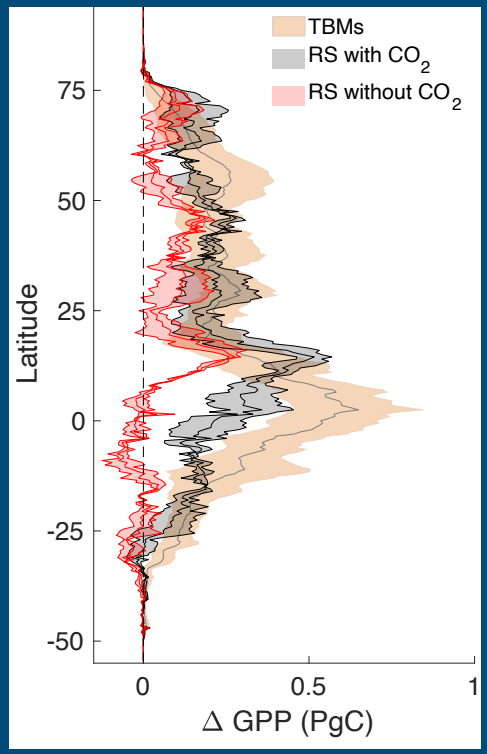


Keenan et al. (2020)

CO_2 and light use efficiency

General convergence in satellite and DGVM sensitivity





But what are we converging to?

Keenan et al. (2020)

CO_2 and light use efficiency

There is a lack of reliable observational constraints

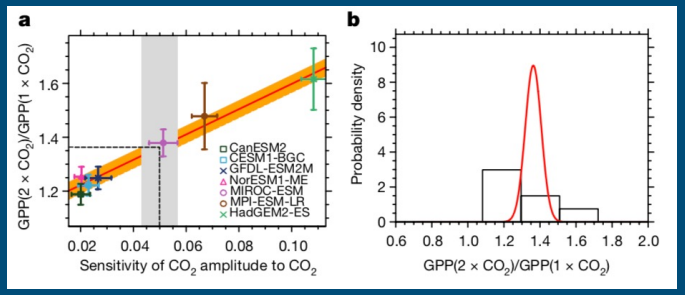
LETTER

doi:10.1038/nature19772

Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO_2

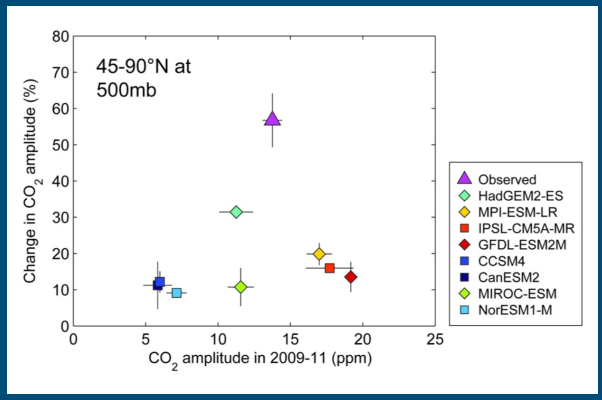
Sabrina Wenzel[1], Peter M. Cox[2], Veronika Eyring[1] & Pierre Friedlingstein[2]

2016



Enhanced Seasonal Exchange of CO_2 by Northern Ecosystems Since 1960

H. D. Graven,[1]* R. F. Keeling,[1] S. C. Piper,[1] P. K. Patra,[2] B. B. Stephens,[3] S. C. Wofsy,[4] L. R. Welp,[1] C. Sweeney,[5] P. P. Tans,[5] J. J. Kelley,[6] B. C. Daube,[4] E. A. Kort,[7†] G. W. Santoni,[4] J. D. Bent[1]



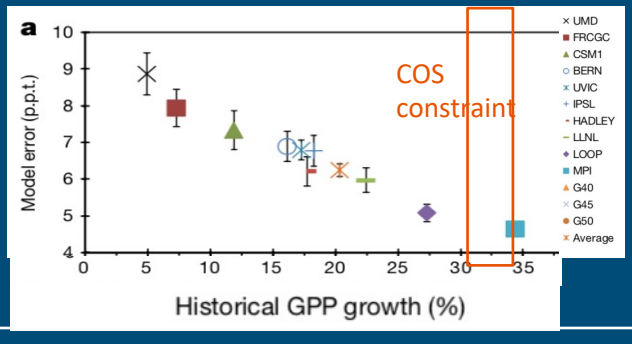
LETTER

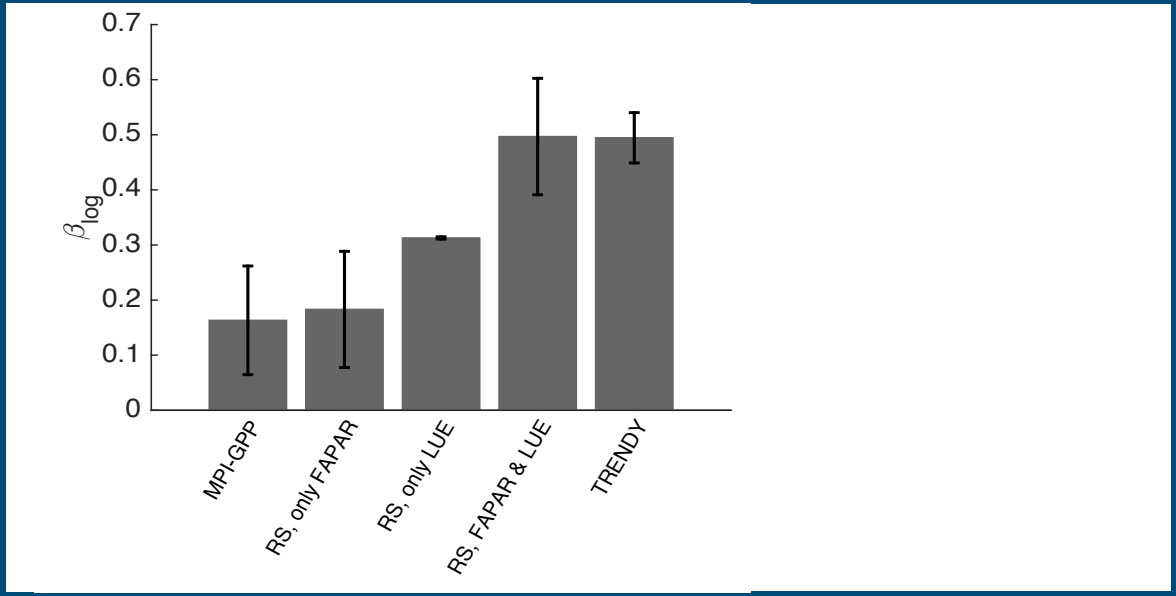
doi:10.1038/nature22030

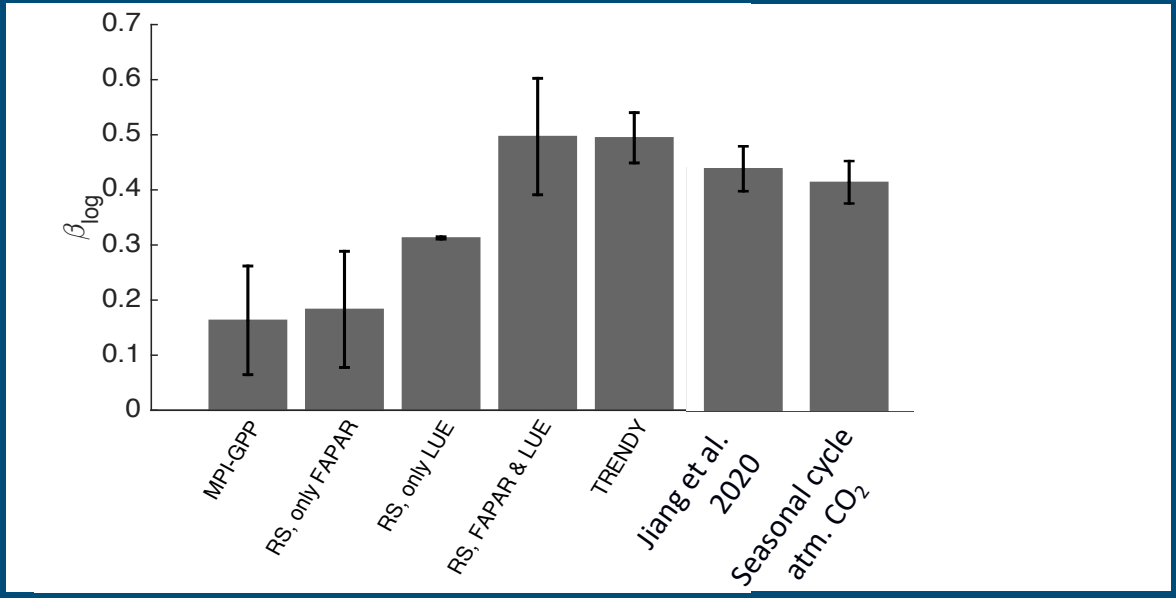
Large historical growth in global terrestrial gross primary production

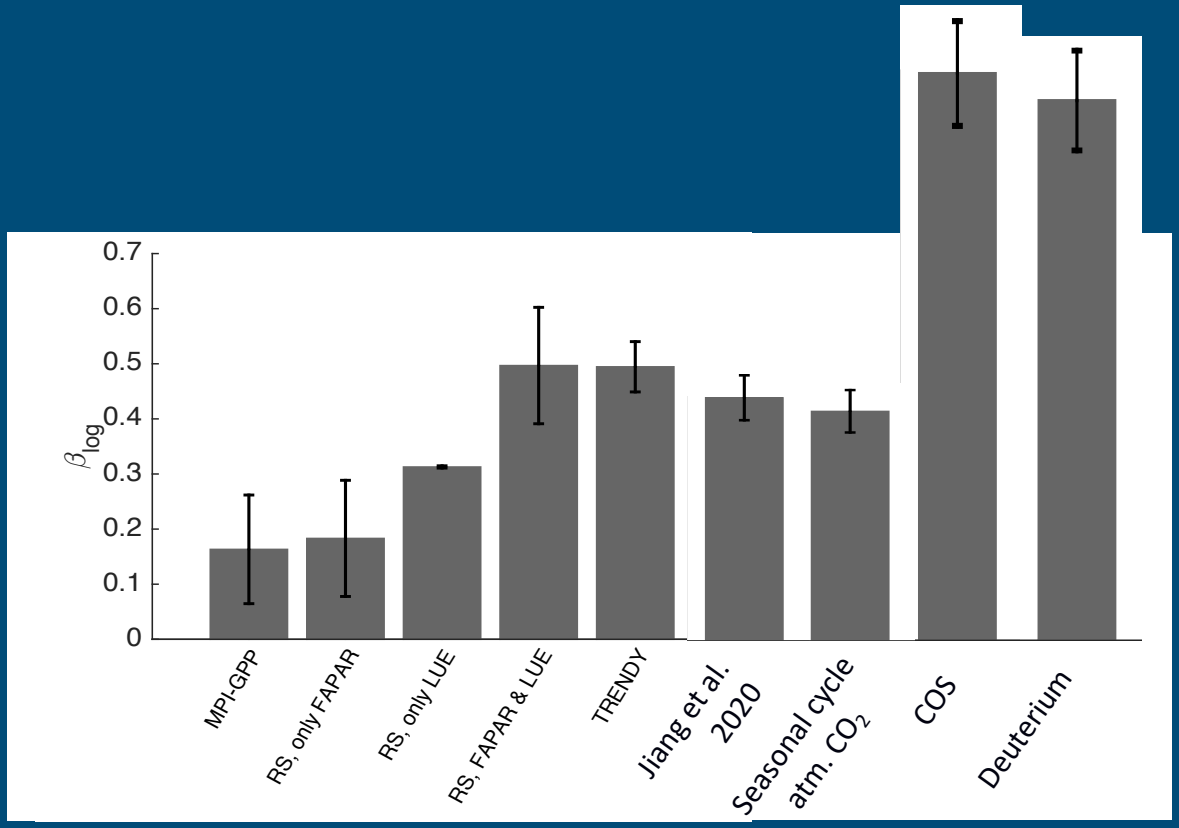
J. E. Campbell[1], J. A. Berry[2], U. Seibt[3], S. J. Smith[4], S. A. Montzka[5], T. Launois[6†], S. Belviso[6], L. Bopp[6†] & M. Laine[7]

2017

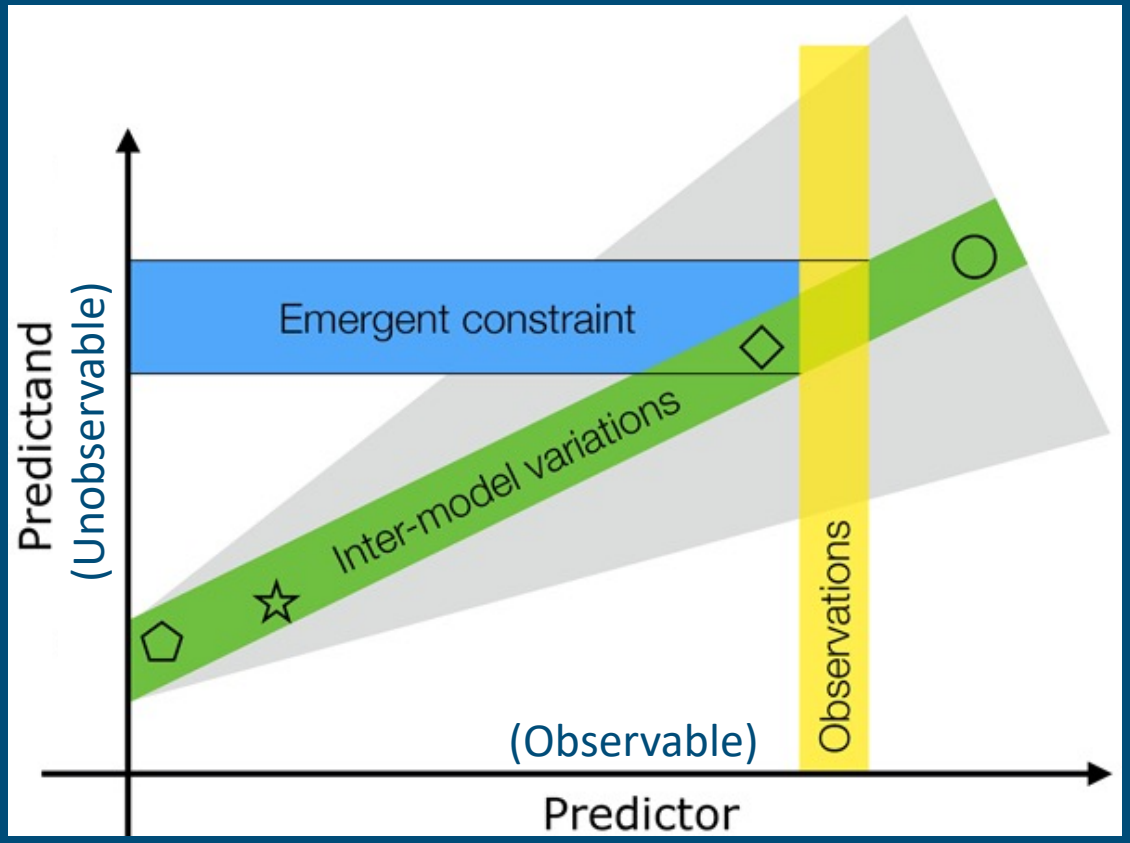


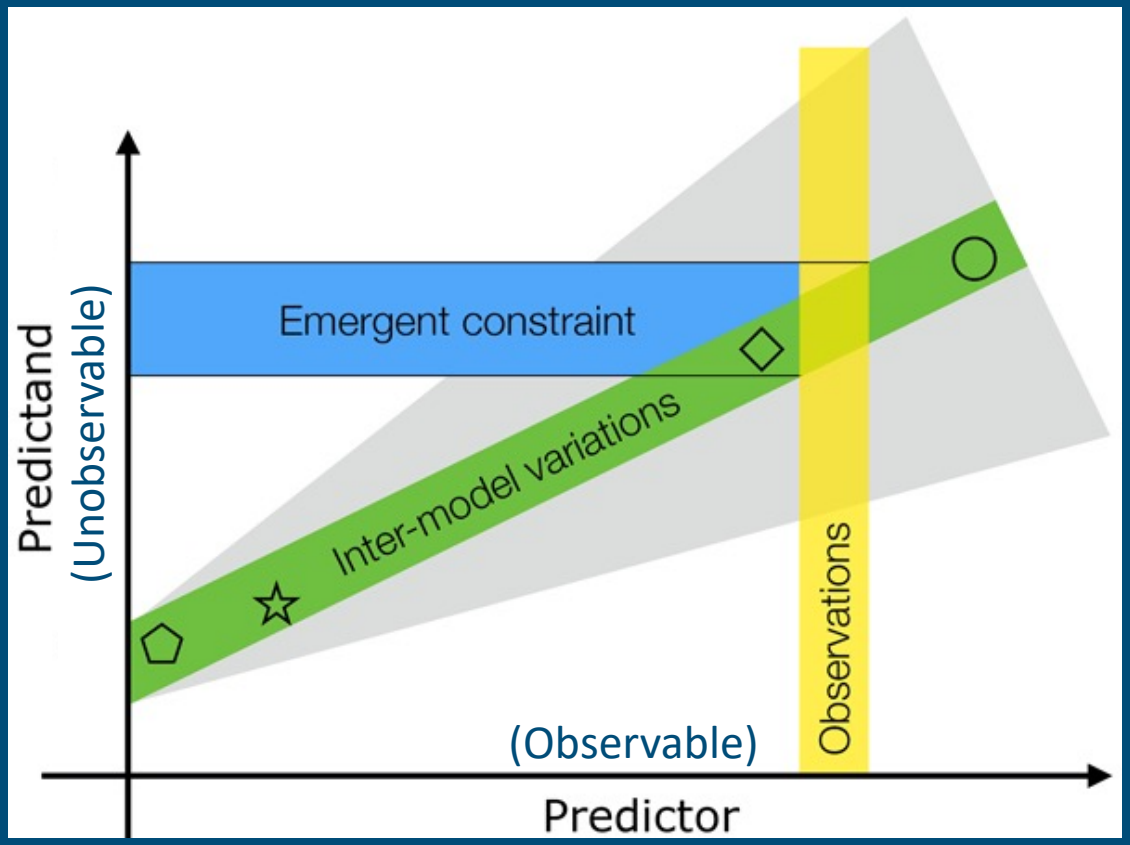

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
β_{log}
MPI-GPP
RS, only FAPAR
RS, only LUE
RS, FAPAR & LUE
TRENDY


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
β_{log}
MPI-GPP
RS, only FAPAR
RS, only LUE
RS, FAPAR & LUE
TRENDY
Jiang et al. 2020
Seasonal cycle atm. CO_2


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
β_{log}
MPI-GPP
RS, only FAPAR
RS, only LUE
RS, FAPAR & LUE
TRENDY
Jiang et al. 2020
Seasonal cycle atm. CO_2
COS
Deuterium

Emergent constraints?


Predictand
(Unobservable)
Emergent constraint
Inter-model variations
Observations
(Observable)
Predictor


fAPAR
Predictand
(Unobservable)
Emergent constraint
Inter-model variations
Observations
(Observable)
Predictor
Greenness

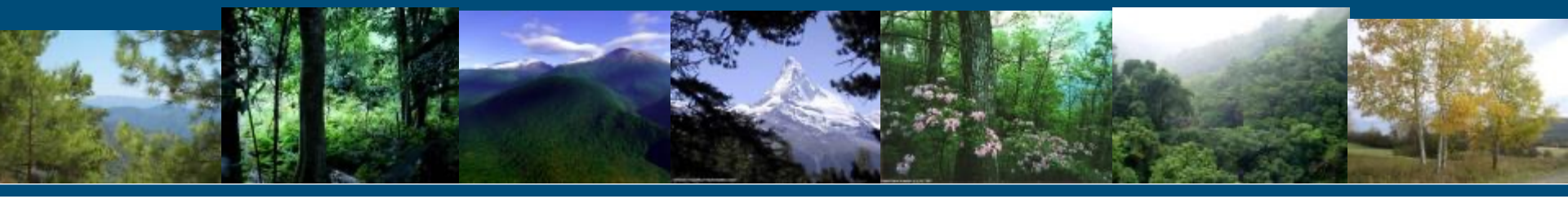
Requirements

- A plausible physical mechanism
- Theory - led (i.e. a hypothesis-driven approach to testing)
- Avoid fishing expeditions and implicit assumptions about space for time extrapolations

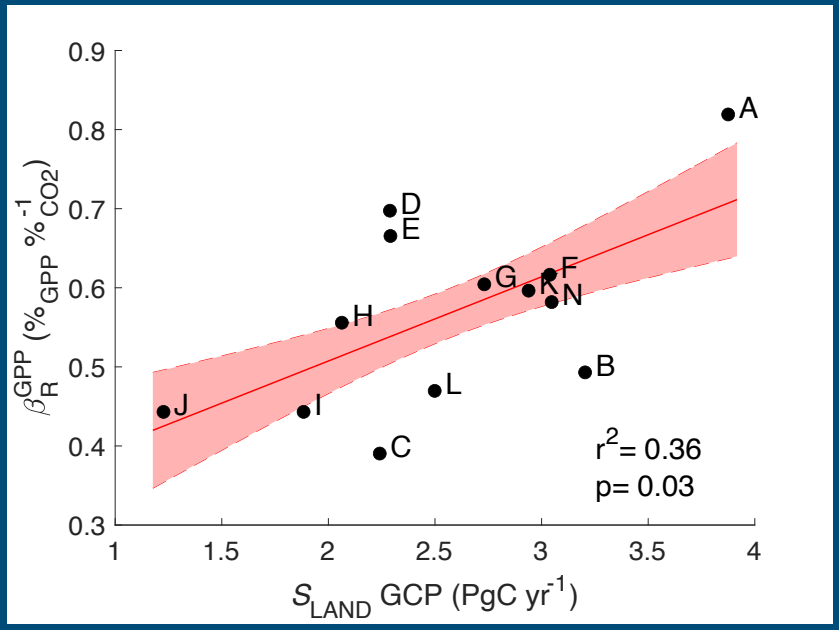
"Emergent constraints will **therefore remain conditional on the model ensembles used to define them** and will be subject to systematic biases in the model ensemble. Most obviously, if an important process is neglected in all models (e.g. nutrient limitations on CO2 fertilization, or the impacts of forest fires on the interannual variability of CO2), this has the potential to lead to spurious emergent constraints on the real Earth System." Cox et al. 2019

Emergent constraints?

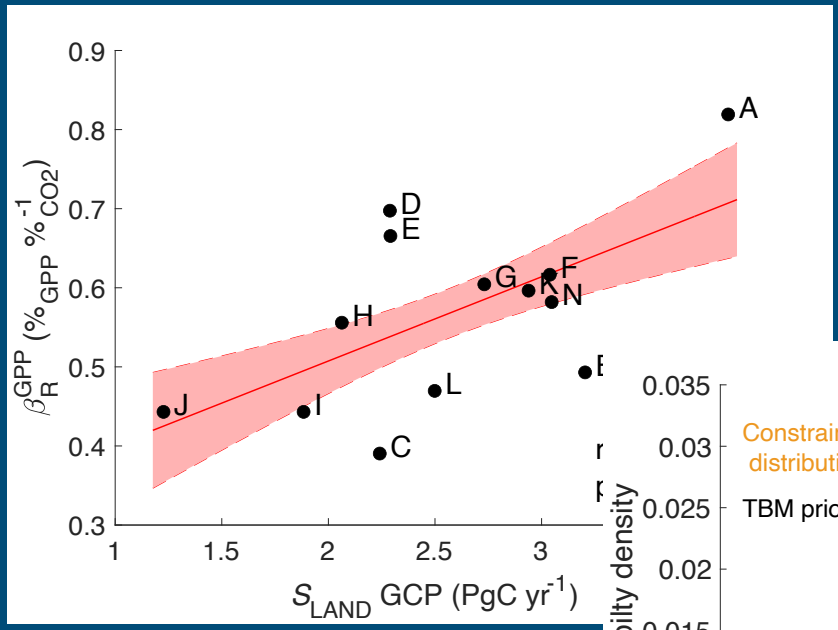
Could the magnitude of the land sink be related to the CO_2 fertilization effect on photosynthesis?

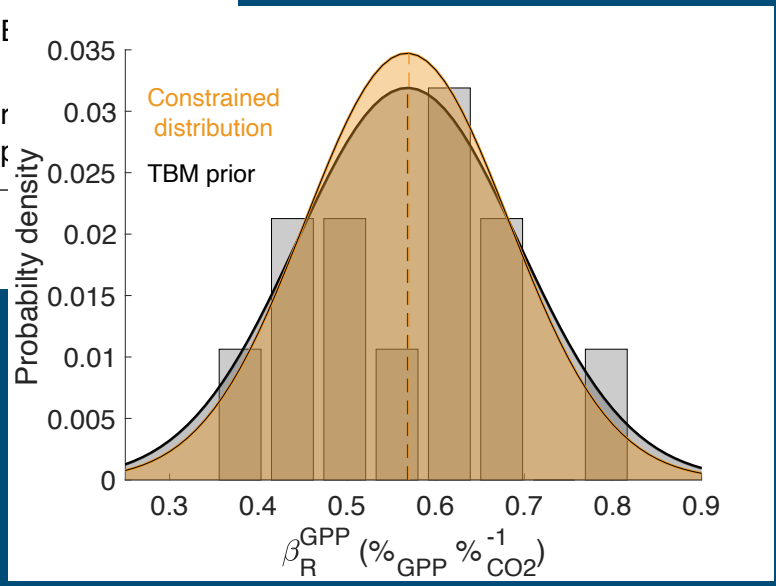


Sort of…

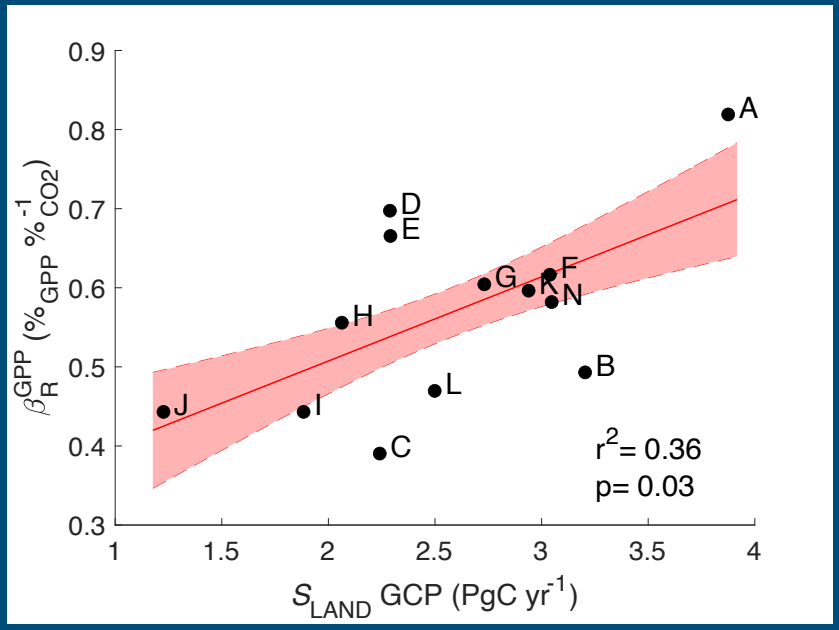

0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
4
A
D
E
G
F
K
N
H
B
L
J
I
C
r^2= 0.36
p= 0.03
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
S_{LAND} GCP (PgC yr^{-1})

Sort of…


0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
A
D
E
G
F
K
N
H
L
J
I
C
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
S_{LAND} GCP (PgC yr^{-1})

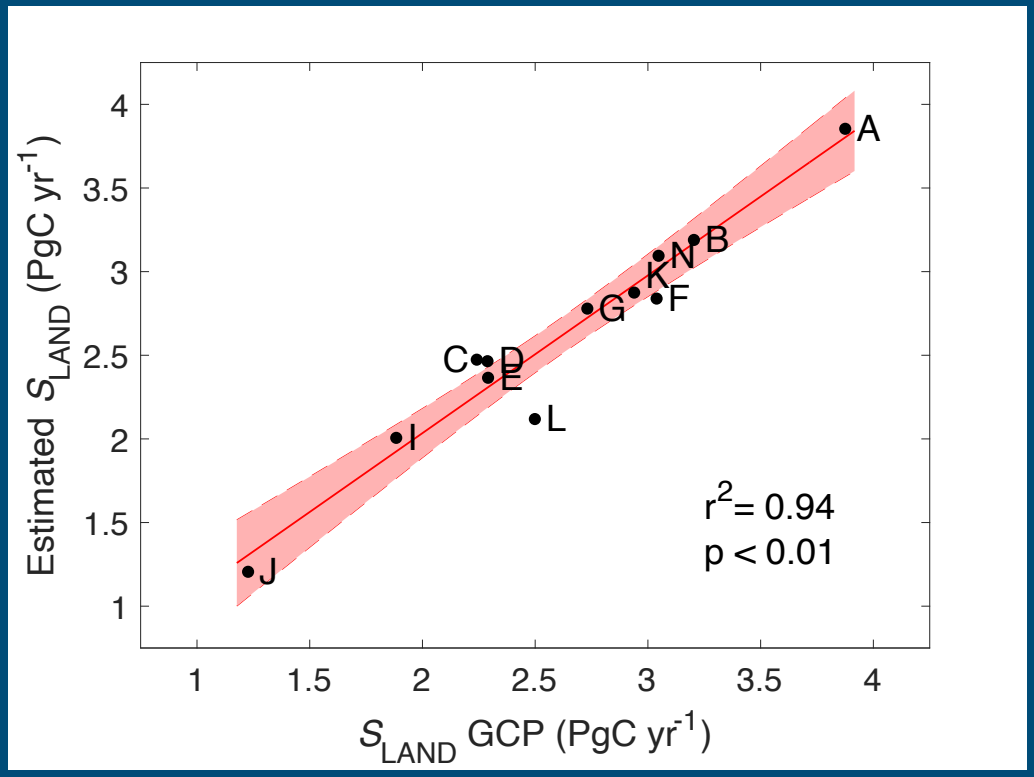

0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Constrained distribution
TBM prior
Probability density
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)

Sort of…

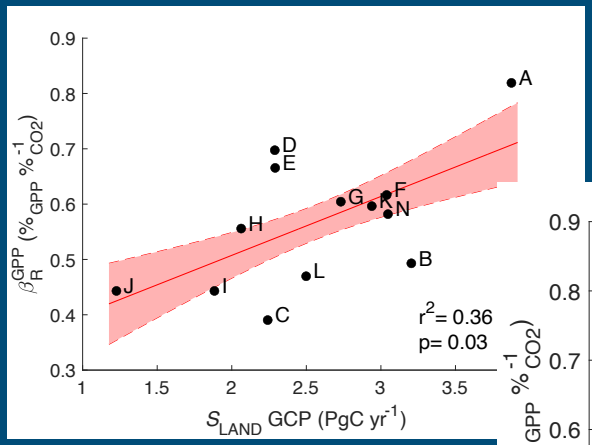


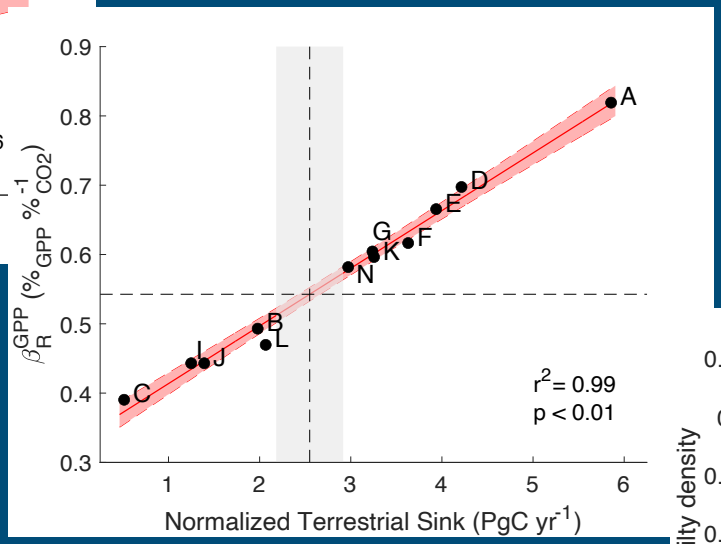
But this is the univariate relationship. What about the partial relationship between ß^{GPP} and S_{LAND}?

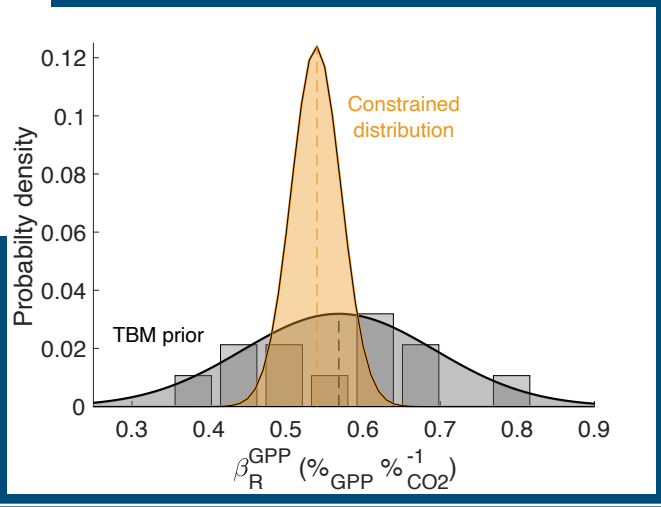
Between-model differences in S_{LAND} predicted via a linear model

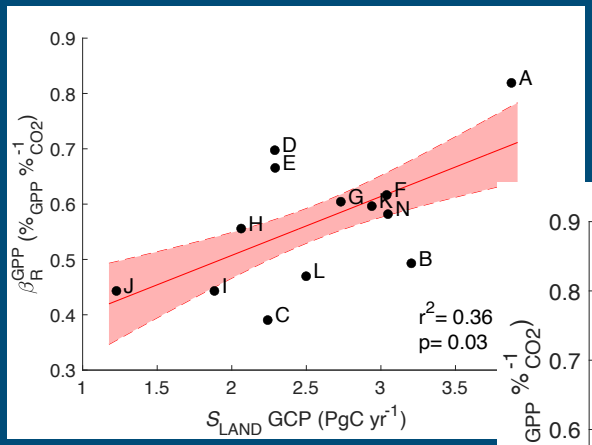


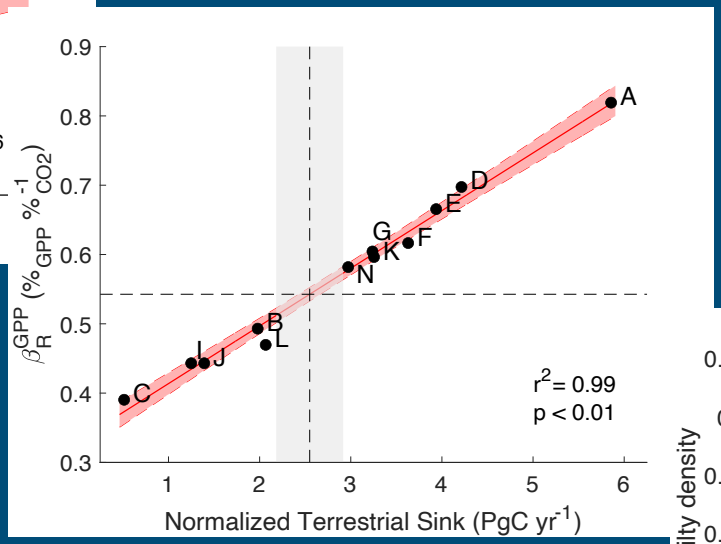
$$S_{LAND} \sim ß^{GPP} + ß^{RECO} + ß^{RECO}:\gamma$$

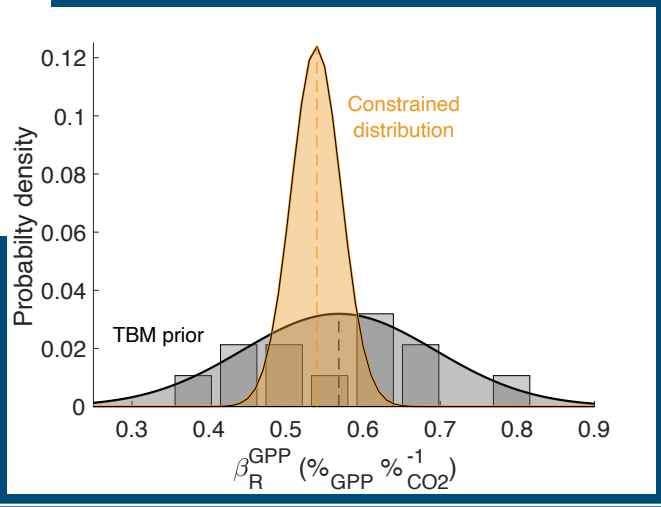

A
D
E
G
F
K
N
H
B
L
J
I
C
r2= 0.36
p= 0.03
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
S_{LAND} GCP (PgC yr^{-1})


A
D
E
G
F
K
N
B
L
I
J
C
r2= 0.99
p < 0.01
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
2
3
4
5
6
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
Normalized Terrestrial Sink (PgC yr^{-1})


Constrained
distribution
TBM prior
0.12
0.1
0.08
0.06
0.04
0.02
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Probability density
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)

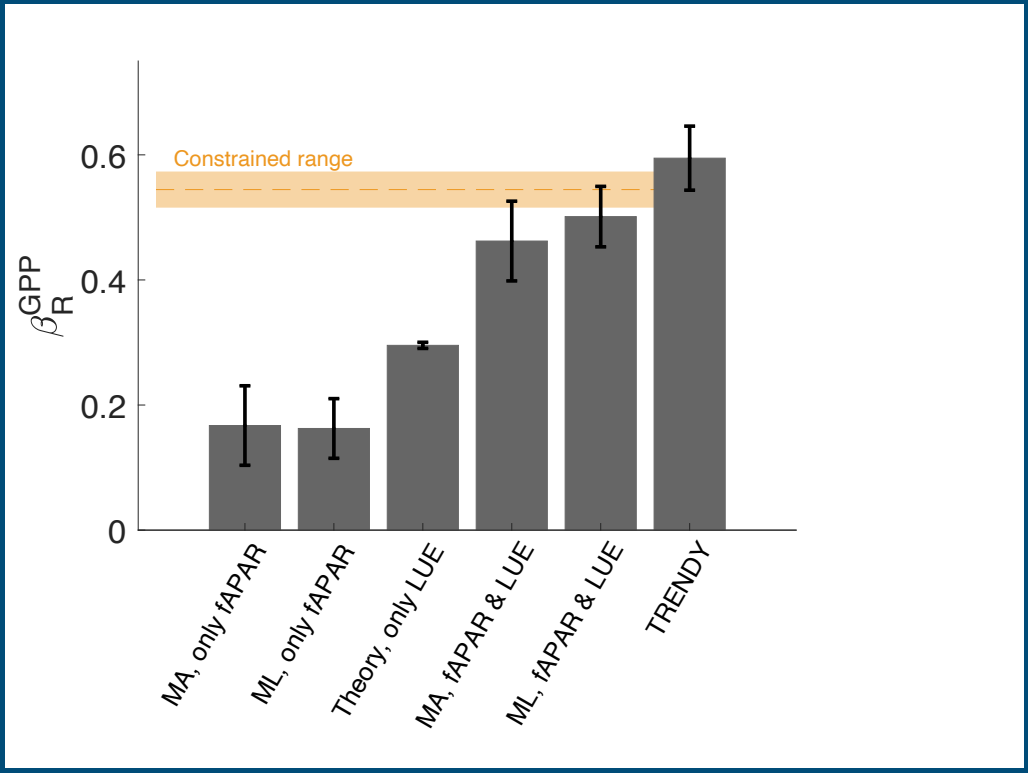

A
D
E
G
F
K
N
H
B
L
J
I
C
r2= 0.36
p= 0.03
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
1.5
2
2.5
3
3.5
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
S_{LAND} GCP (PgC yr^{-1})


A
D
E
G
F
K
N
B
L
I
J
C
r2= 0.99
p < 0.01
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1
2
3
4
5
6
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)
Normalized Terrestrial Sink (PgC yr^{-1})


Constrained
distribution
TBM prior
0.12
0.1
0.08
0.06
0.04
0.02
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Probability density
β_R^{GPP} (%$_{GPP}$ %$^{-1}_{CO2}$)

Improved confidence in global photosynthesis responses to CO2?

Improved confidence in global photosynthesis responses to CO2?

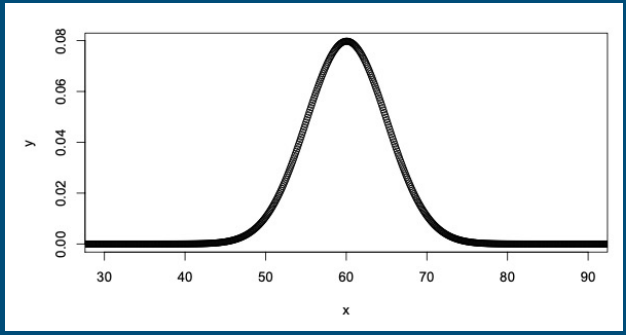


But….

- Uncertainties remain:
  -
  -
  -
  -
  -

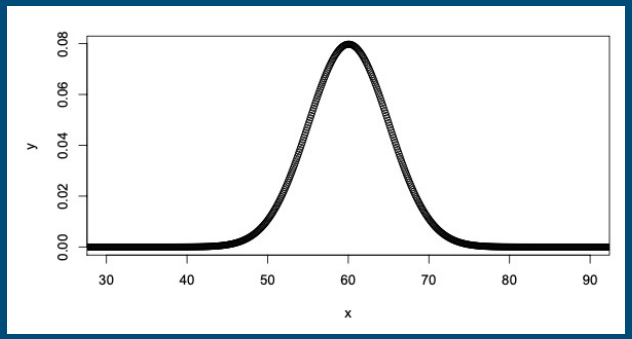
But….

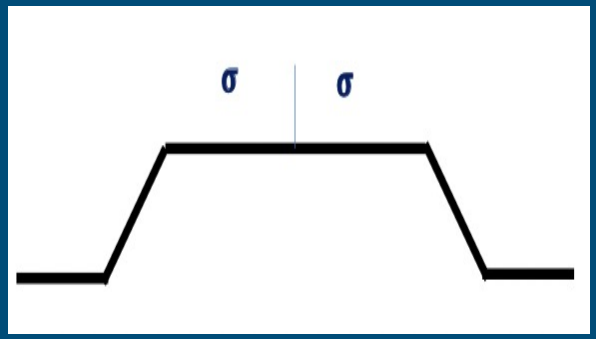
- Uncertainties remain:
  - GCP Sland uncertainty is …..
  -
  -
  -
  -



But….

- Uncertainties remain:
  - GCP Sland uncertainty is …..
  -
  -
  -
  -





But….

- Uncertainties remain:
  - GCP Sland uncertainty is …..
  - Could be systematic biases across models
  -
  -
  -

But….

- Uncertainties remain:
  - GCP Sland uncertainty is …..
  - Could be systematic biases across models
  - What about climate change and climate sensitivities?
  -
  -

But….

- Uncertainties remain:
  - GCP Sland uncertainty is …..
  - Could be systematic biases across models
  - What about climate change and climate sensitivities?
  - Implicit assumption that each model $ß_{RECO}$ is equally likely but represents a realization from a random normal distribution
  -

But….

- Uncertainties remain:
  - GCP Sland uncertainty is …..
  - Could be systematic biases across models
  - What about climate change and climate sensitivities?
  - Implicit assumption that each model $ß_{RECO}$ is equally likely but represents a realization from a random normal distribution
  - Ultimately a global constraint provides limited inference for regional dynamics, which could compensate each other

Take home messages:

1. Despite uncertainty regarding the magnitude and pathway, elevated CO_2 is stimulating increased plant C uptake
2. CO_2 is also stimulating increased C release from ecosystems
3. The net effect is a large increase in terrestrial C uptake
4. The balance of direct and indirect pathways, and the sensitivity of each to CO_2 remain poorly characterized.

Implications:

1. We need to understand the relative contribution of each of ∂LUE and ∂WUE in order to project when the sink will saturate
2. Previous results using long-term trends in GPP or NPP from remote sensing/machine learning may need to be re-evaluated

BERKELEY LAB
Lawrence Berkeley National Laboratory

Berkeley
UNIVERSITY OF CALIFORNIA

fin

...

Thank you!

U.S. DEPARTMENT OF ENERGY | Office of Science

AMERIFLUX

NASA

DOE, NASA,

TRENDY modeling teams

Collaborators:

Remi Luo

Martin De Kauwe

Belinda Medlyn

Colin Prentice

Beni Stocker

Nick Smith

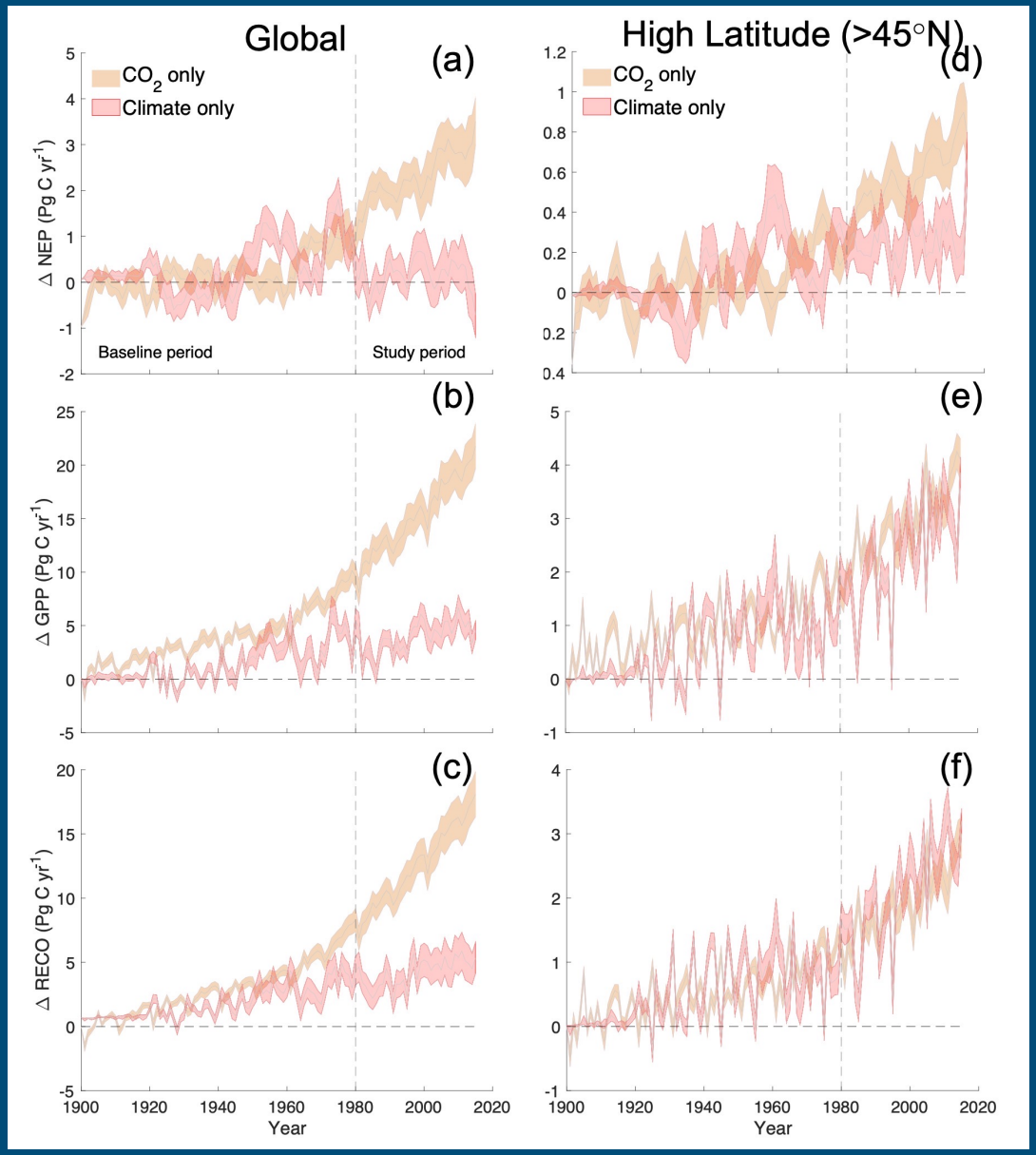
Cesar Terrer

Wang Han

Sha Zhou

Yao Zhang

@trevorkeenan


Global
High Latitude (>45°N)
(a)
(b)
(c)
(d)
(e)
(f)
CO2 only
Climate only
Δ NEP (Pg C yr-1)
Δ GPP (Pg C yr-1)
Δ RECO (Pg C yr-1)
Baseline period
Study period
Year
1900
1920
1940
1960
1980
2000
2020