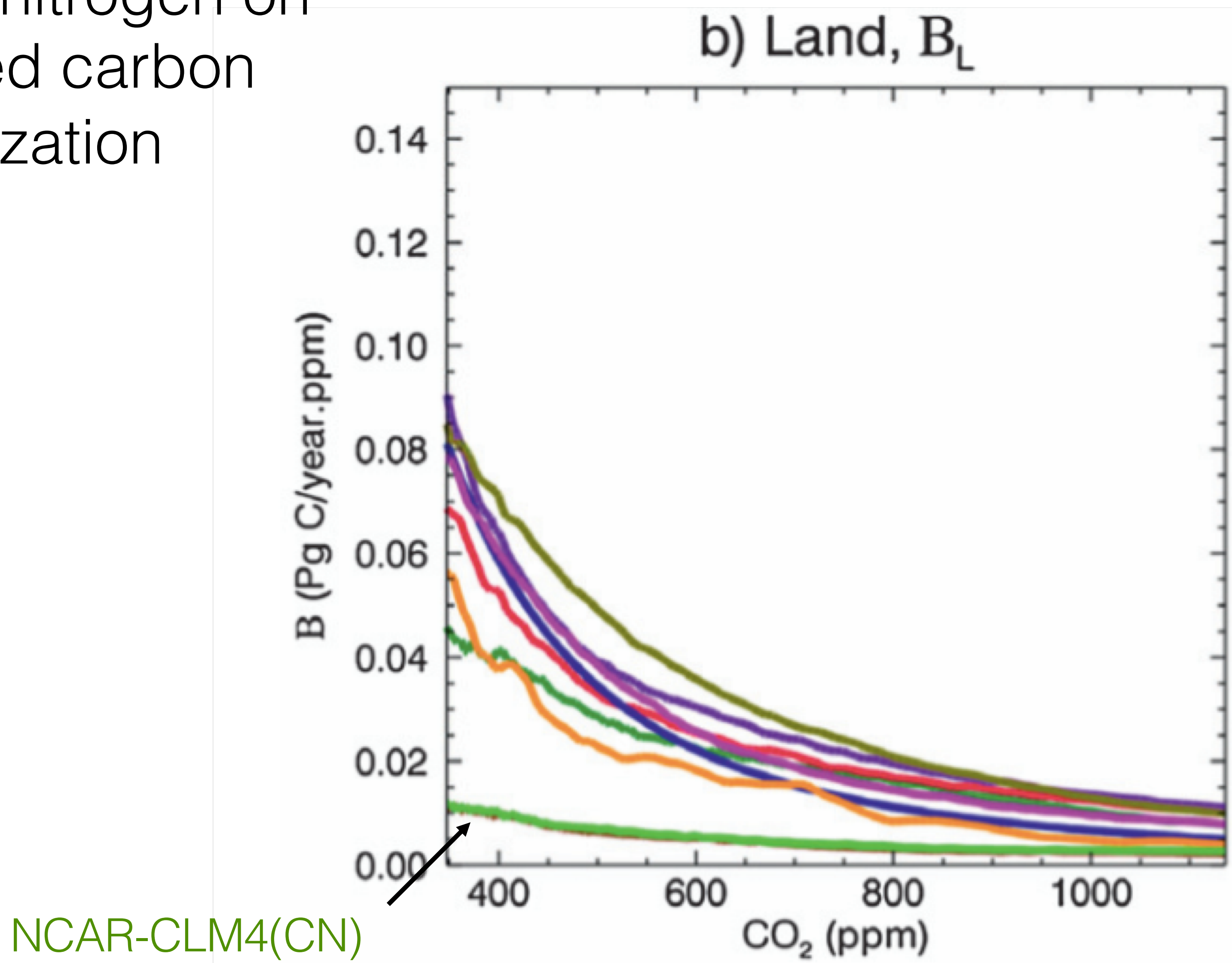
The CLM5 Nitrogen cycle

Rosie Fisher, Dave Lawrence, Will Wieder,
Gordon Bonan, Keith Oleson, Peter Lawrence, Sean Swenson,
Danica Lombardozzi, Ahmed Tawfik, Justin Perket,
Erik Kluzek, Ben Andre, Bill Sacks, Mariana Vertenstein

Charlie Koven, Bill Riley, Bardan Ghmire (LBNL)
Anthony Walker (ORNL), Chonggang Xu, Ashehad Ali (LANL)
Mingjie Shi & Josh Fisher (NASA-JPL)
Eddie Brzostek (WVU), Quinn Thomas (VT),

Impact of nitrogen on simulated carbon fertilization



Carbon–Concentration and Carbon–Climate Feedbacks in CMIP5 Earth System Models

Vivek K. Arora,[a] George J. Boer,[a] Pierre Friedlingstein,[b] Michael Eby,[c] Chris D. Jones,[d] James R. Christian,[a] Gordon Bonan,[e] Laurent Bopp,[f] Victor Brovkin,[g] Patricia Cadule,[f] Tomohiro Hajima,[h] Tatiana Ilyina,[g] Keith Lindsay,[e] Jerry F. Tjiputra,[i] and Tongwen Wu[j]

the Evolution of a land model

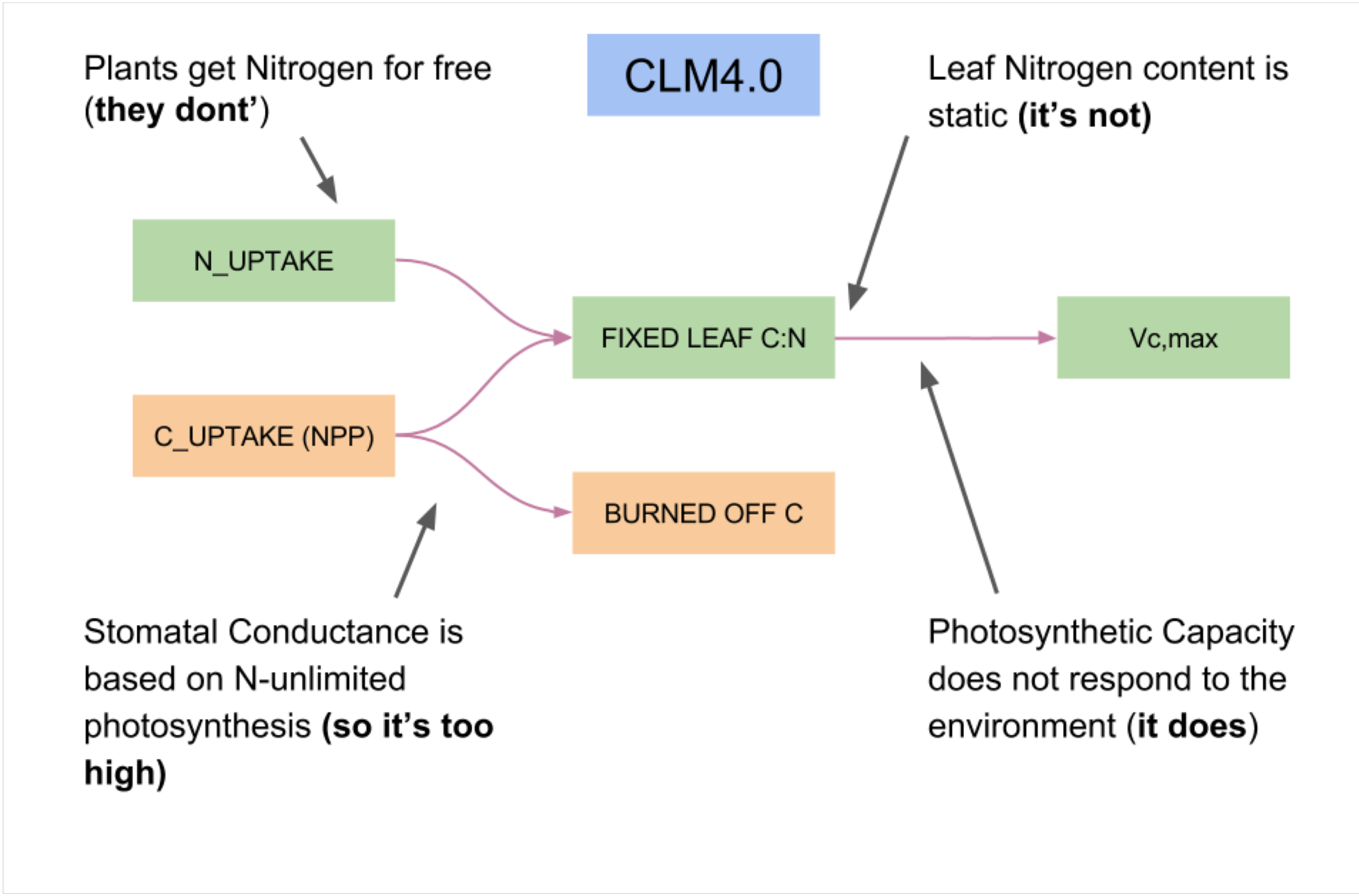
CLM 4.0 | CLM4.5 | CLM5.0

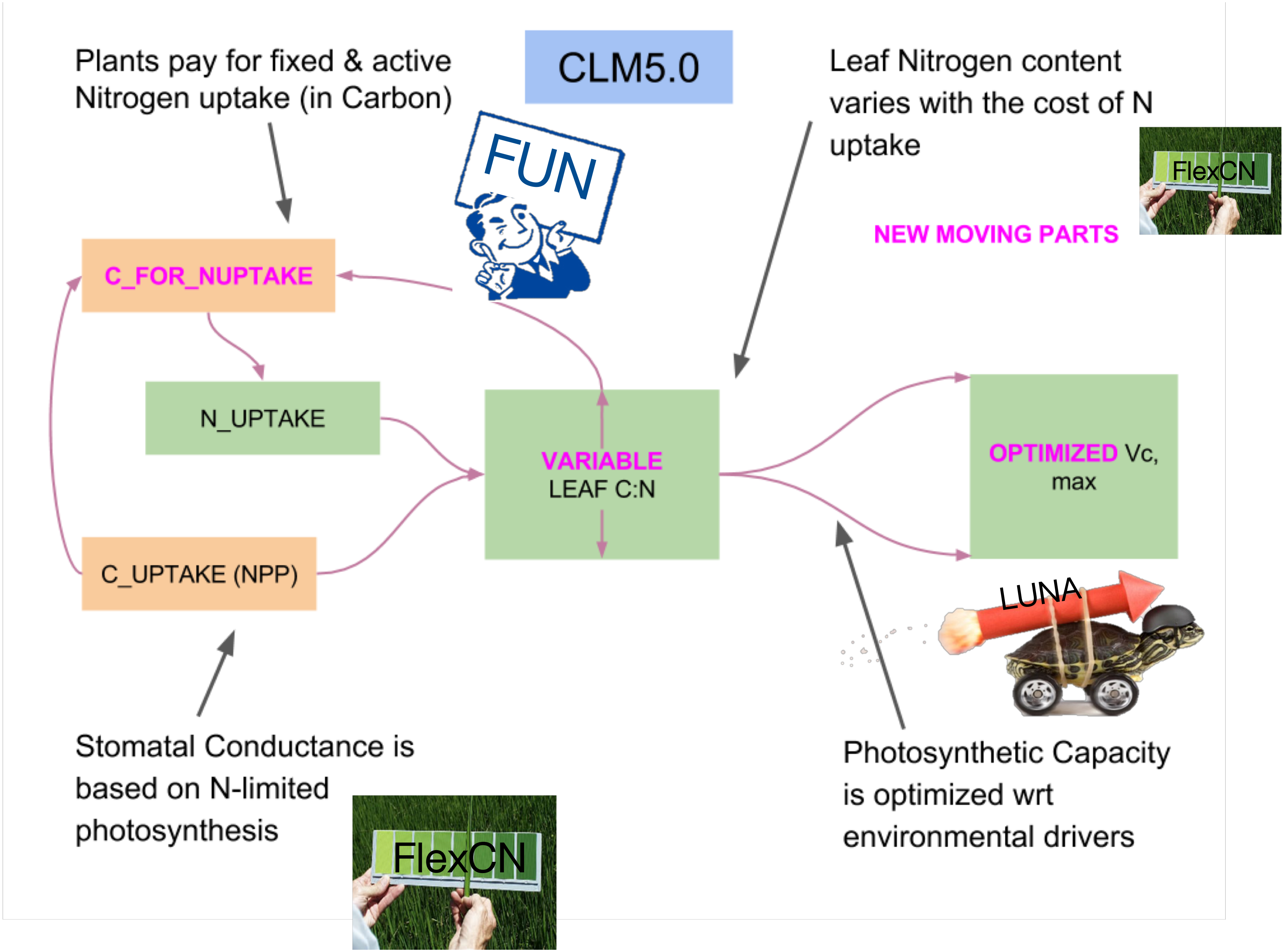
2007

2013

2018

Issues raised with the CLM4.0(CN) & CLM4.5(BGC)





CLM5.0
Plants pay for fixed & active Nitrogen uptake (in Carbon)
FUN
Leaf Nitrogen content varies with the cost of N uptake
FlexCN
NEW MOVING PARTS
C_FOR_NUPTAKE
N_UPTAKE
VARIABLE LEAF C:N
OPTIMIZED Vc, max
C_UPTAKE (NPP)
LUNA
Stomatal Conductance is based on N-limited photosynthesis
FlexCN
Photosynthetic Capacity is optimized wrt environmental drivers

Nitrogen assumptions in CLM4 & 4.5

"Leaf Nitrogen content is static"

"Stomatal conductance is based on N-unlimited photosynthesis"

"Photosynthetic capacity does NOT respond to the environment"

"Plants get Nitrogen for free"

“Leaf Nitrogen content is static”

“Stomatal conductance is based on N-unlimited photosynthesis” –CLM4 & 4.5

Table 8.1. Plant functional type (PFT) photosynthetic parameters.

PFT	m	α	CN_L	F_{LNR}	SLA_0	ψ_o	ψ_c	V_{cmax25}
NET Temperate	9	–	35	0.0509	0.010	-66000	-255000	62.5
NET Boreal	9	–	40	0.0466	0.008	-66000	-255000	62.6
NDT Boreal	9	–	25	0.0546	0.024	-66000	-255000	39.1
BET Tropical	9	–	30	0.0461	0.012	-66000	-255000	55.0
BET temperate	9	–	30	0.0515	0.012	-66000	-255000	61.5
BDT tropical	9	–	25	0.0716	0.030	-35000	-224000	41.0
BDT temperate	9	–	25	0.1007	0.030	-35000	-224000	57.7
BDT boreal	9	–	25	0.1007	0.030	-35000	-224000	57.7
BES temperate	9	–	30	0.0517	0.012	-83000	-428000	61.7

“Leaf Nitrogen content is variable”

“Stomatal conductance is based on N-limited photosynthesis”

`use_flexiblecn = .true.`

`[bgc only]`

Code base:

[biogeochem/NutrientCompetitionFlexibleCNMod.F90]()

Technical note:

[2.16: CN Pools]()

[2.19: CN Allocation]()

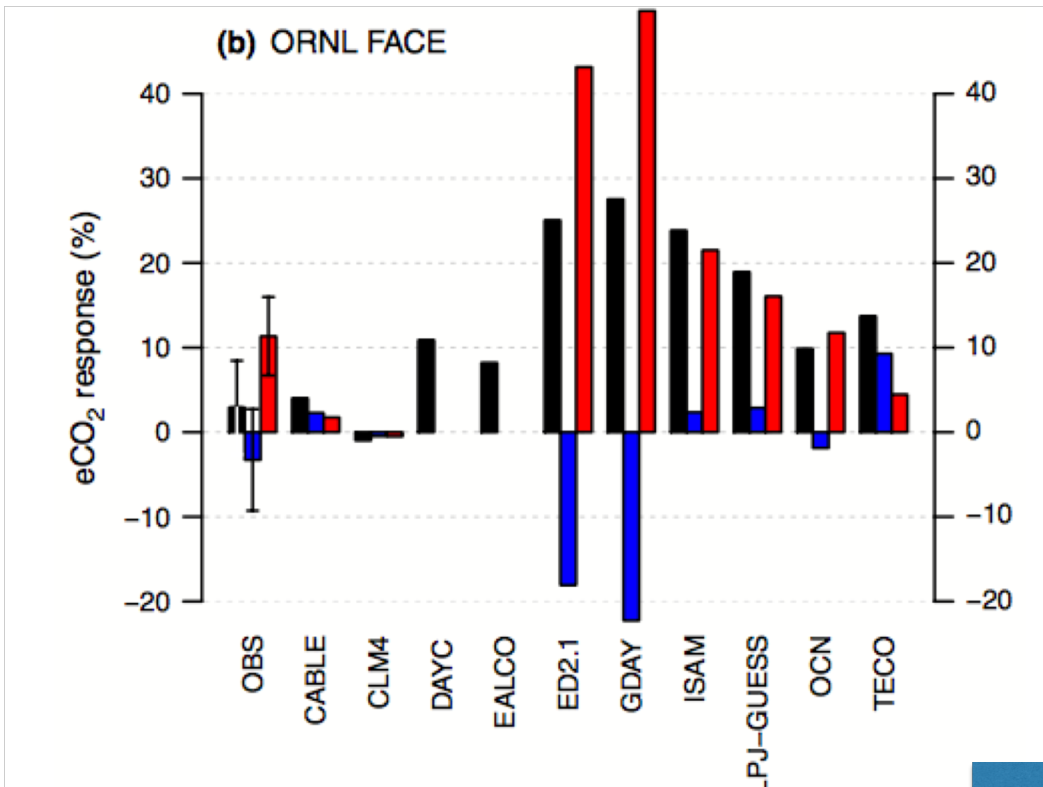
The FlexCN Model

Variable carbon:nitrogen ratios

Representing leaf and root physiological traits in CLM improves global carbon and nitrogen cycling predictions

Bardan Ghimire[1], William J. Riley[1], Charles D. Koven[1], Mingquan Mu[2], and James T. Randerson[2]

Increase in productivity due to change C:N ratio
Increase in productivity due to increased NUE (fertilization)
Increase in productivity due to increased leaf allocation

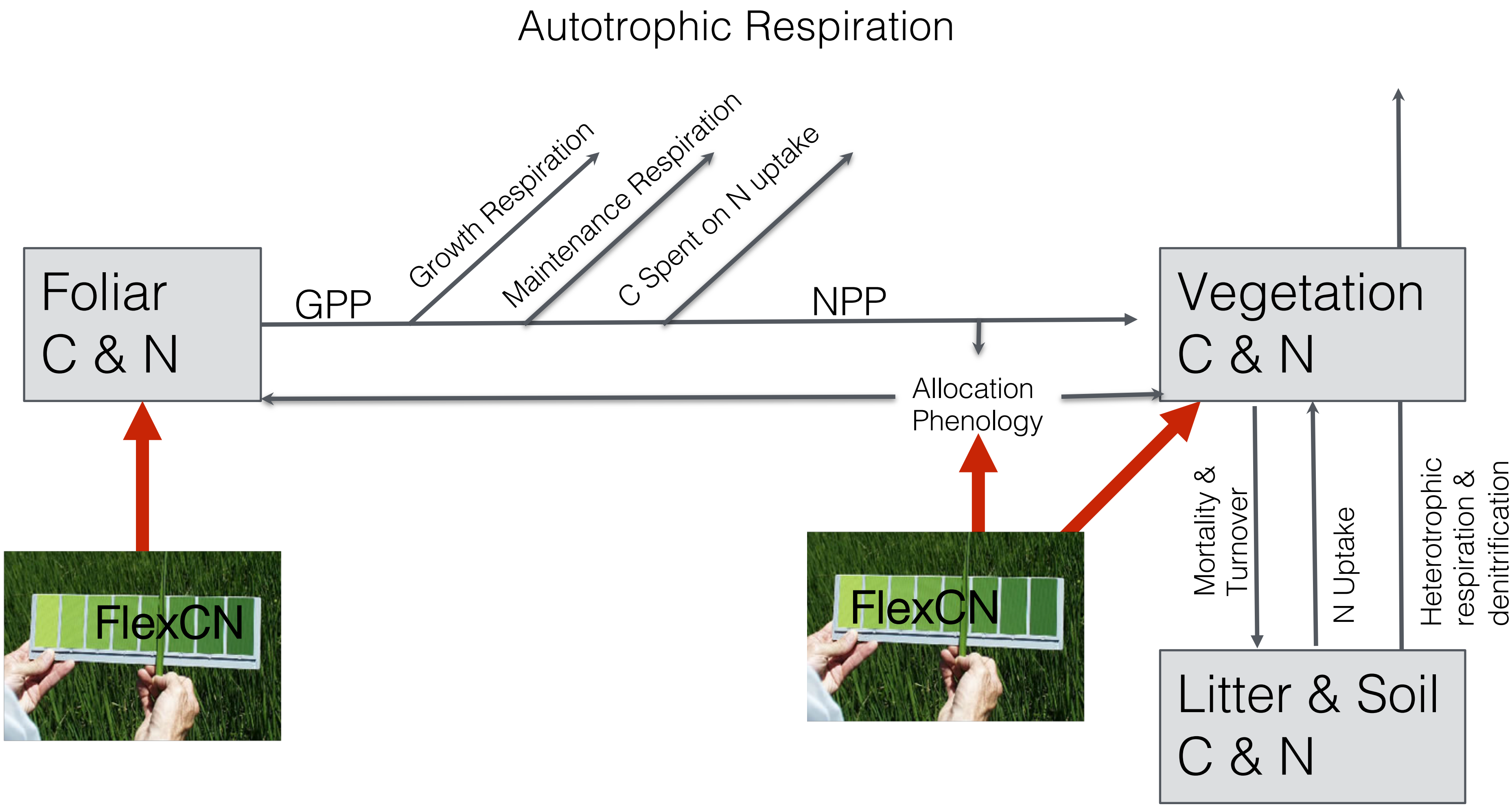


Zaehle et al. 2014

'FlexCN' allows for tissue-level variation in C:N ratio relative to target parameter.

Standalone FlexCN model tested in CLM4.5* by Ghimire et al. (2016) JAMES

Hypothesis: Plants will vary their tissue Carbon:Nitrogen ratio as N availability varies in space and time

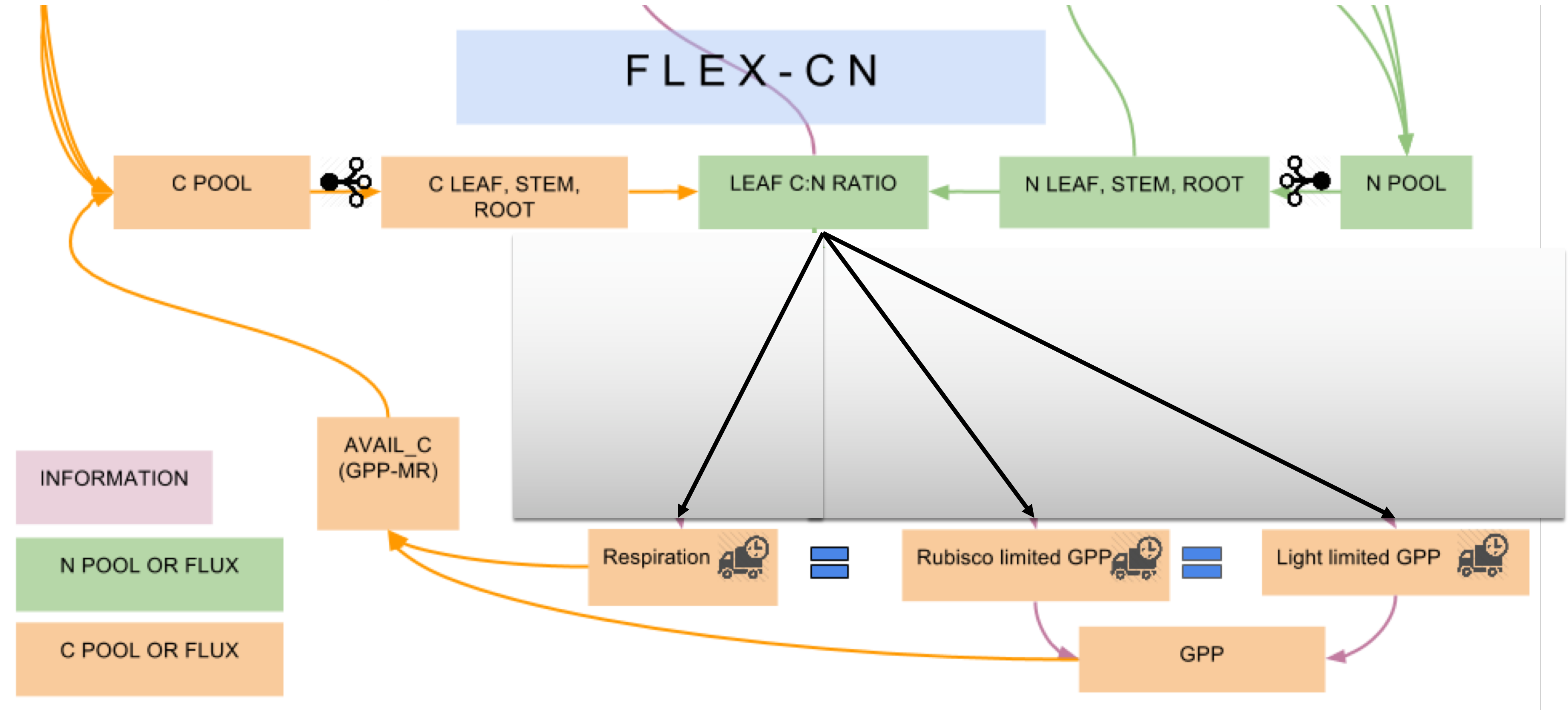


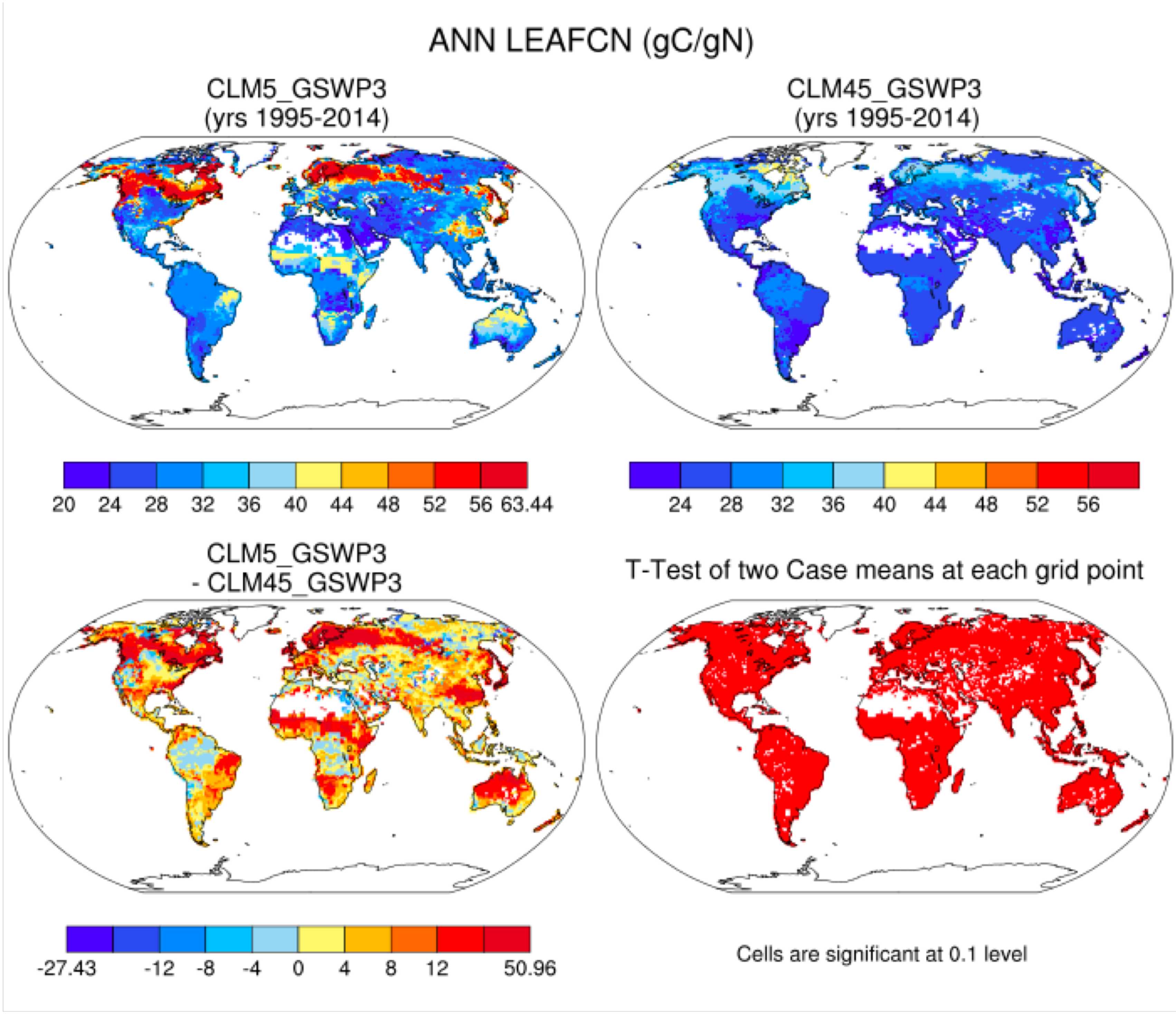
If N uptake is too low, C:N ratios will increase

If N uptake is too low,
Foliar C:N ratios will increase
Photosynthesis will decreases

$$V_{c\max 25} = N_a F_{LNR} F_{NR} a_{R25} \quad (8.17)$$

$$N_a = \frac{1}{CN_L \; SLA_0} \quad (8.18)$$





http://www.cesm.ucar.edu/experiments/cesm2.0/land/diagnostics/clm_diag_PCKG.html

"Photosynthetic capacity does NOT respond to the environment" –CLM4 & 4.5

$$V_{c\max 25} = N_a F_{LNR} F_{NR} a_{R25} \quad (8.17)$$

Table 8.1. Plant functional type (PFT) photosynthetic parameters.

PFT	m	α	CN_L	F_{LNR}	SLA_0	ψ_o	ψ_c	V_{cmax25}
NET Temperate	9	–	35	0.0509	0.010	-66000	-255000	62.5
NET Boreal	9	–	40	0.0466	0.008	-66000	-255000	62.6
NDT Boreal	9	–	25	0.0546	0.024	-66000	-255000	39.1
BET Tropical	9	–	30	0.0461	0.012	-66000	-255000	55.0
BET temperate	9	–	30	0.0515	0.012	-66000	-255000	61.5
BDT tropical	9	–	25	0.0716	0.030	-35000	-224000	41.0
BDT temperate	9	–	25	0.1007	0.030	-35000	-224000	57.7
BDT boreal	9	–	25	0.1007	0.030	-35000	-224000	57.7
BES temperate	9	–	30	0.0517	0.012	-83000	-428000	61.7

“Photosynthetic capacity DOES respond to the environment” –LUNA

```
use_luna = .true.
[sp or bgc mode]
```

Code base: [src/biogeophys/LunaMod.F90]() & src/biogeophys/PhotosynthesisMod.F90

Technical note: [2.10: Photosynthetic capacity]()

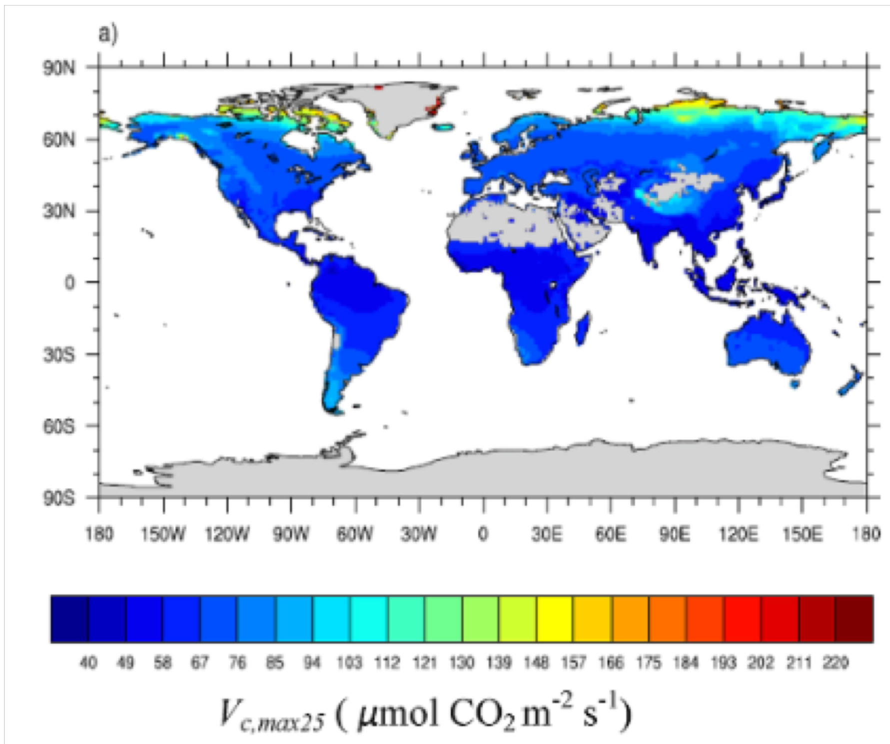
The LUNA* Model

How best to use the Nitrogen you have?

*Leaf Use of Nitrogen for Assimilation

Predicted optimal photosynthetic capacity

Prognostic V_{cmx25} & J_{mx25}

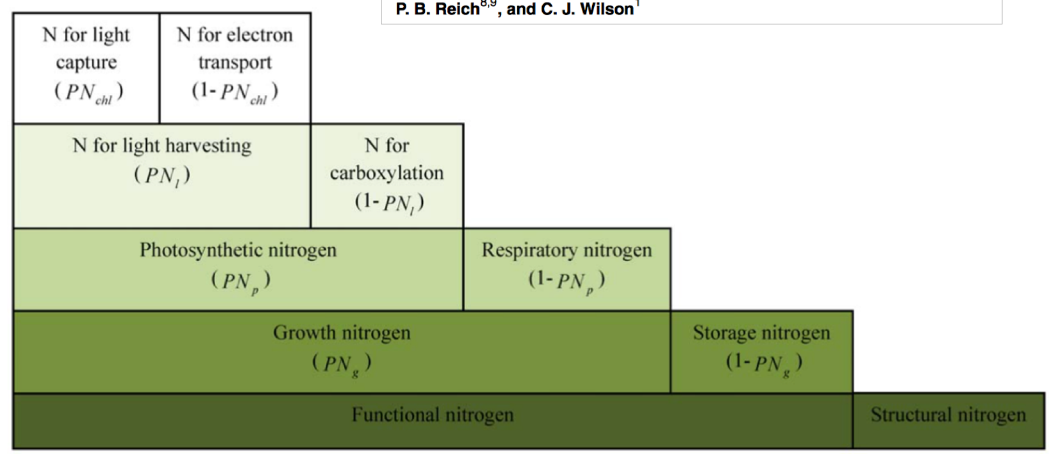


Toward a Mechanistic Modeling of Nitrogen Limitation on Vegetation Dynamics

Chonggang Xu[1]*, Rosie Fisher[2], Stan D. Wullschleger[3], Cathy J. Wilson[1], Michael Cai[4], Nate G. McDowell[1]

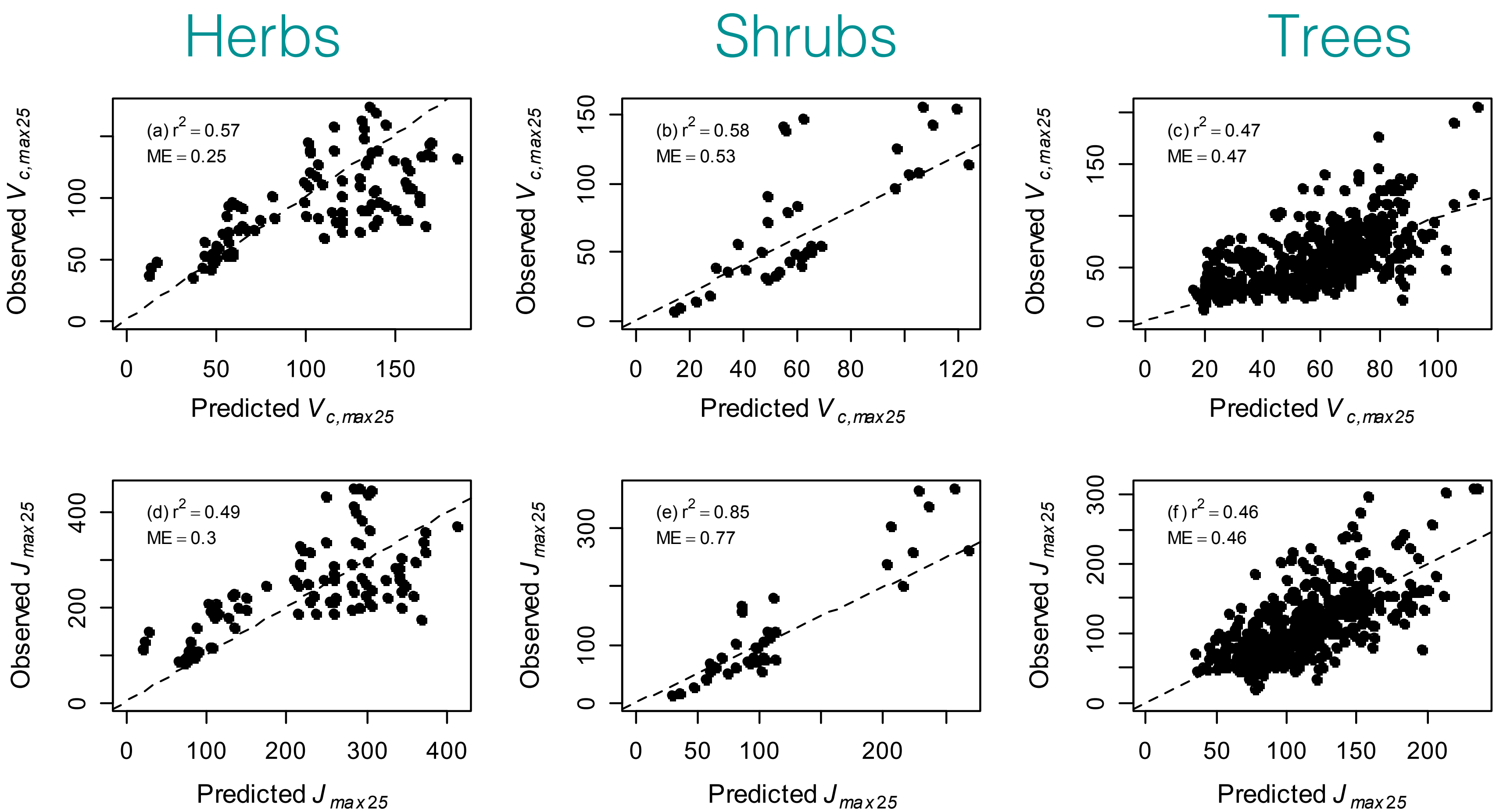
A global scale mechanistic model of the photosynthetic capacity

A. A. Ali[1,2], C. Xu[1], A. Rogers[3], R. A. Fisher[4], S. D. Wullschleger[5], N. G. McDowell[1], E. C. Massoud[2], J. A. Vrugt[2,6], J. D. Muss[1], J. B. Fisher[7], P. B. Reich[8,9], and C. J. Wilson[1]

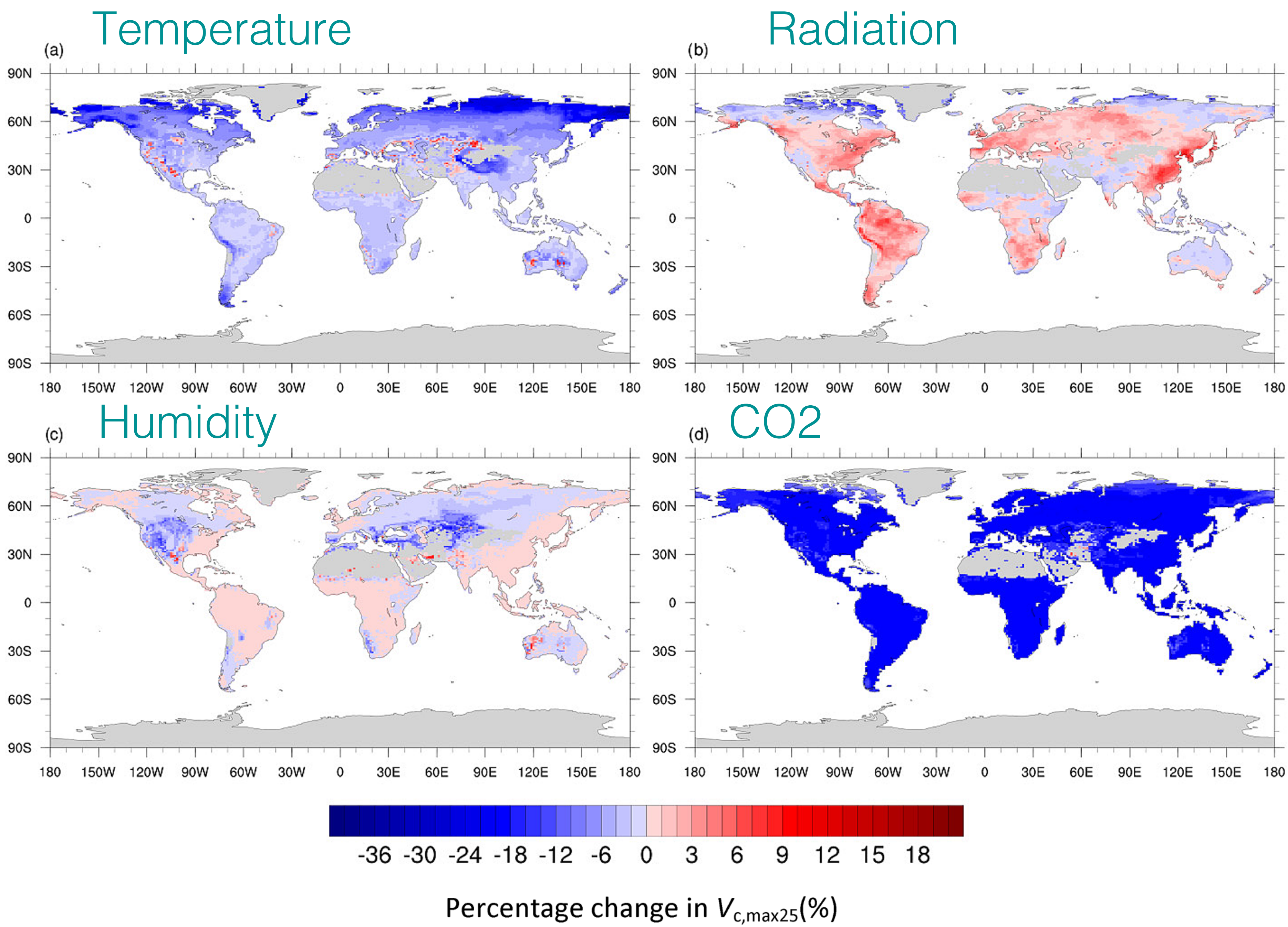


Hypothesis: Leaf Nitrogen is distributed so that light capture, carboxylation and respiration are co-limiting

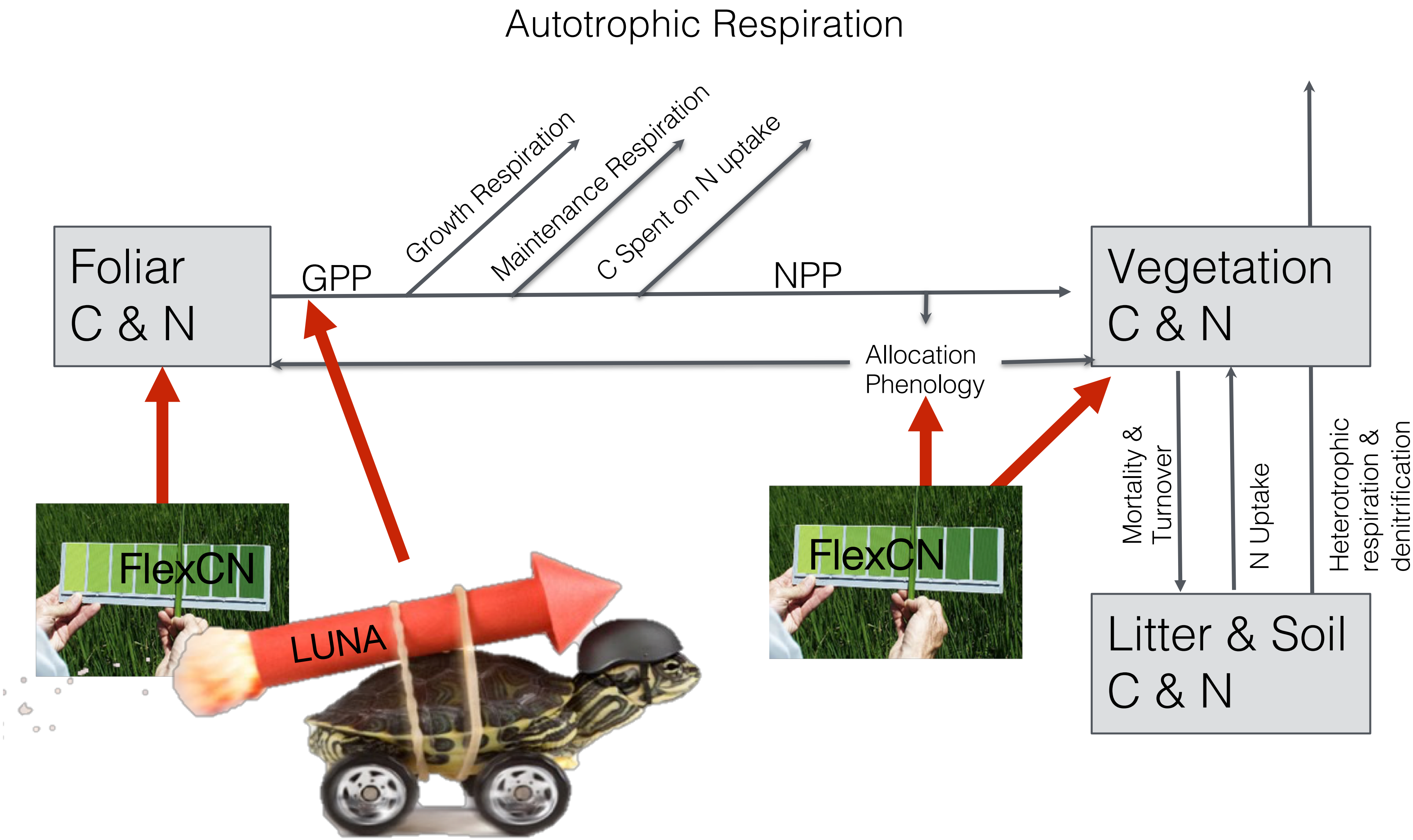
LUNA performance vs. observations

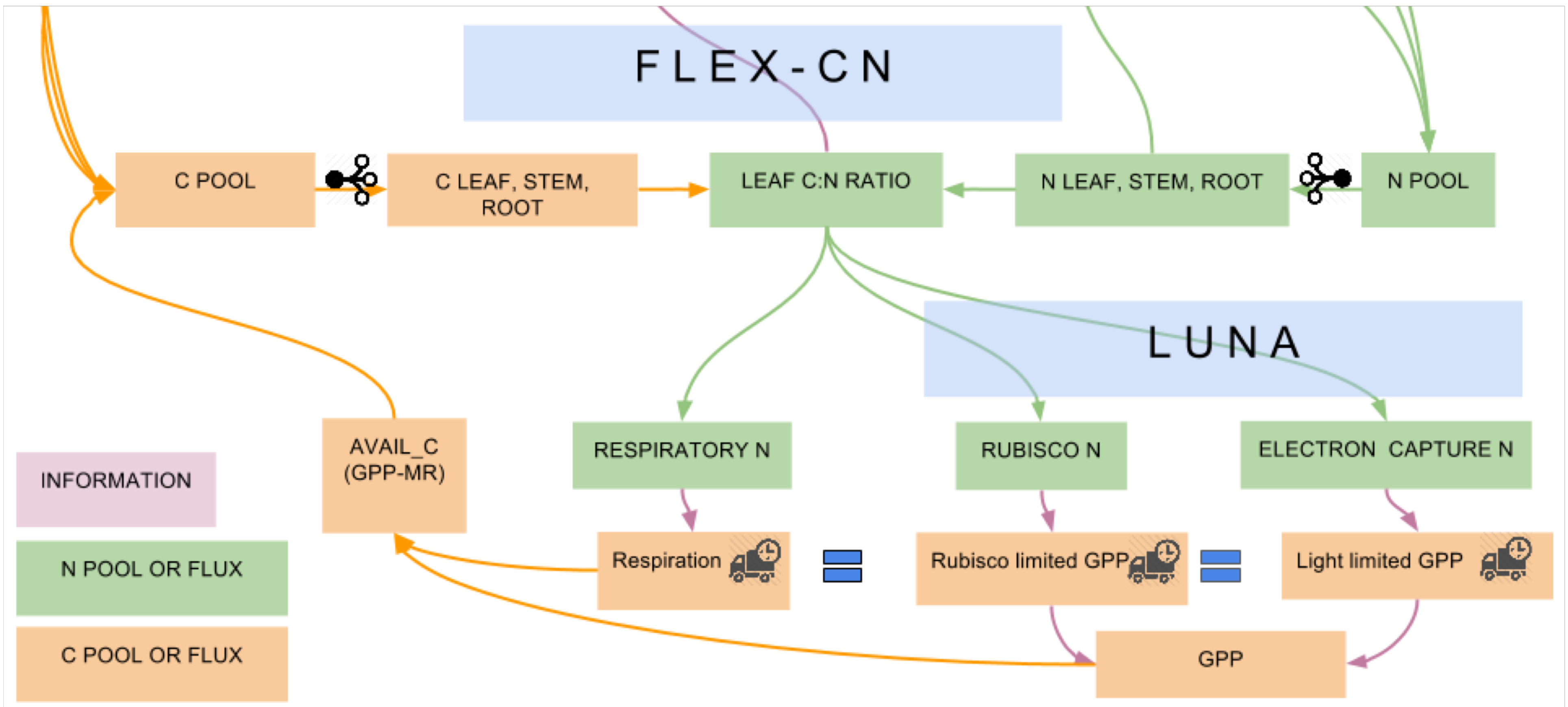


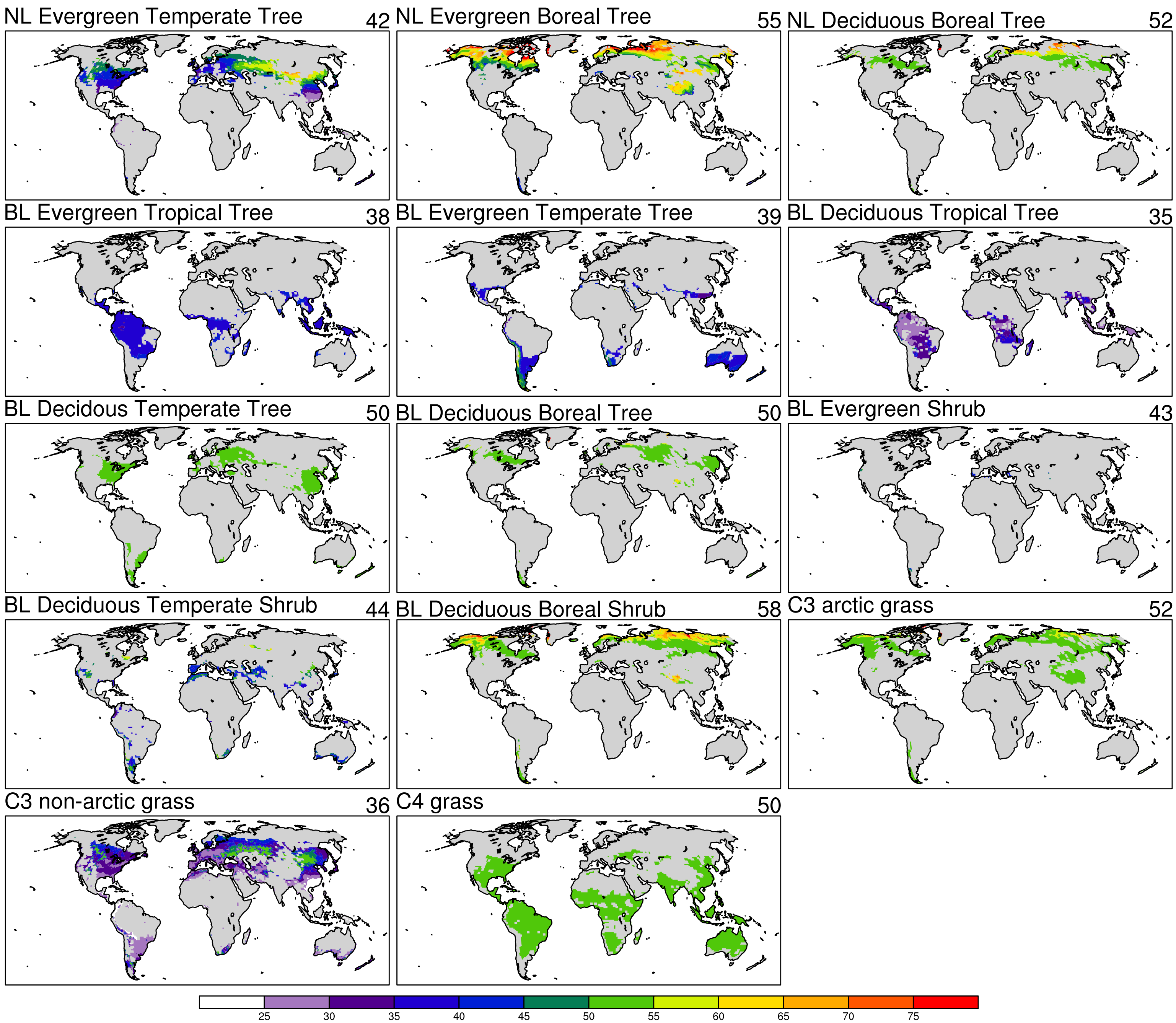
Ali et al. 2016 GMD



Ali et al. 2016 GMD


Autotrophic Respiration
Growth Respiration
Maintenance Respiration
C Spent on N uptake
Foliar
C & N
GPP
NPP
Vegetation
C & N
Allocation
Phenology
Mortality &
Turnover
N Uptake
Heterotrophic
respiration &
denitrification
FlexCN
LUNA
FlexCN
Litter & Soil
C & N


FLEX-CN
C POOL
C LEAF, STEM, ROOT
LEAF C:N RATIO
N LEAF, STEM, ROOT
N POOL
LUNA
INFORMATION
N POOL OR FLUX
C POOL OR FLUX
AVAIL_C (GPP-MR)
RESPIRATORY N
RUBISCO N
ELECTRON CAPTURE N
Respiration
Rubisco limited GPP
Light limited GPP
GPP



Lawrence et al. in review JAMES

* Changes with time, annual max of monthly averages

“plants pay carbon costs for nitrogen uptake” -FUN

```
use_fun = .true.
[bgc only]
```

Code base: [biogeochem/CNFUNMod.F90]

Technical note: [2.18: FUN]

The FUN* Model

A marketplace for Nitrogen Uptake

*Fixation and Uptake of Nitrogen

Standalone FUN model tested in CLM4.0 by [Shi et al. (2016) Global Change Biology]

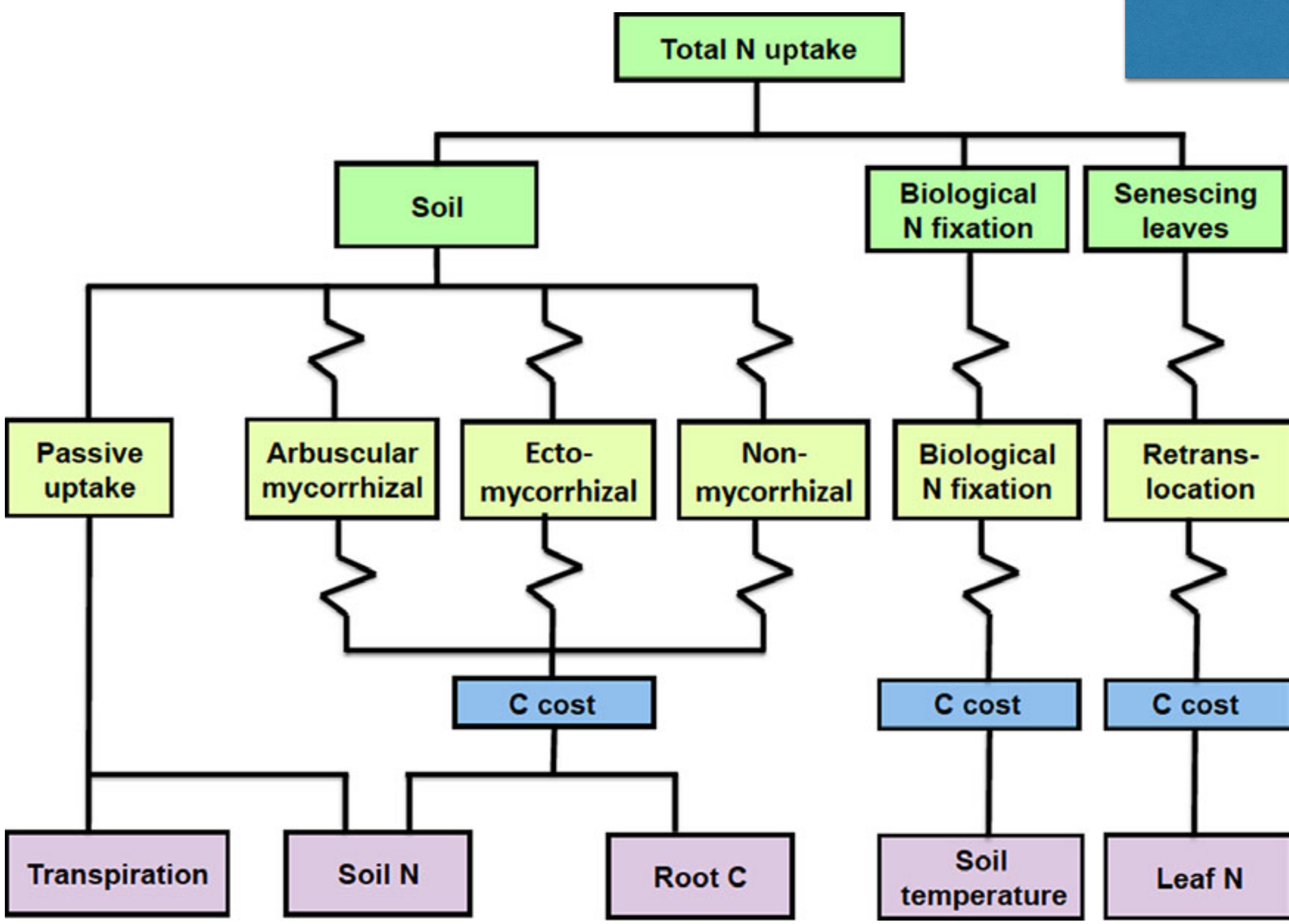
Carbon cost of plant nitrogen acquisition: A mechanistic, globally applicable model of plant nitrogen uptake, retranslocation, and fixation

J. B. Fisher,[1] S. Sitch,[2] Y. Malhi,[1] R. A. Fisher,[3] C. Huntingford,[4] and S.-Y. Tan[1]

Modeling the carbon cost of plant nitrogen acquisition: Mycorrhizal trade-offs and multipath resistance uptake improve predictions of retranslocation

Edward R. Brzostek[1], Joshua B. Fisher[2,3], and Richard P. Phillips[1]

Hypothesis:
Plants will take up N from the cheapest sources



Solution to FUN model

$$C_{nuptake} = \frac{GPP - Mresp}{CNtarget/CN_{uptake\_cost} + 1}$$

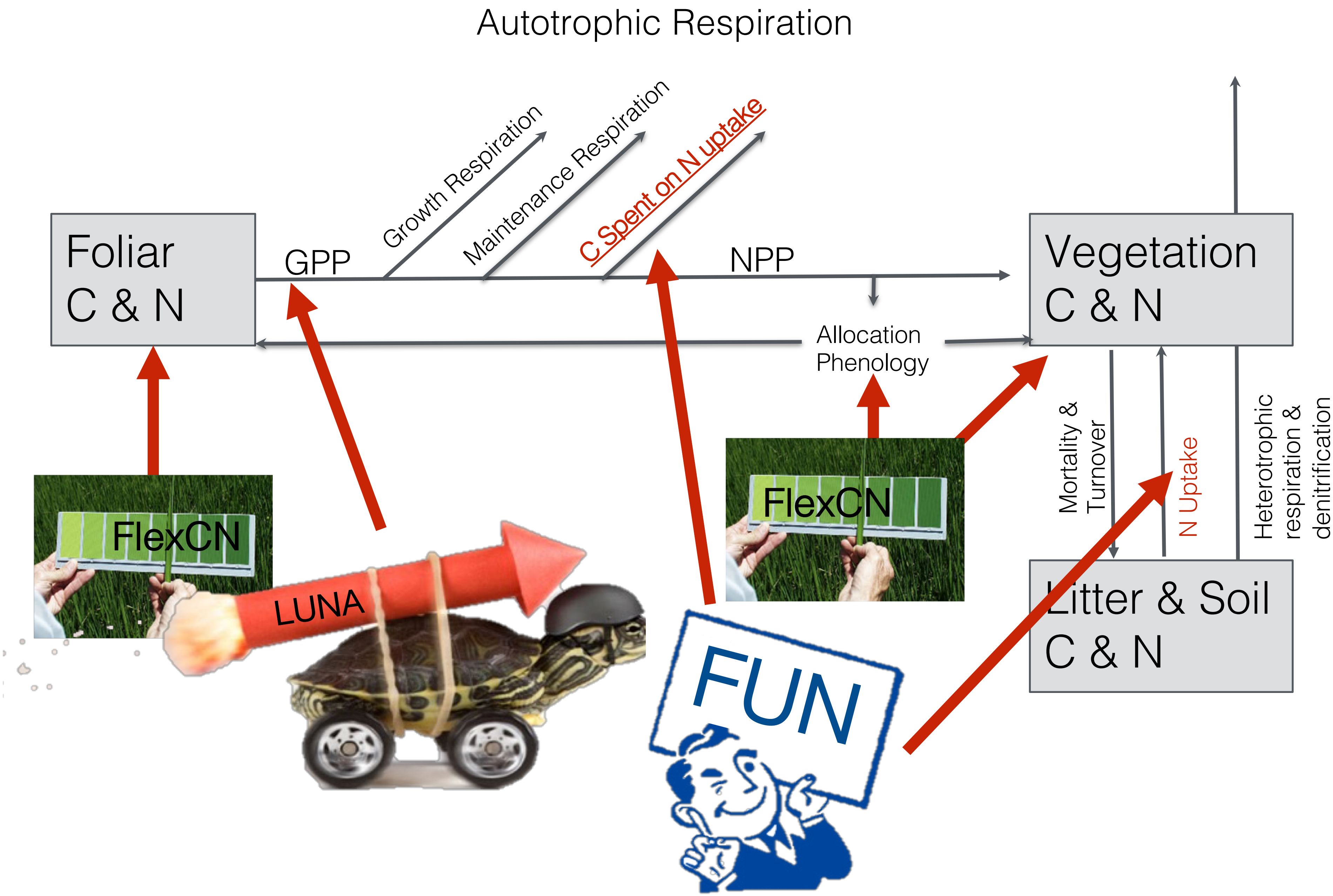
Solve for maximum growth

$C_{growth} = C_{npp} - C_{nuptake}$

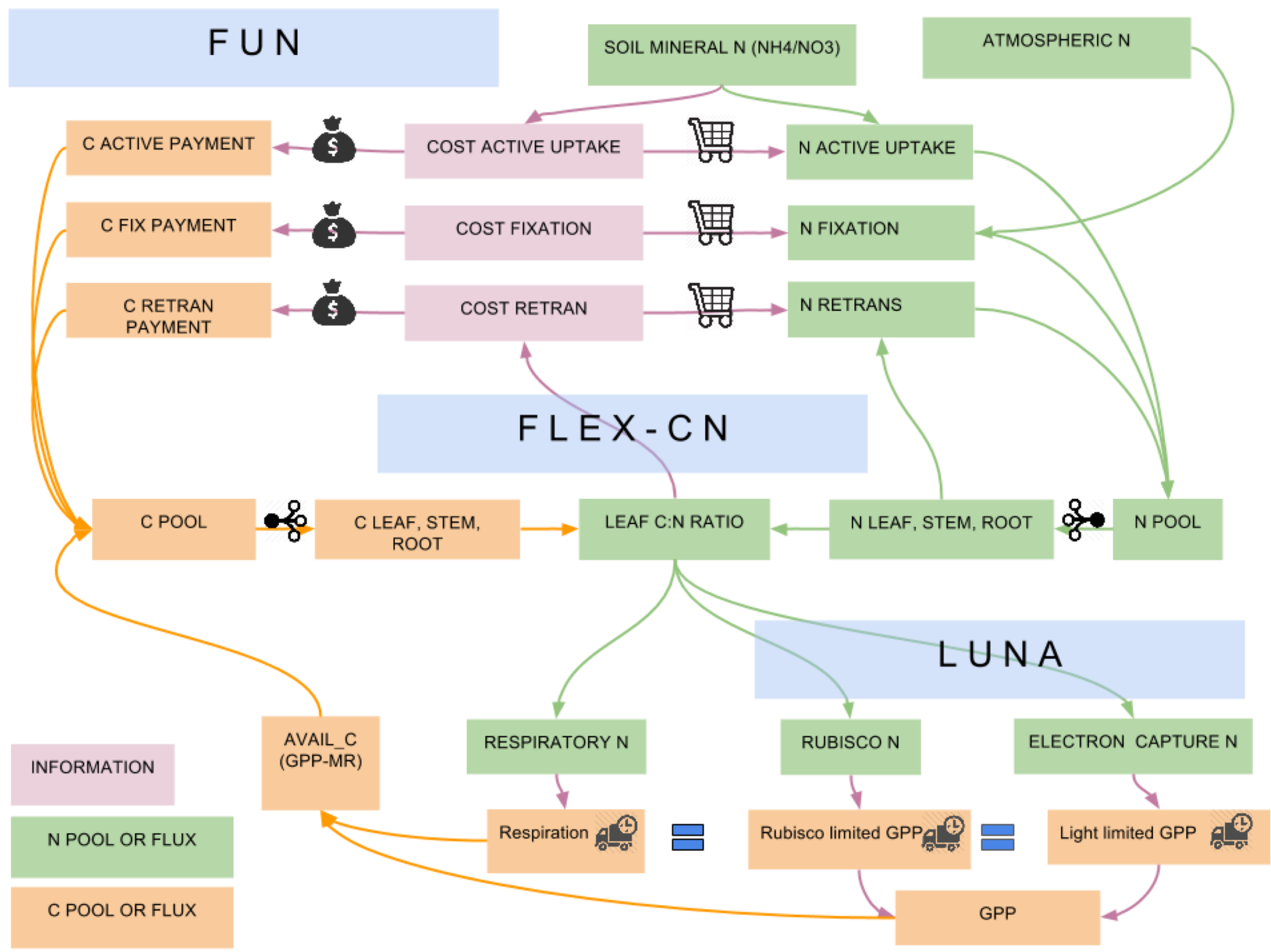
$N_{growth} = N_{uptake}$

$N_{uptake} = C_{nuptake} / CN_{uptake\_cost}$

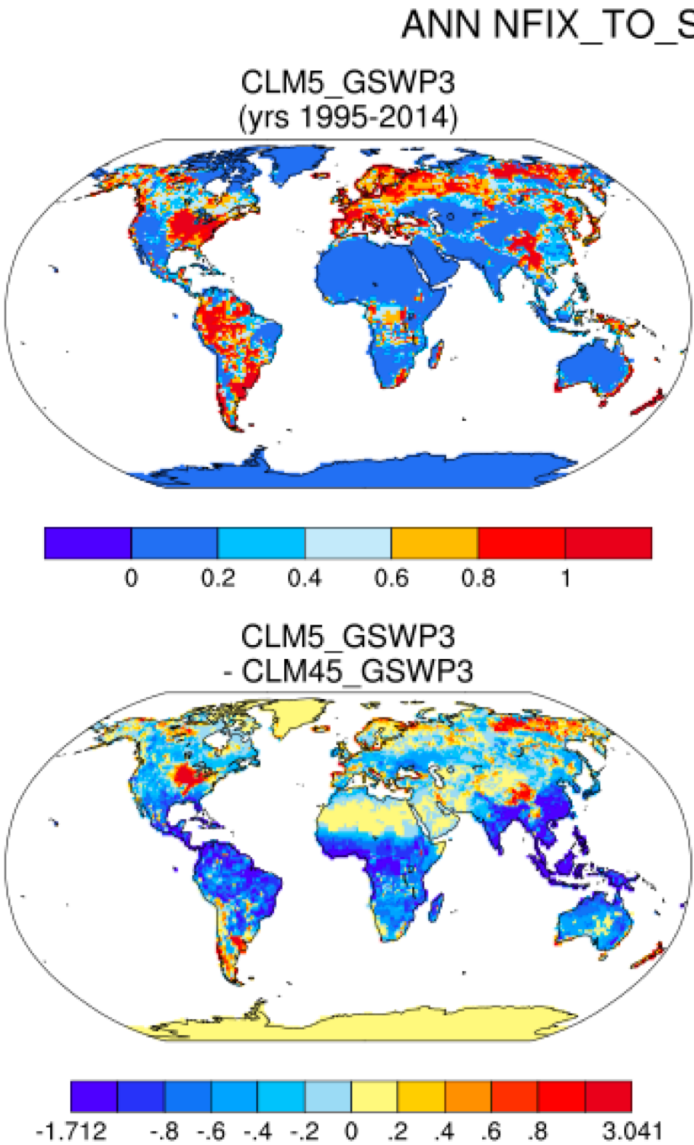
$N_{growth} = C_{growth} / CN_{target}$

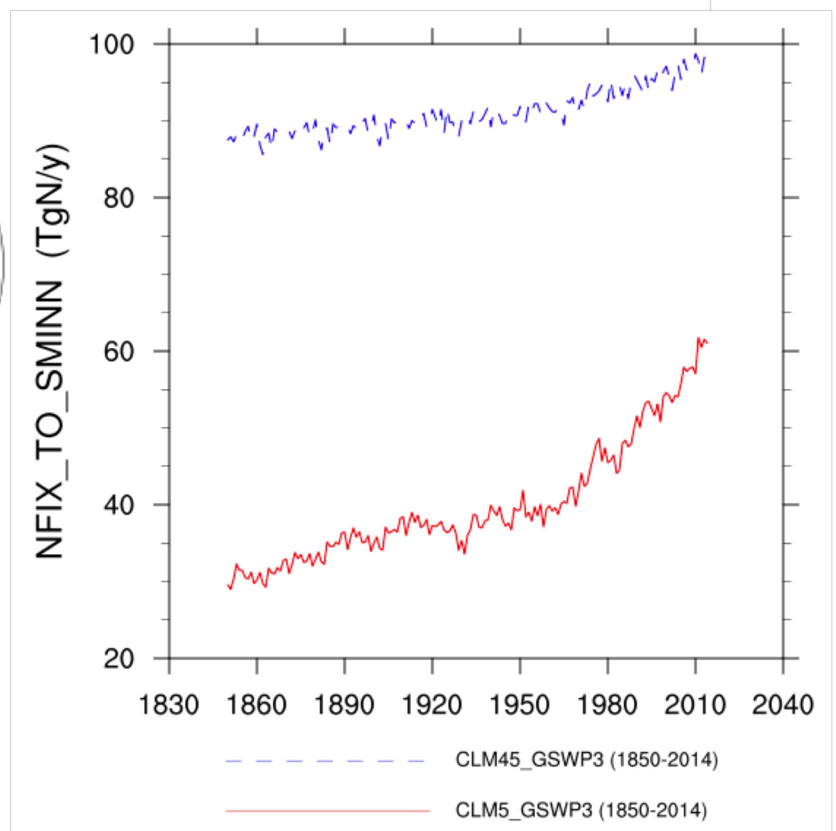


Autotrophic Respiration
Growth Respiration
Maintenance Respiration
C Spent on N uptake
Foliar C & N
GPP
NPP
Vegetation C & N
Allocation Phenology
Mortality & Turnover
N Uptake
Heterotrophic respiration & denitrification
FlexCN
LUNA
FlexCN
FUN
Litter & Soil C & N


FUN
SOIL MINERAL N (NH4/NO3)
ATMOSPHERIC N
C ACTIVE PAYMENT
COST ACTIVE UPTAKE
N ACTIVE UPTAKE
C FIX PAYMENT
COST FIXATION
N FIXATION
C RETRAN PAYMENT
COST RETRAN
N RETRANS
FLEX-CN
C POOL
C LEAF, STEM, ROOT
LEAF C:N RATIO
N LEAF, STEM, ROOT
N POOL
LUNA
AVAIL_C (GPP-MR)
RESPIRATORY N
RUBISCO N
ELECTRON CAPTURE N
INFORMATION
N POOL OR FLUX
C POOL OR FLUX
Respiration
Rubisco limited GPP
Light limited GPP
GPP

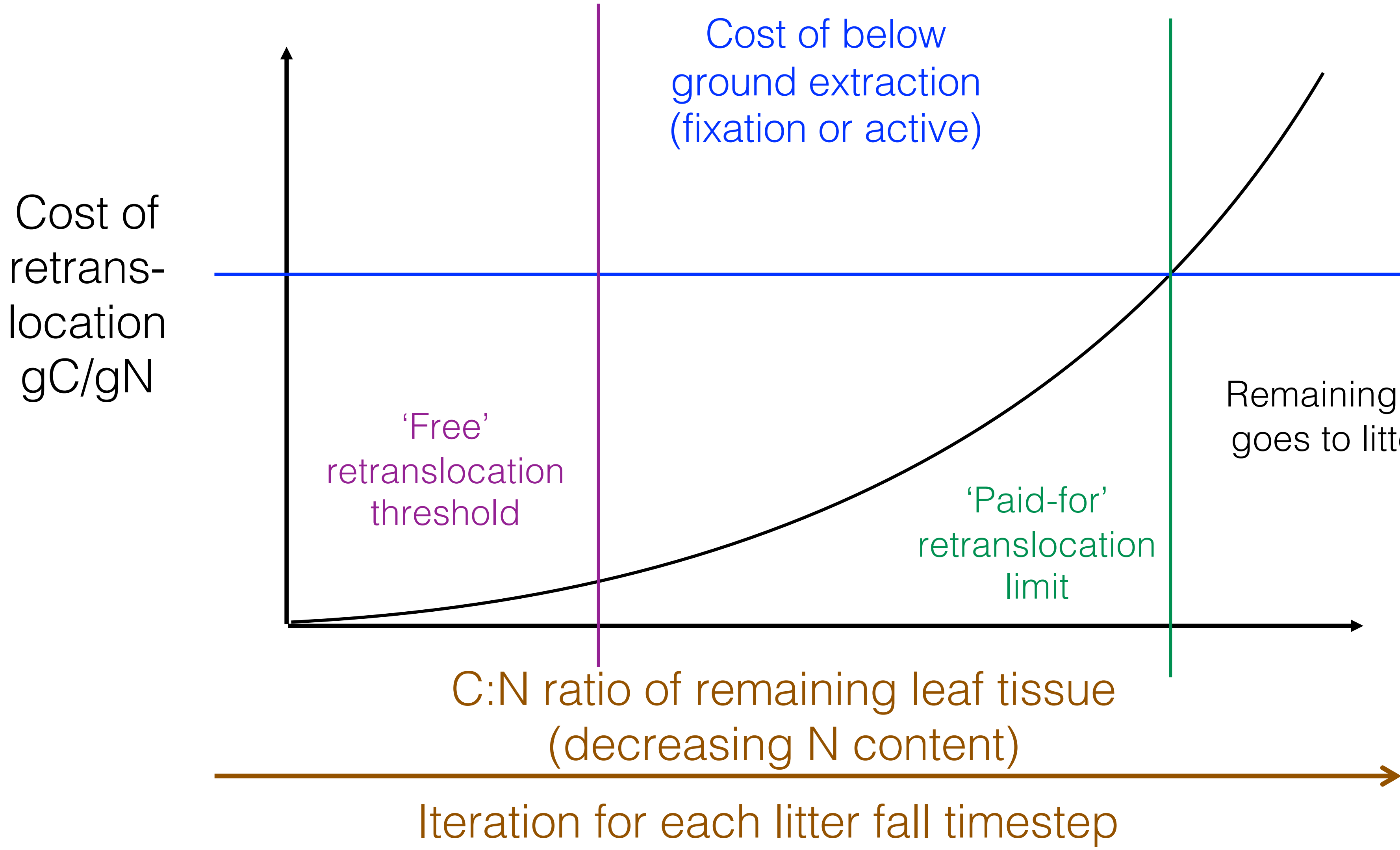
CLM5 has new diagnostic variables
NFIX & FFIX_TO_SMINN






Retranslocation

Schematic of Retranslocation Algorithm



Note, the current CLM5 code base has a bug related to woodCN ratios and retranslocation, stay tuned to github for more.


FUN flex-CN reconciliation

FUN-FlexCN coupling

- The FUN model **targets** a fixed C/N ratio
- This intrinsically does **not** allow flexible CN ratio.
- We thus need to change $C_{nuptake}$ to allow for this

$$C_{nuptake} = \frac{GPP - Mresp}{CNtarget/CN_{uptake\_cost} + 1}$$

Solve for maximum growth

$$C_{growth} = C_{npp} - C_{nuptake}$$

$$N_{growth} = N_{uptake}$$

$$N_{uptake} = C_{nuptake} / CN_{uptake\_cost}$$

$$N_{growth} = C_{growth} / CN_{target}$$

C allocation to uptake responds to $CN_{uptake-cost}$ and CN_{actual}

Adjustment factor

FUN equation

$$Cnuptake = C_{adj} \times \frac{(GPP-MR)}{(CN_{target} / CN_{uptake-cost}) + 1.0}$$

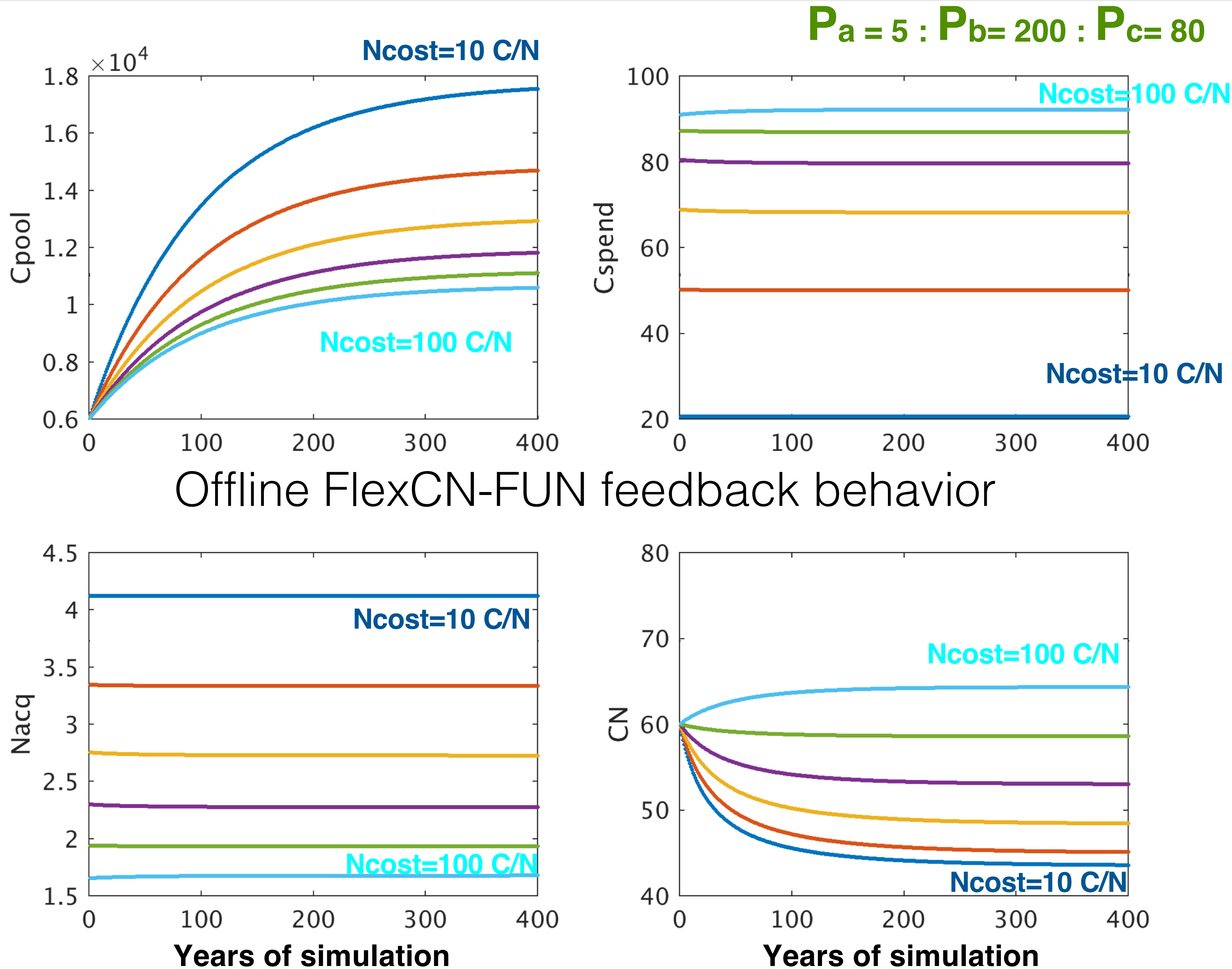
$$C_{adj} = 1.0 - (CN_{uptake-cost} - P_a) / P_b$$

Reduce C allocation with cost

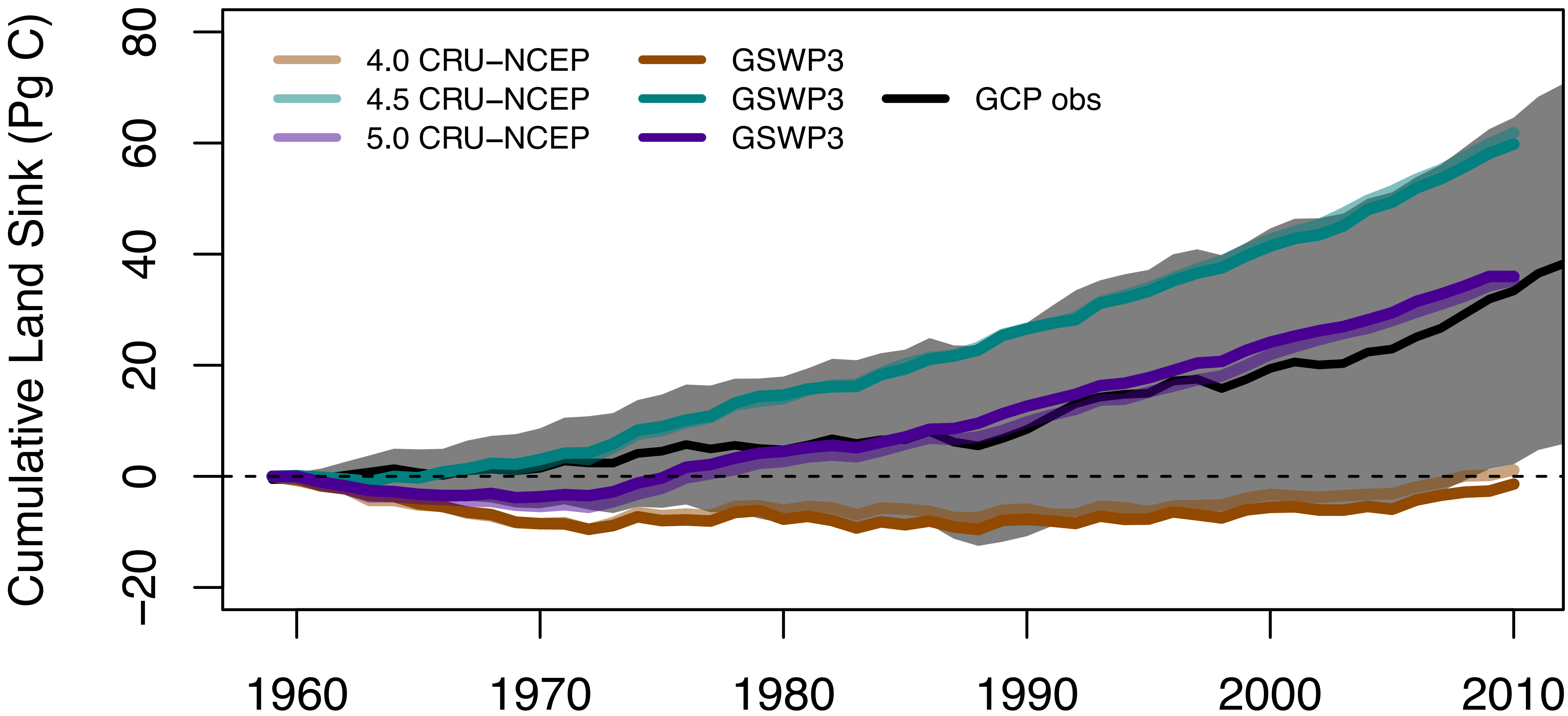
$$C_{adj} = C_{adj} + (1.0 - C_{adj}) \times (CN_{actual} - CN_{target}) / P_c$$

Increase C allocation with high C:N

Note, the current CLM5 code base has a bug related to this FlexCN-FUN coupling, stay tuned to github for more


Pa = 5 : Pb= 200 : Pc= 80
Offline FlexCN-FUN feedback behavior
Ncost=10 C/N
Ncost=100 C/N
Cpool
×10^4
Cspend
Nacq
CN
Years of simulation

land carbon uptake



Bonan et al in review
Lawrence it al in review

Control (GSWP3)

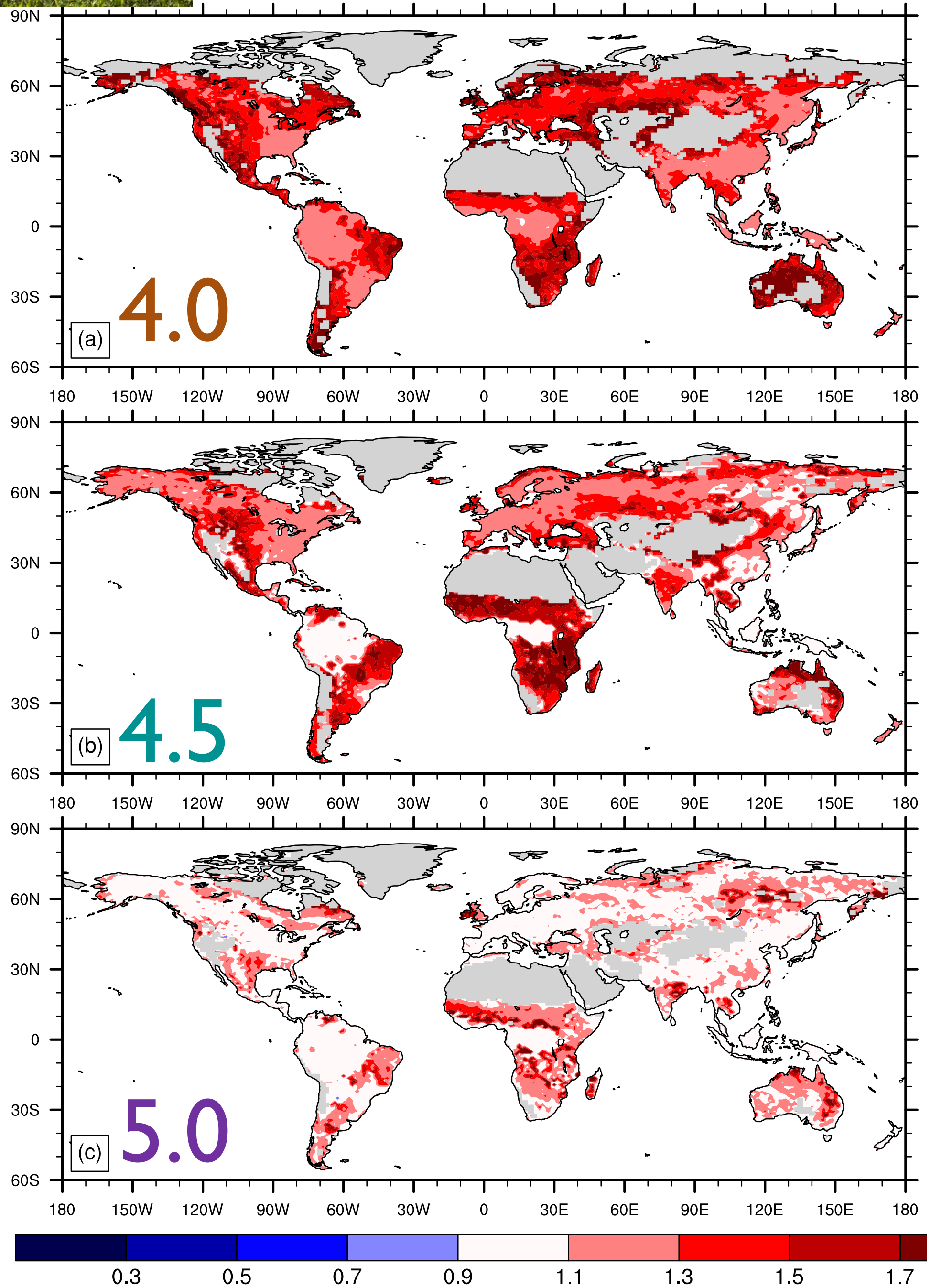
+N (50 kg N ha^{-1} y^{-1})

+CO_2 (200 ppm)

(treatment / control)

Medlyn et al. 2015 *Nature Clim. Change*
Wieder et al. 2019, GBC, In review

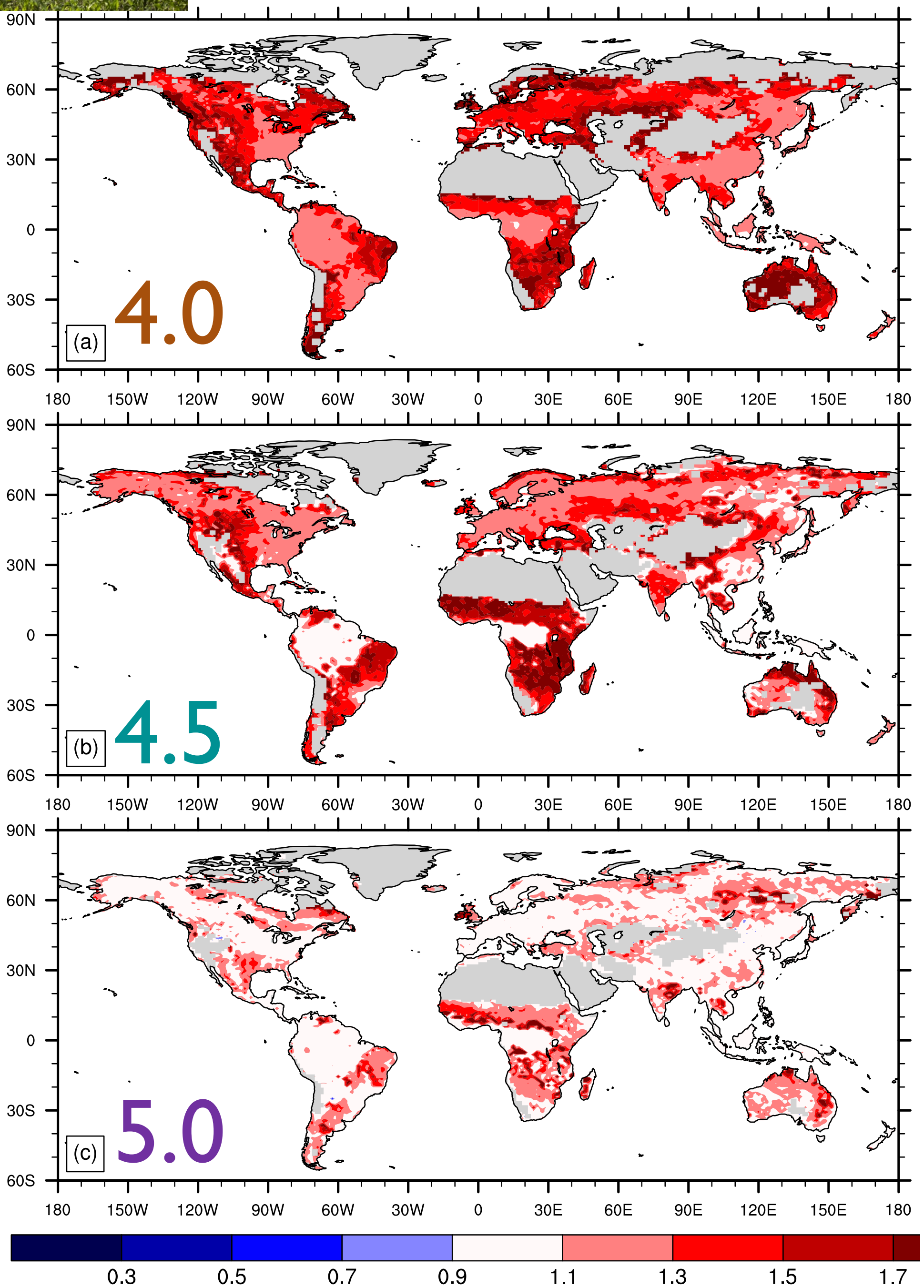
GPP +N (treatment / control)

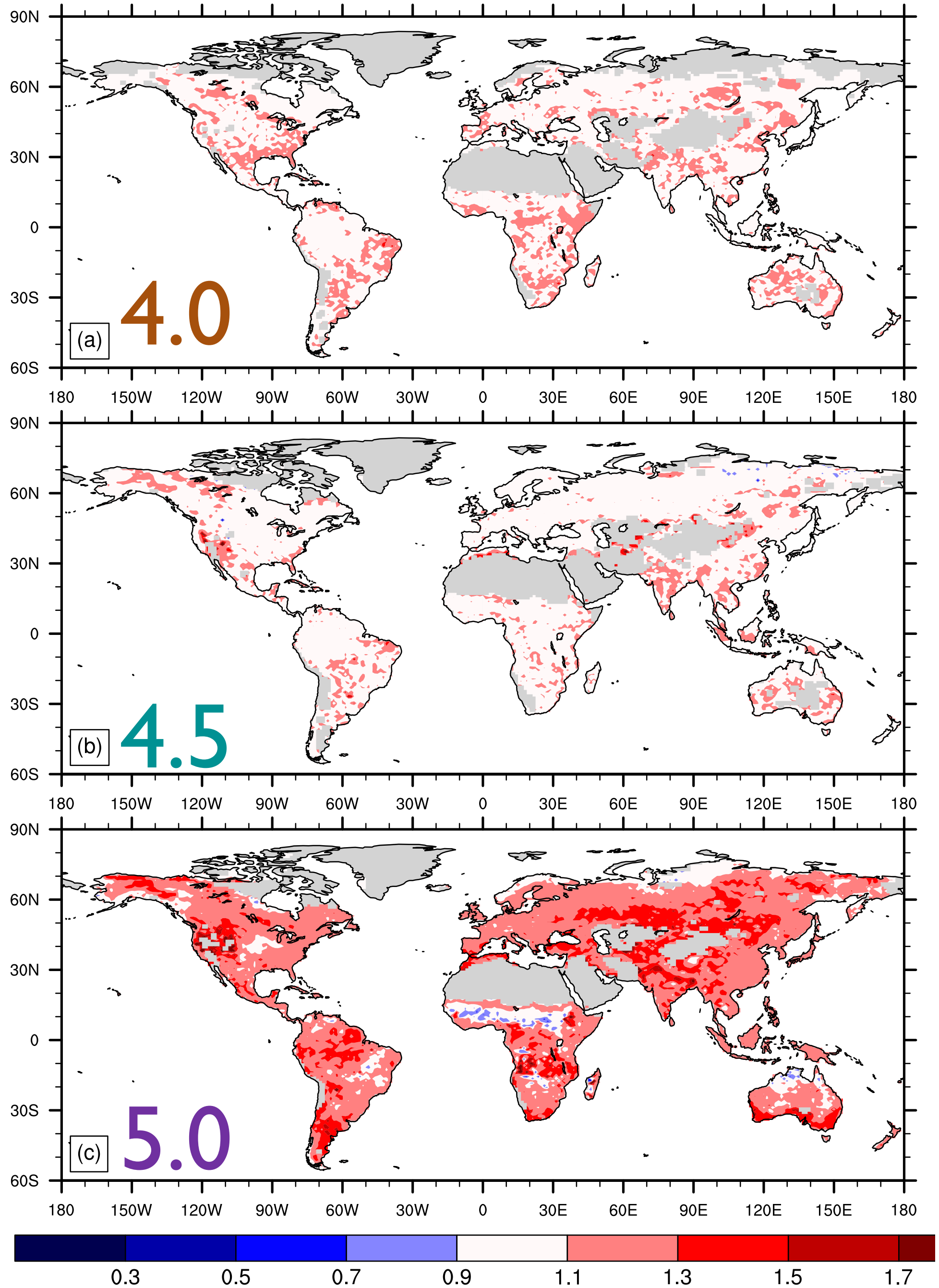


GPP +N

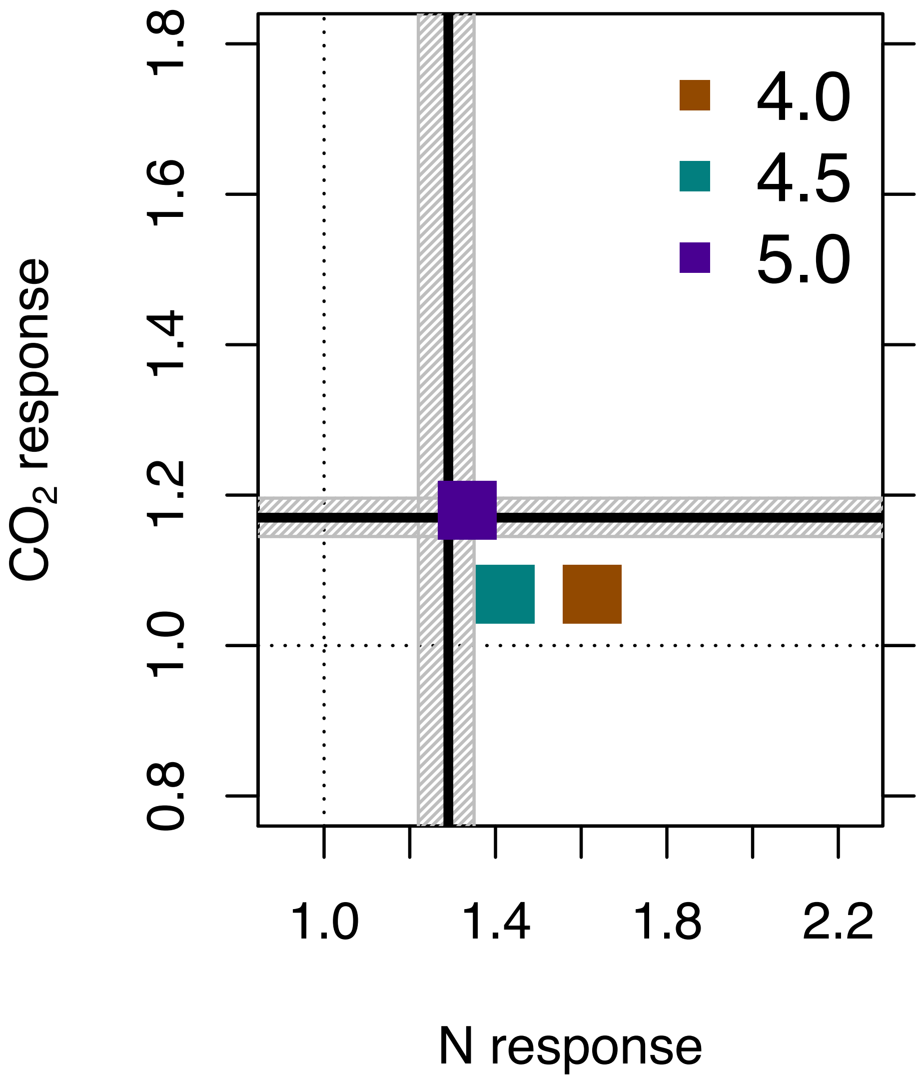
(treatment / control)

GPP $+CO_2$



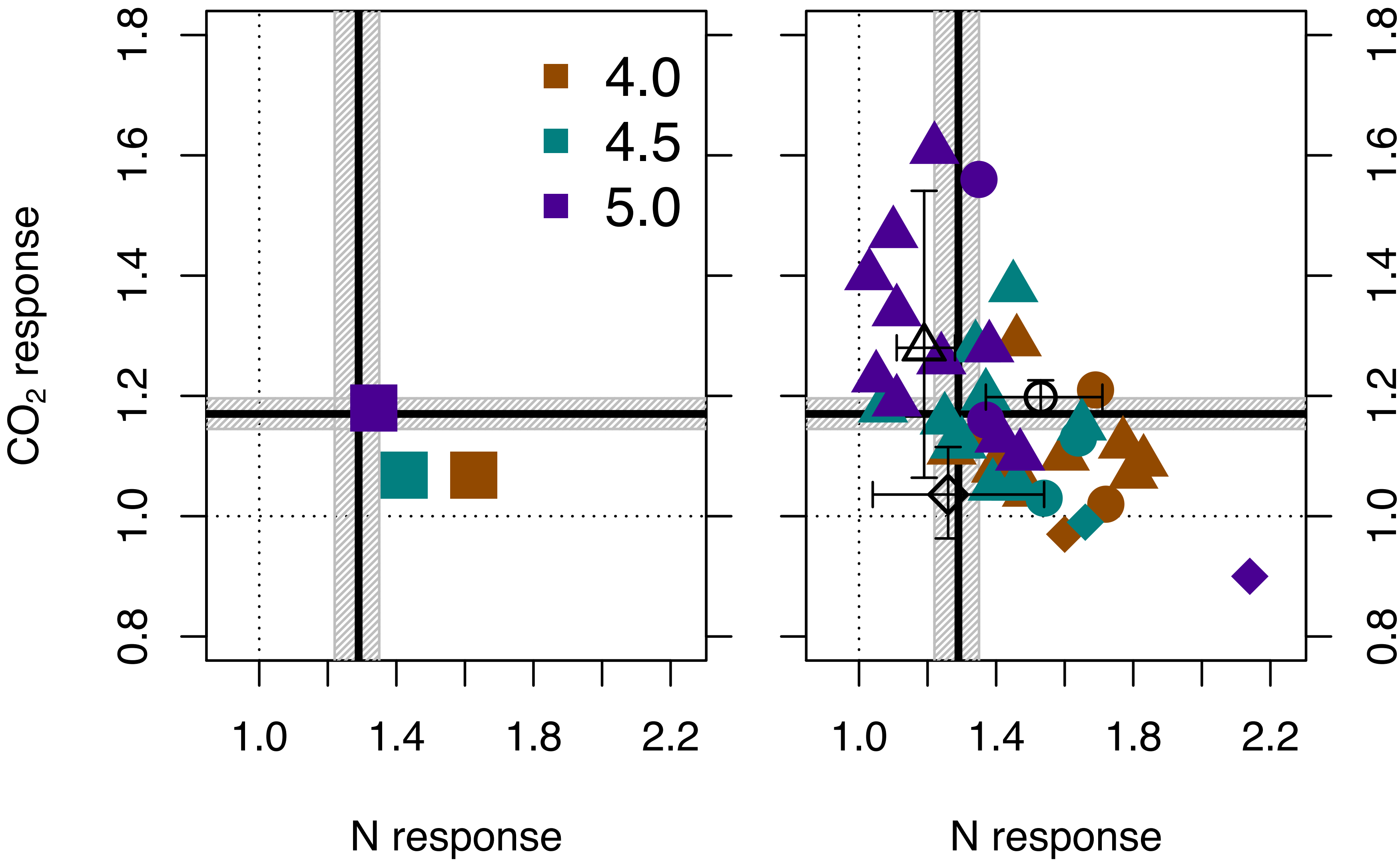


NPP Response



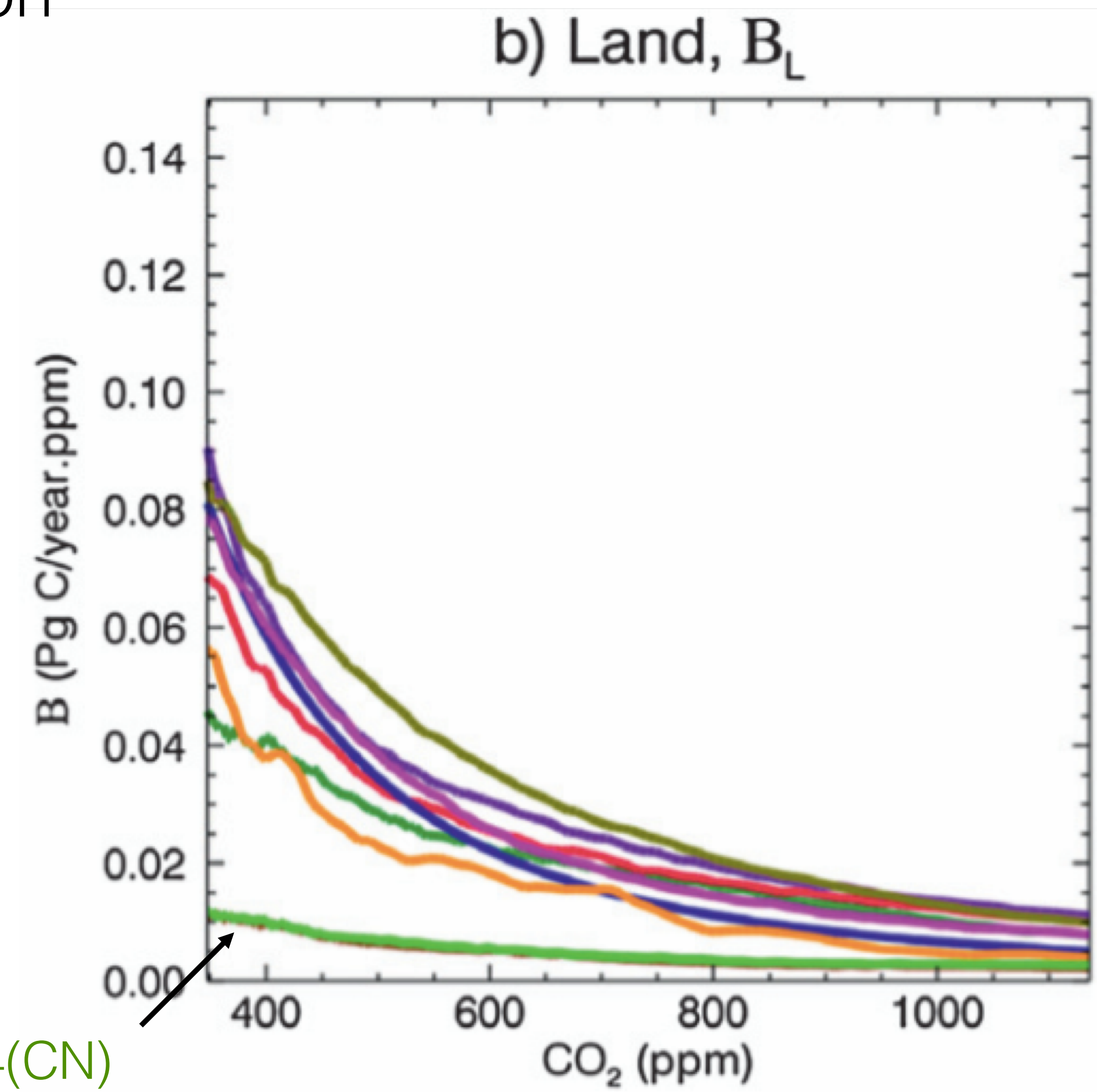
LeBauer & Treseder 2008
Ainsworth & Long 2005

NPP Response



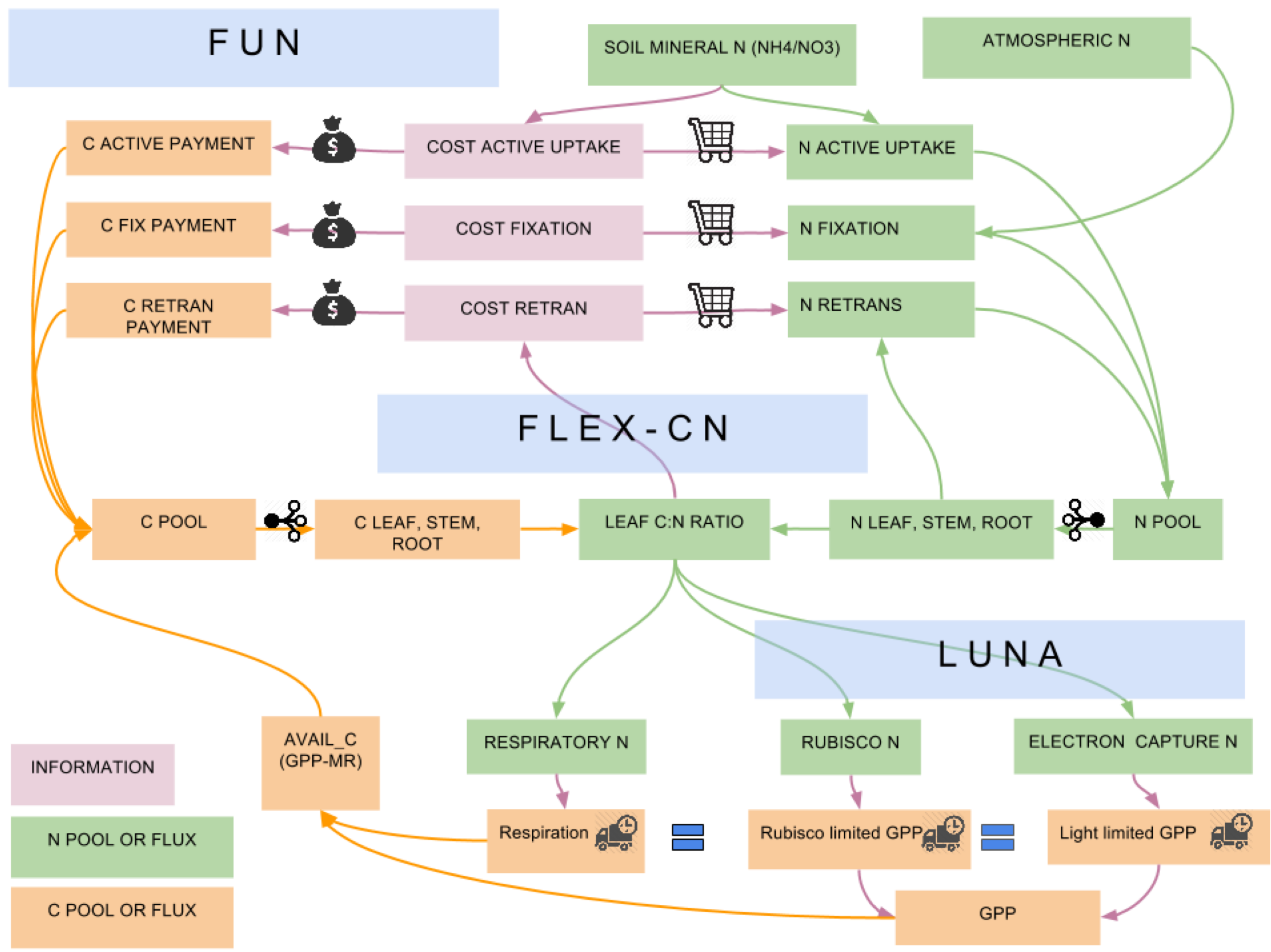
LeBauer & Treseder 2008
Ainsworth & Long 2005

Impact of nitrogen on simulated carbon fertilization



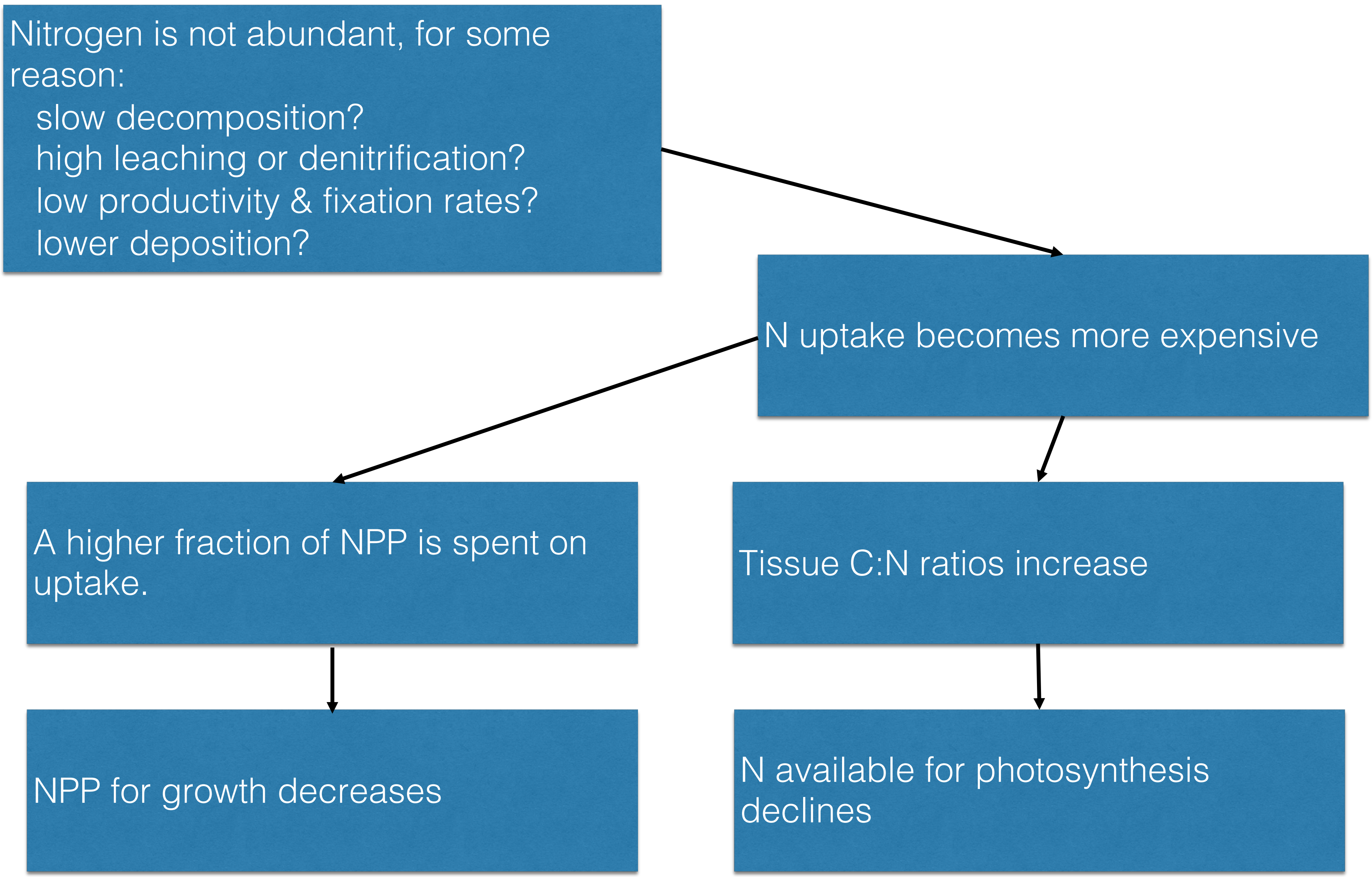
Carbon–Concentration and Carbon–Climate Feedbacks in CMIP5 Earth System Models

Vivek K. Arora,[a] George J. Boer,[a] Pierre Friedlingstein,[b] Michael Eby,[c] Chris D. Jones,[d] James R. Christian,[a] Gordon Bonan,[e] Laurent Bopp,[f] Victor Brovkin,[g] Patricia Cadule,[f] Tomohiro Hajima,[h] Tatiana Ilyina,[g] Keith Lindsay,[e] Jerry F. Tjiputra,[i] and Tongwen Wu[j]

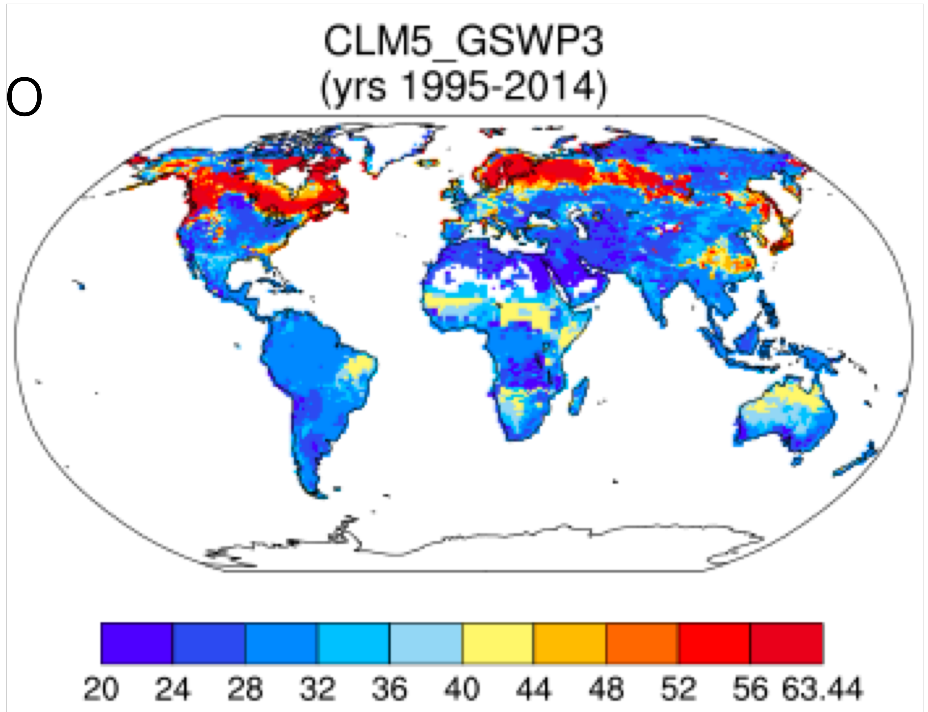


FUN
SOIL MINERAL N (NH4/NO3)
ATMOSPHERIC N
C ACTIVE PAYMENT
COST ACTIVE UPTAKE
N ACTIVE UPTAKE
C FIX PAYMENT
COST FIXATION
N FIXATION
C RETRAN PAYMENT
COST RETRAN
N RETRANS
FLEX-CN
C POOL
C LEAF, STEM, ROOT
LEAF C:N RATIO
N LEAF, STEM, ROOT
N POOL
LUNA
RESPIRATORY N
RUBISCO N
ELECTRON CAPTURE N
AVAIL_C (GPP-MR)
Respiration
Rubisco limited GPP
Light limited GPP
GPP
INFORMATION
N POOL OR FLUX
C POOL OR FLUX

N limitation in CLM5



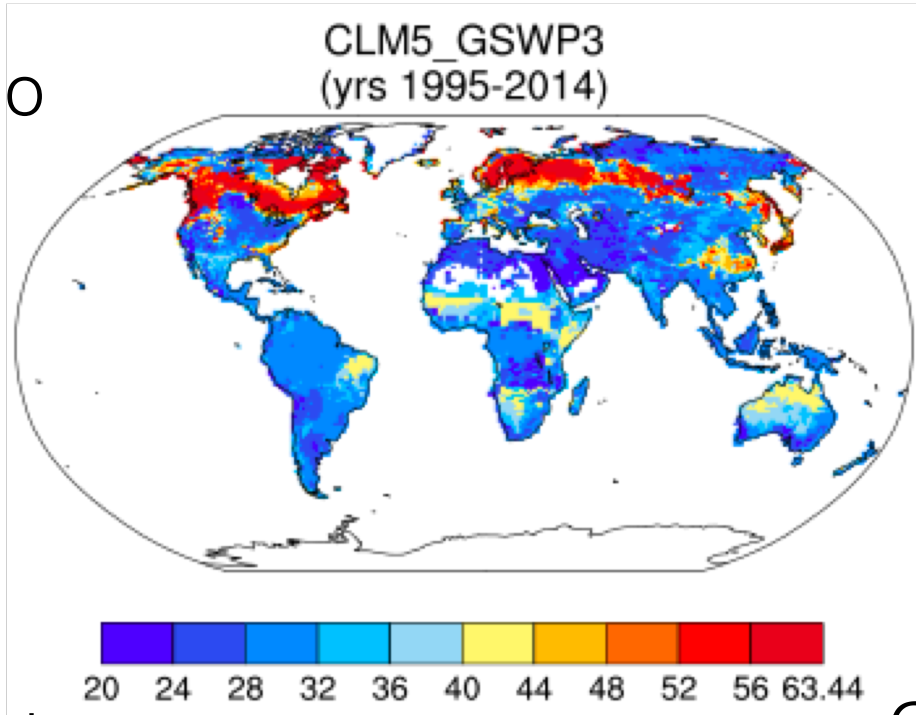
LeafC:N ratio



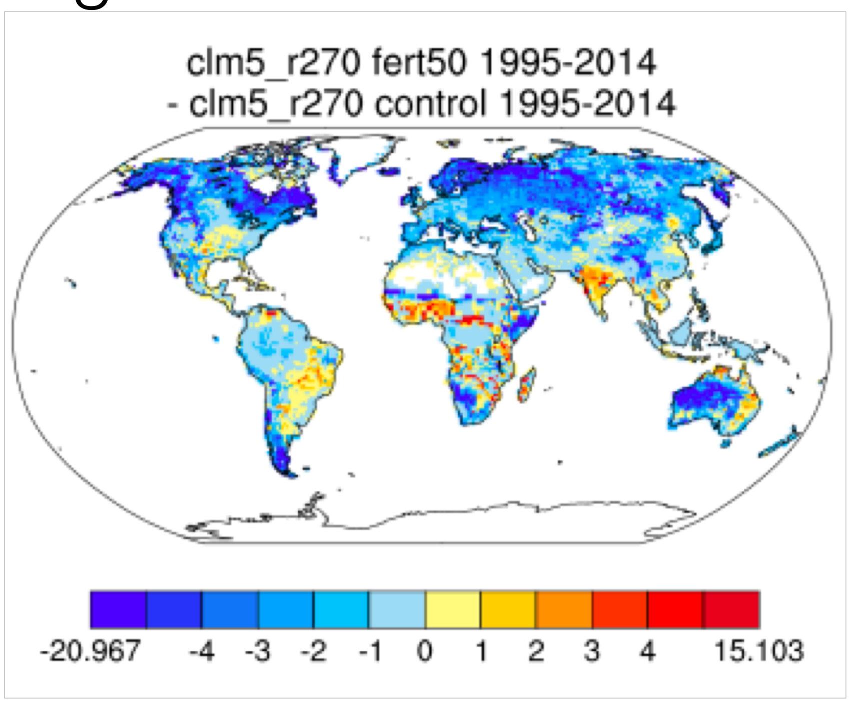
What really matters is the:

1. Change over time
2. Difference from ‘target’ C:N
3. Response to disturbance

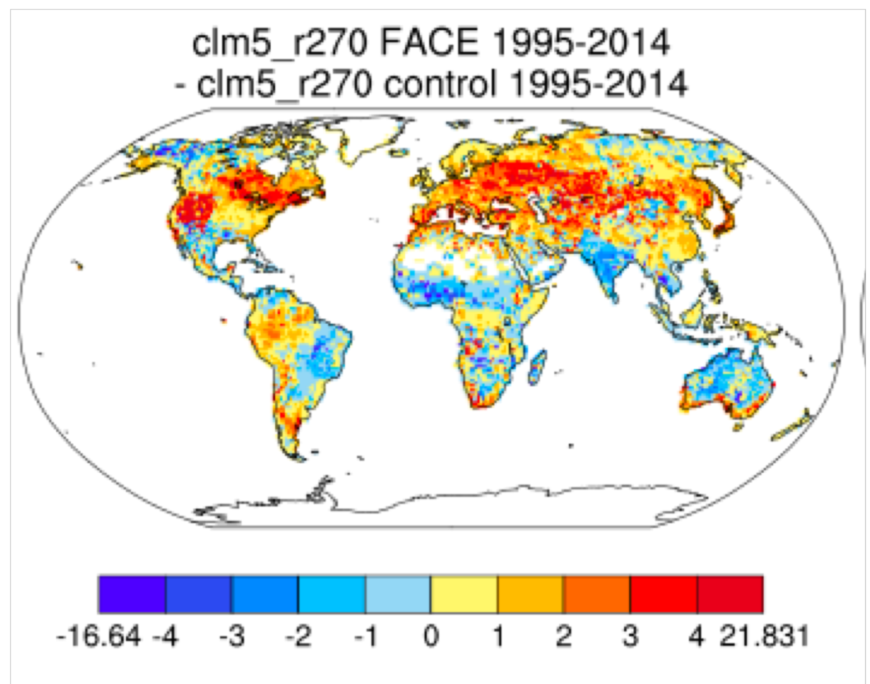
LeafC:N ratio



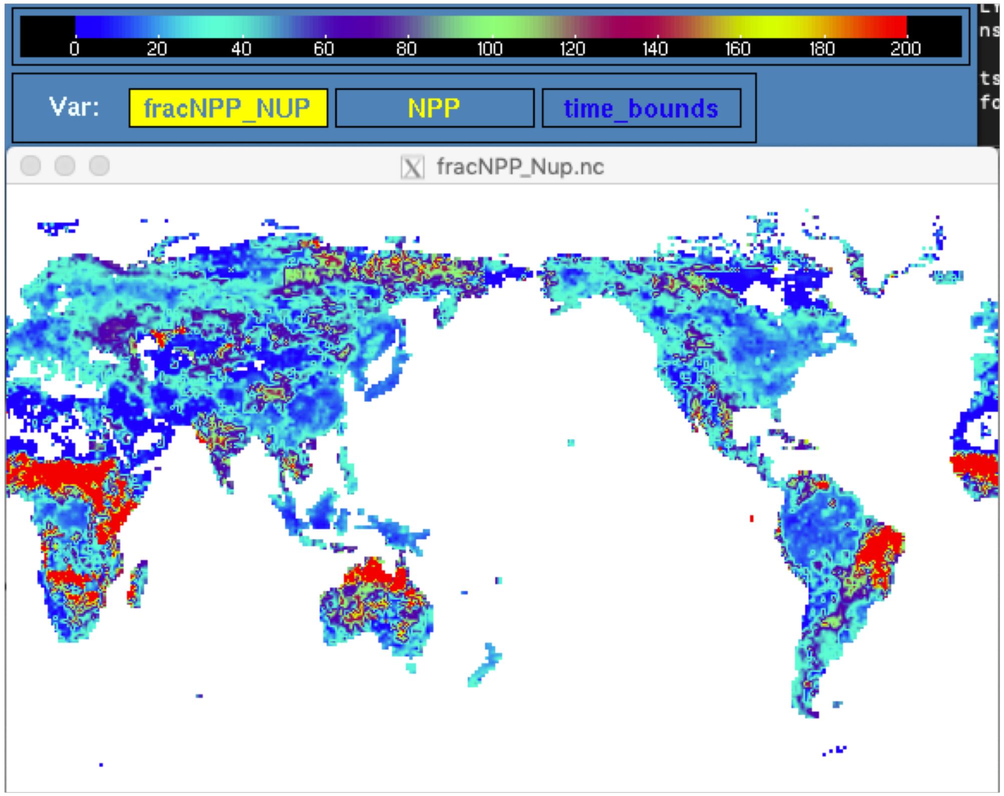
Change with N-Fert



Change w/ FACE



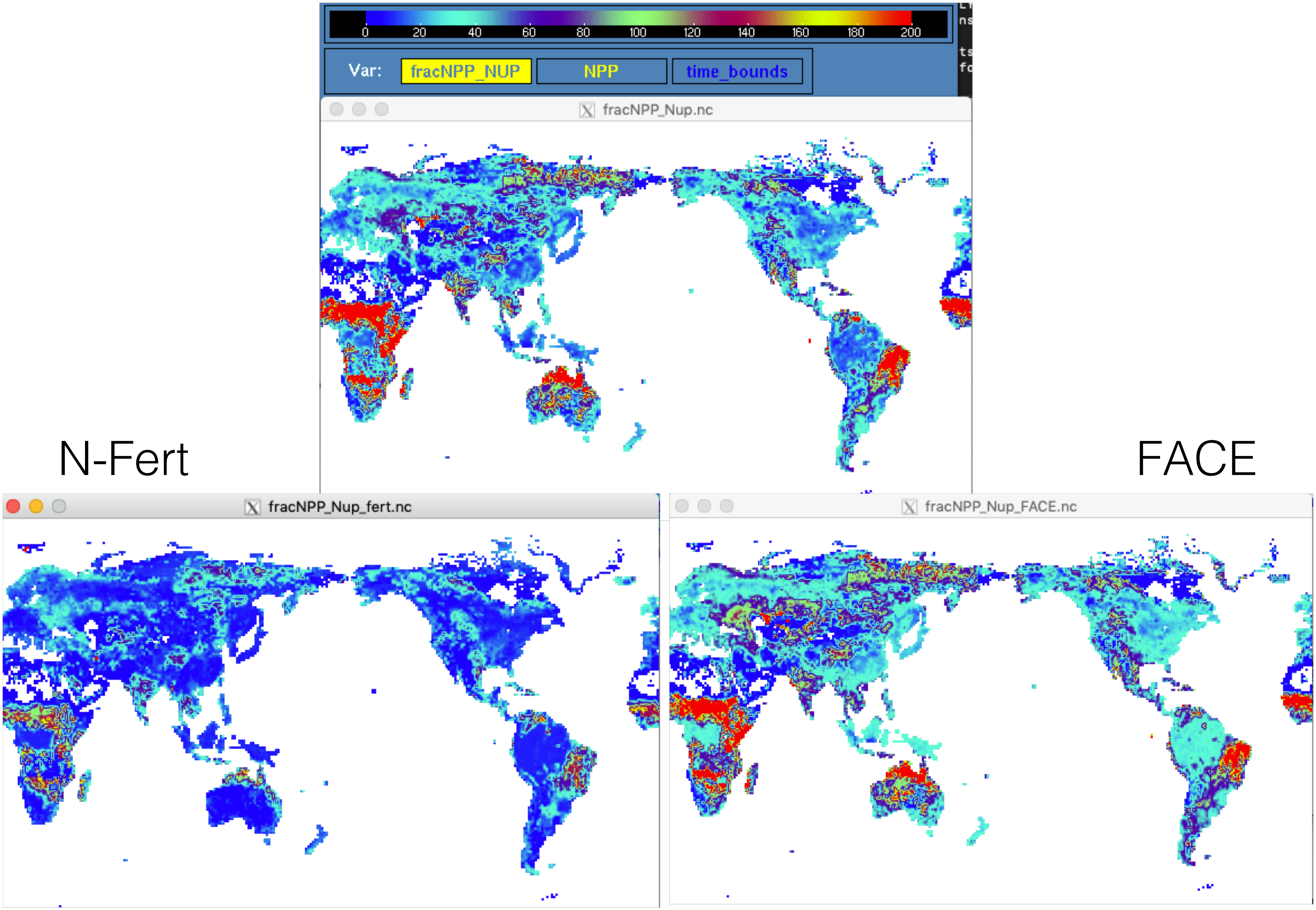
Fraction of NPP spent on N uptake   100*NPP_NUPTAKE / NPP



What really matters is the:

1. Change over time
2. Response to disturbance

Fraction of NPP spent on N uptake

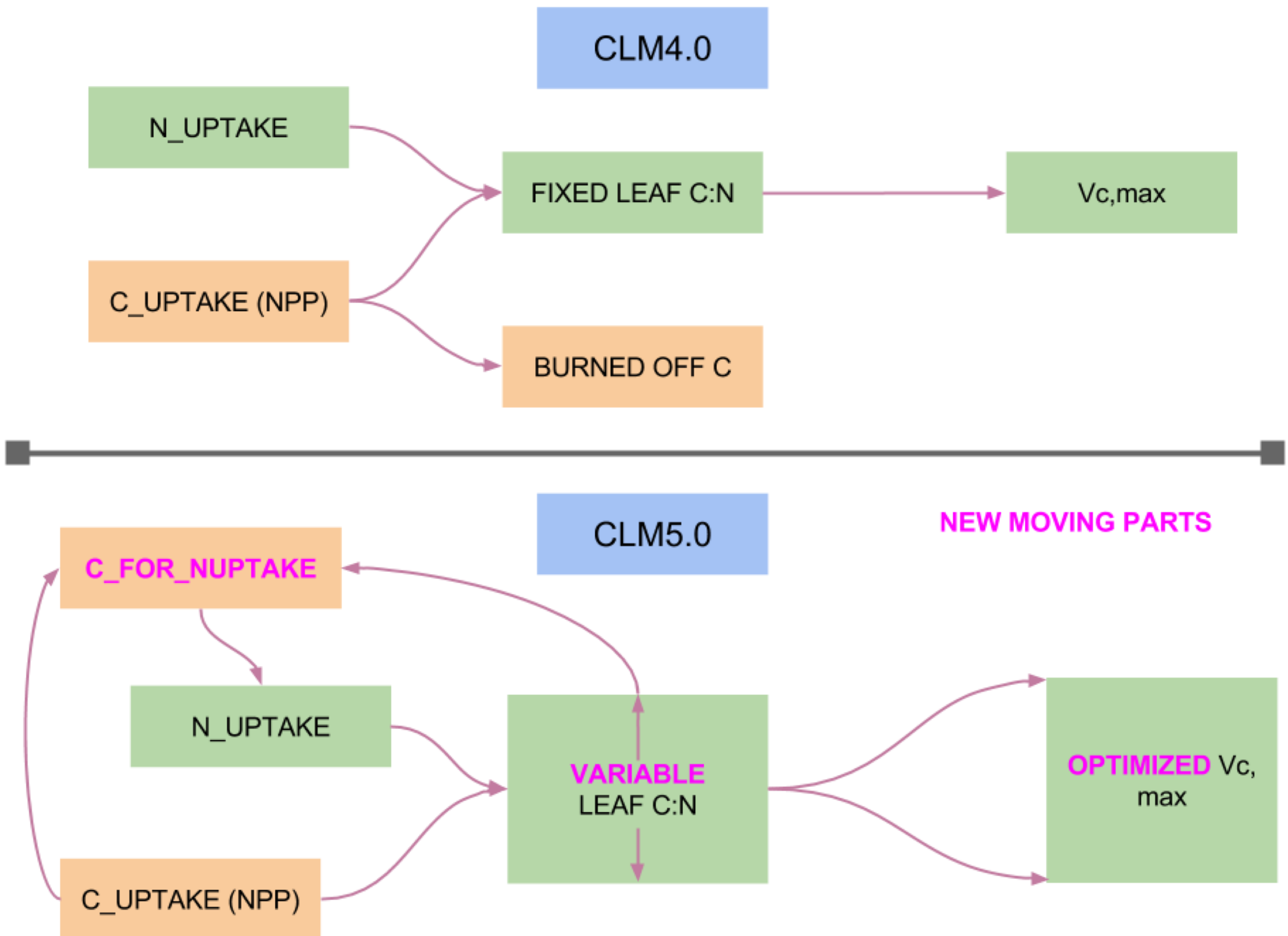


New parameters of N model

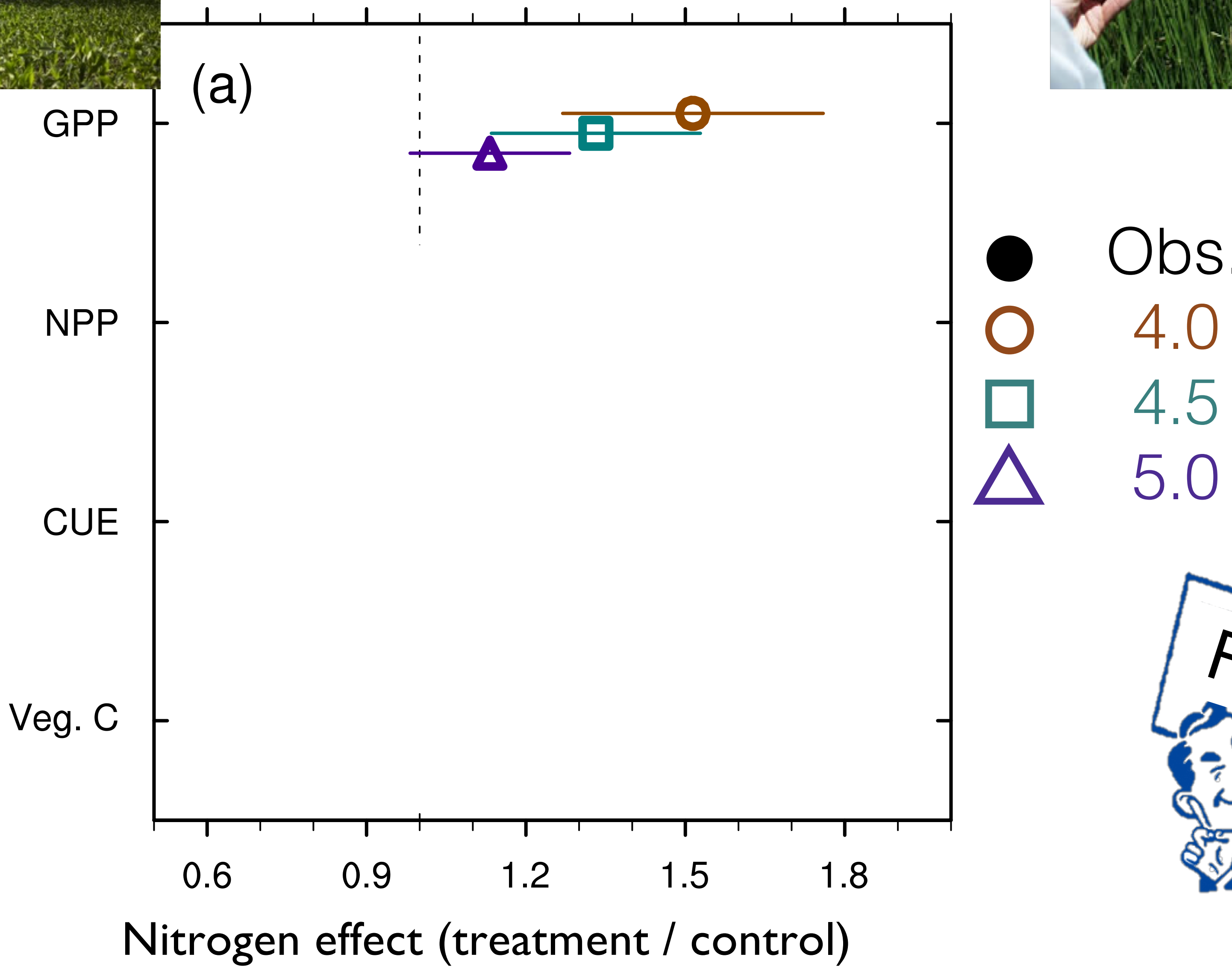
- Nitrogen cost factors
    - Fixation
    - Active uptake
    - Retranslocation
- Target leafCN ratio
- Flexible leafCN parameters
- LUNA parameters (only one is tunable)

Conclusions

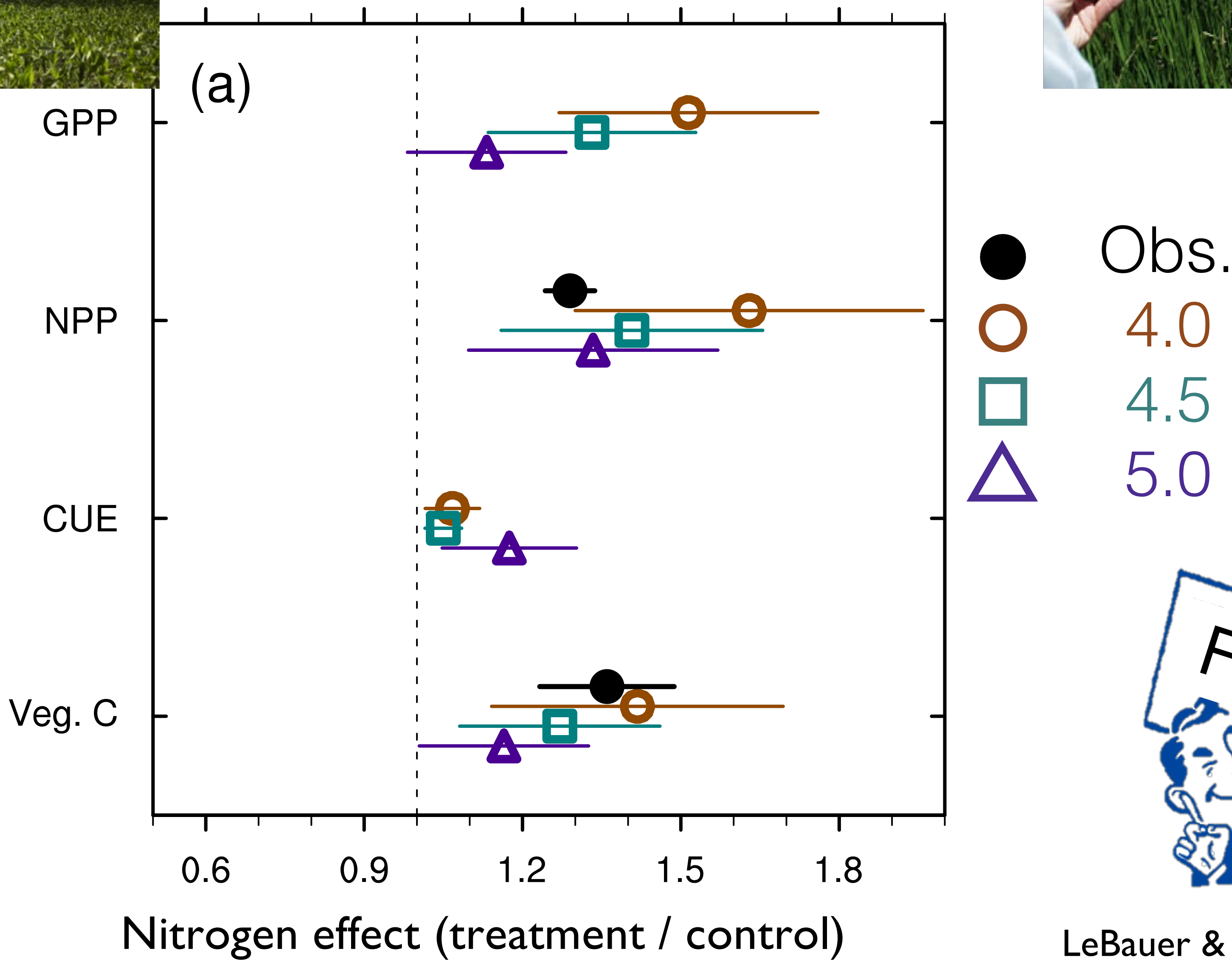
- The new CLM5 nitrogen cycle model is substantially different to the CLM4.5 and CLM4.0.
- We are making progress on understanding the behavior and interactions in the new model
- Much remains to be tested and understood
- The model allows comparisons with many new data streams (N fixation, CN ratio, Vcmax variation)
- …and also fixes numerous theoretical problems with the existing CLM N cycle model


CLM4.0
N_UPTAKE
FIXED LEAF C:N
Vc,max
C_UPTAKE (NPP)
BURNED OFF C
CLM5.0
NEW MOVING PARTS
C_FOR_NUPTAKE
N_UPTAKE
VARIABLE
LEAF C:N
OPTIMIZED Vc,
max
C_UPTAKE (NPP)

Response to +N

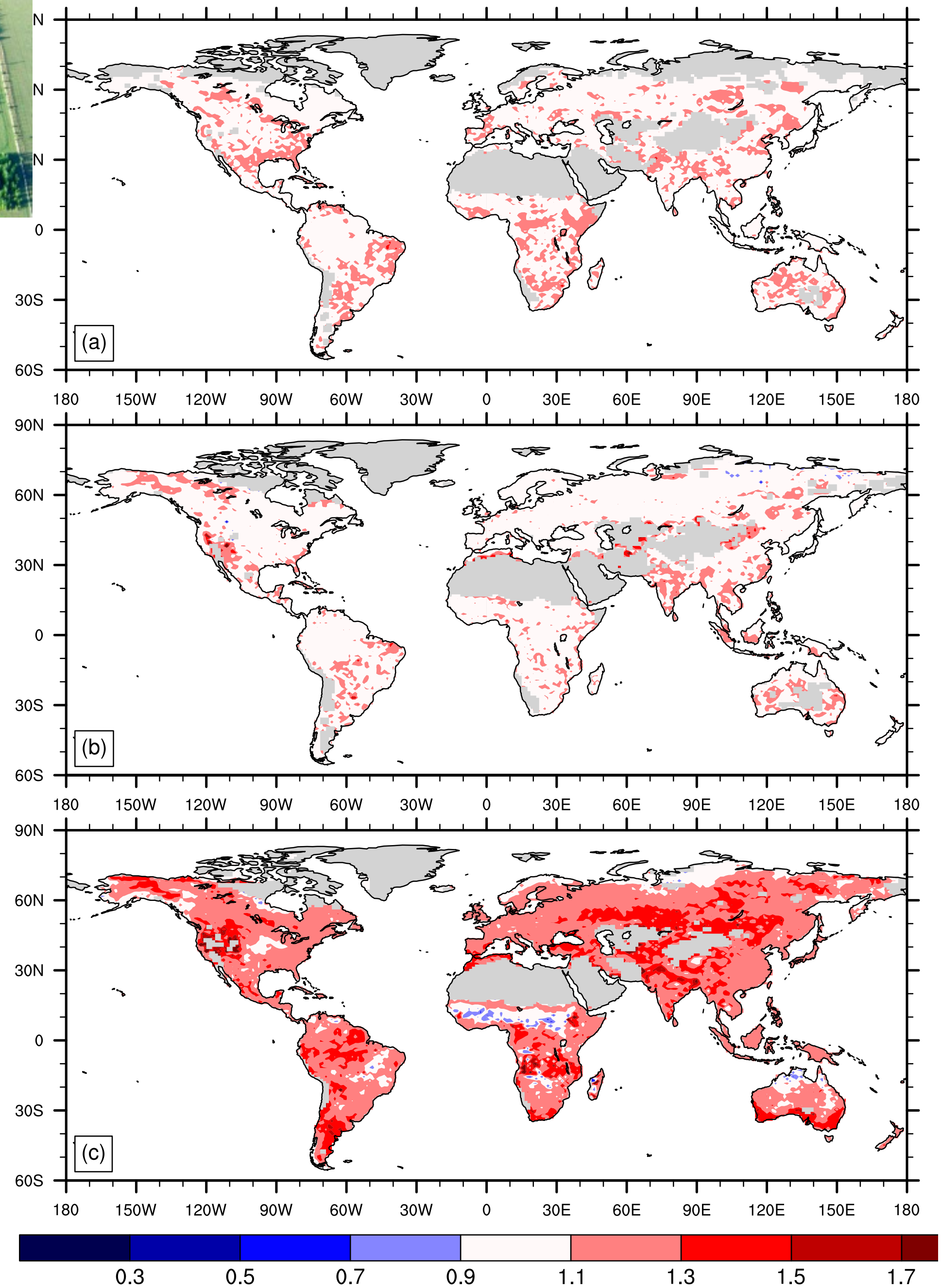


Response to +N



LeBauer & Treseder 2008
Liu & Greaver 2010
Lu et al. 2011

GPP Response to $+CO_2$(treatment / control)

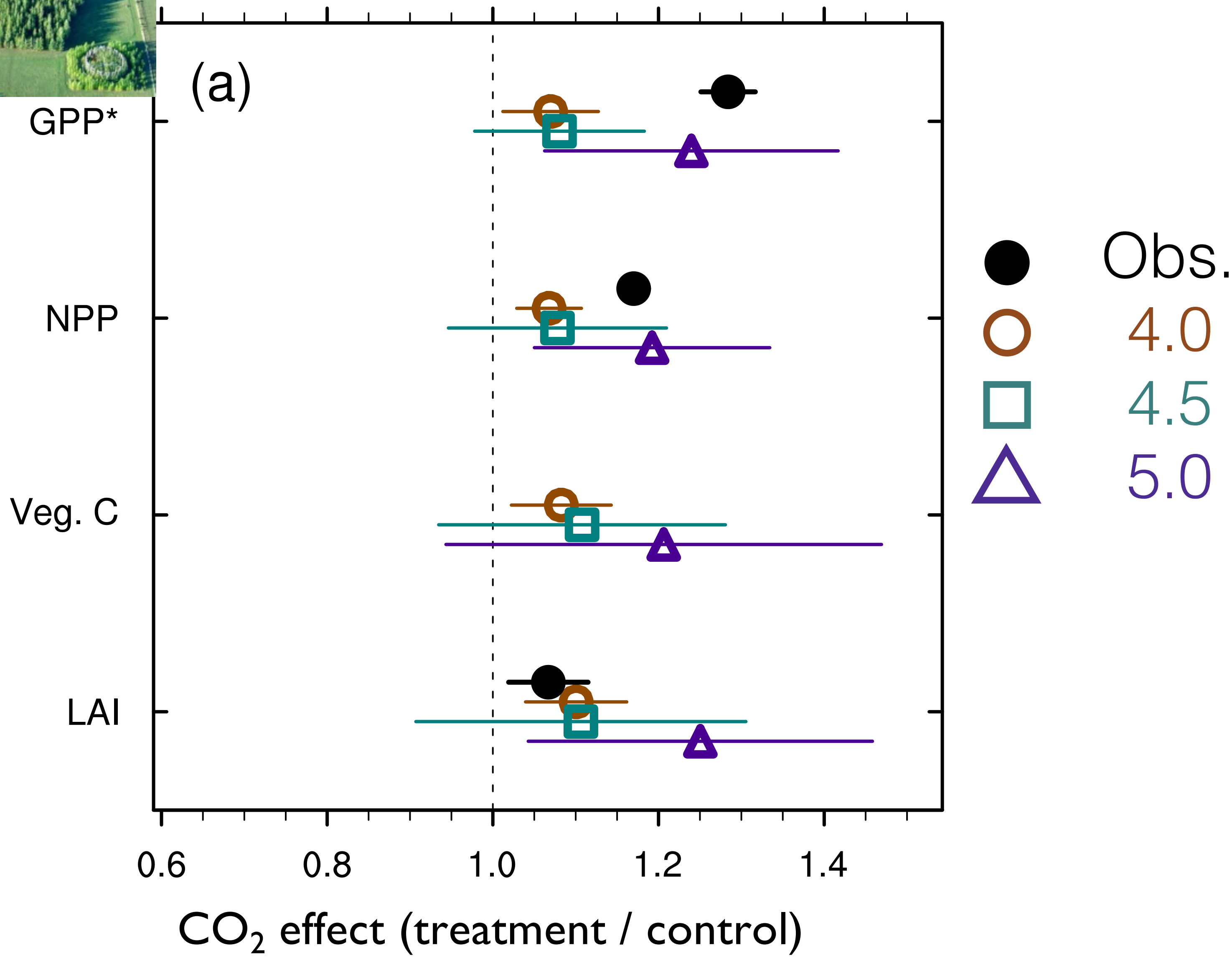


CLM 4.0

CLM 4.5

CLM 5.0

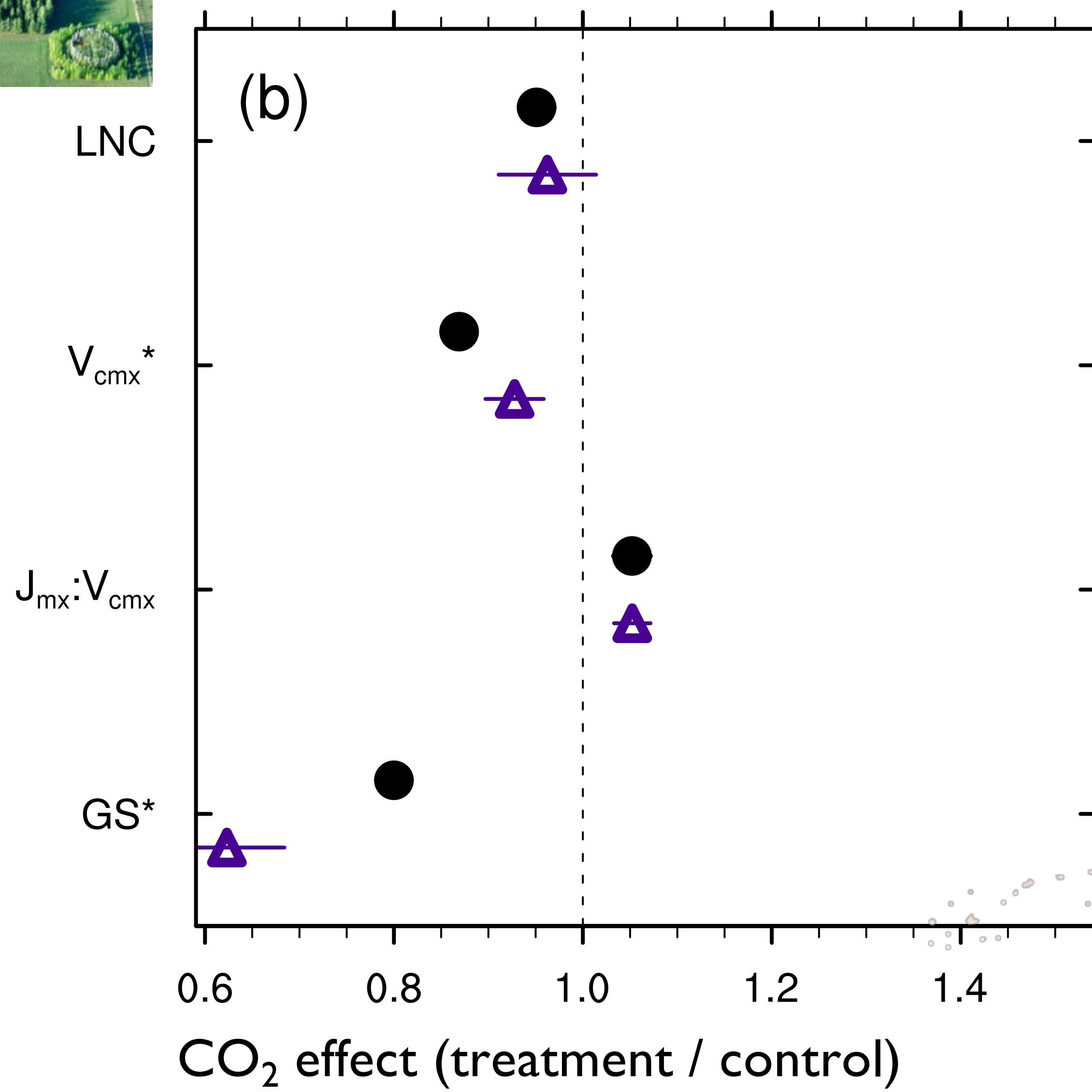
Response to $+CO_2$



* Monthly mean of maximum daily values

Obs. from Ainsworth & Long 2005

Response to +CO_2



* Monthly mean of maximum daily values

Obs from Ainsworth & Long 2005