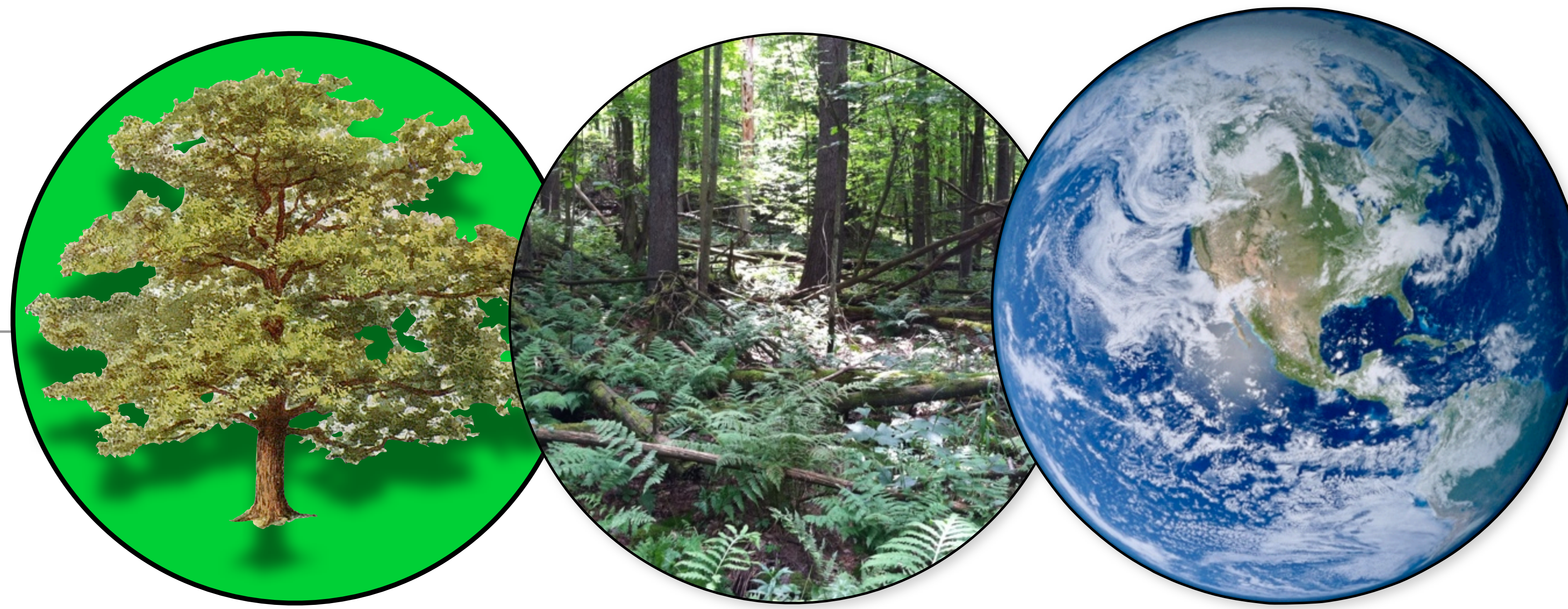
Nitrogen limitation on land: How can it occur in Earth System Models?



R. Quinn Thomas
Forest Resources and Environmental Conservation
Virginia Tech
Blacksburg, VA

VirginiaTech
Invent the Future

What is nitrogen limitation?

Biogeochemistry **13**: 87–115, 1991

**Nitrogen limitation on land and in the sea:
How can it occur?**

PETER M. VITOUSEK[1] & ROBERT W. HOWARTH[2]

[1] *Department of biological Sciences, Stanford University, Stanford, CA 94305, USA*
[2] *Section of Ecology and Systematics, Cornell University, Ithaca, NY 14853, USA*

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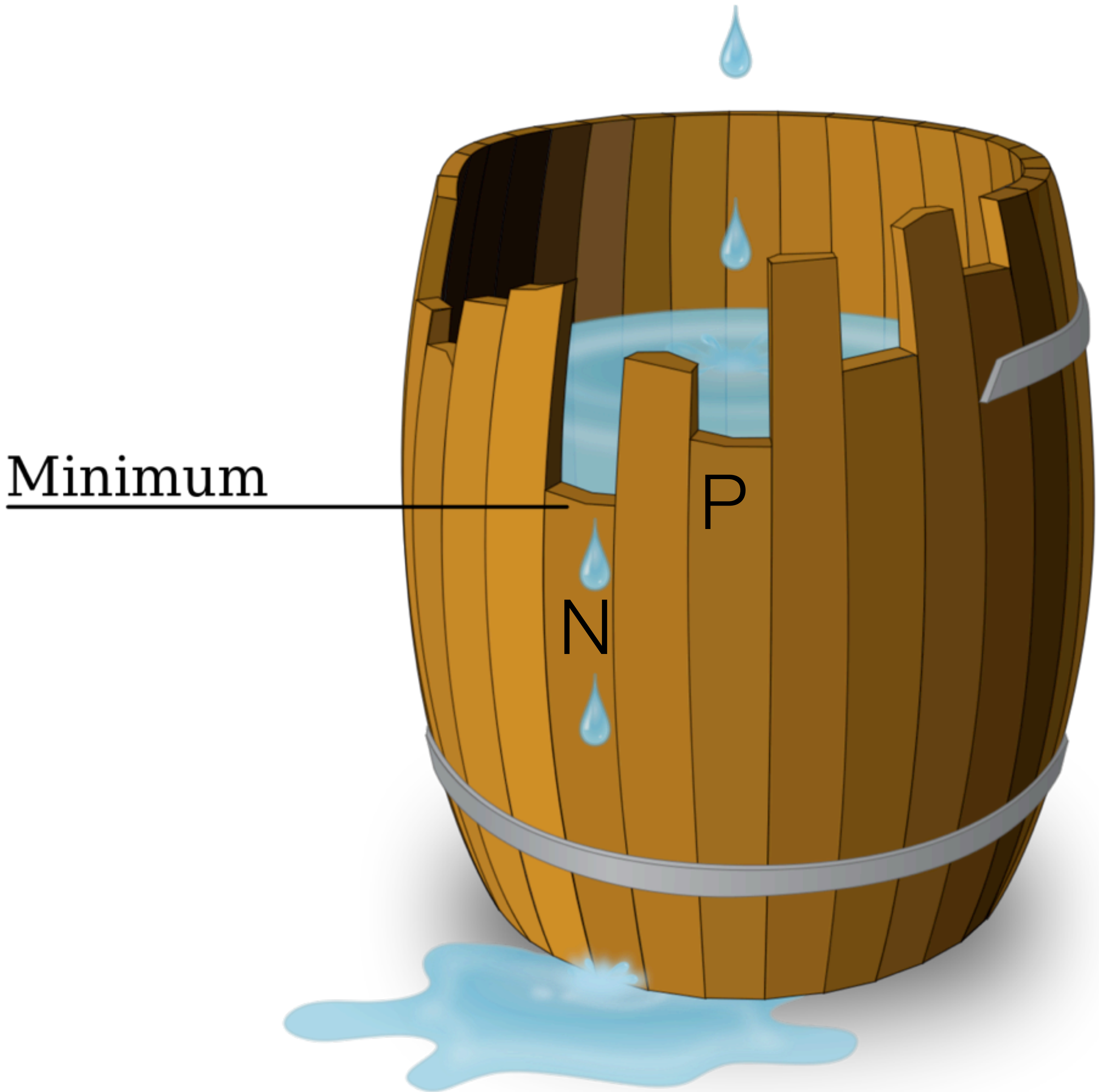

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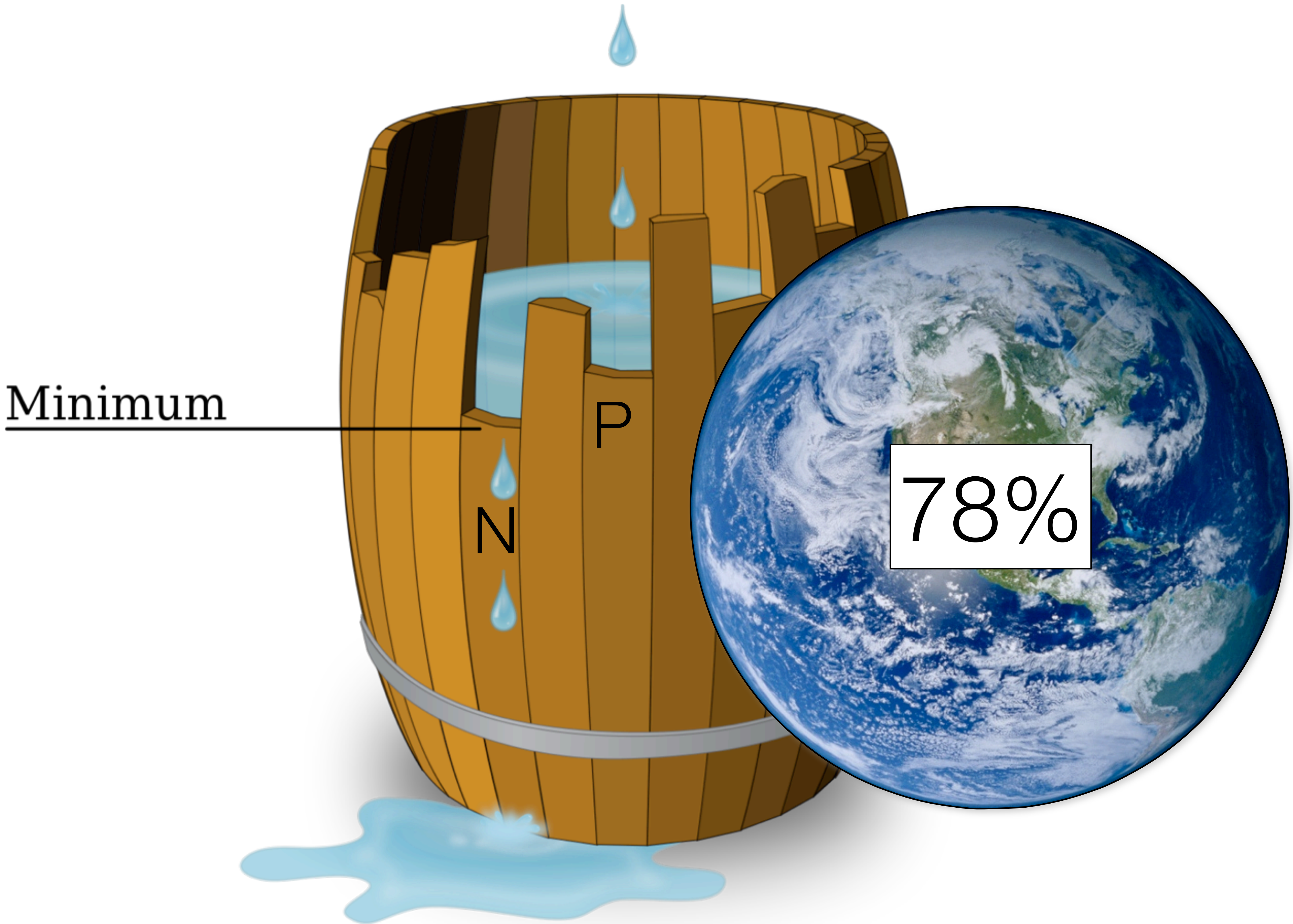

Why is nitrogen limiting?

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- Necessary for photosynthesis and carbon uptake

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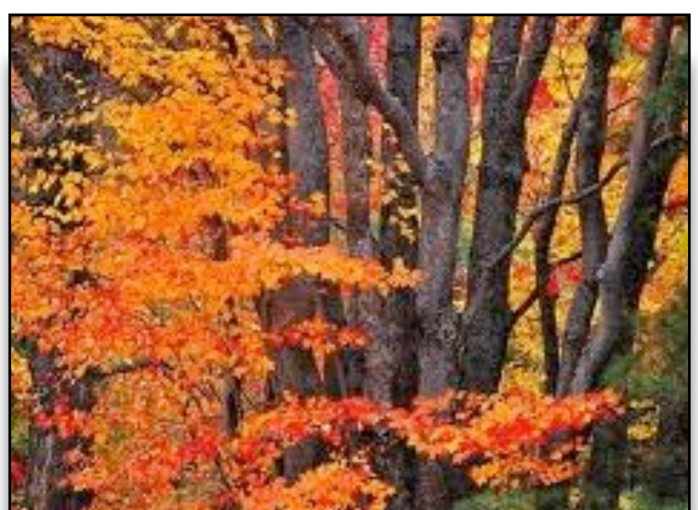
Boreal forests



Temperate forests

Early successional tropical forests

Why is nitrogen limiting?

- Essential element for growth
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‘Disturbed’ ecosystems

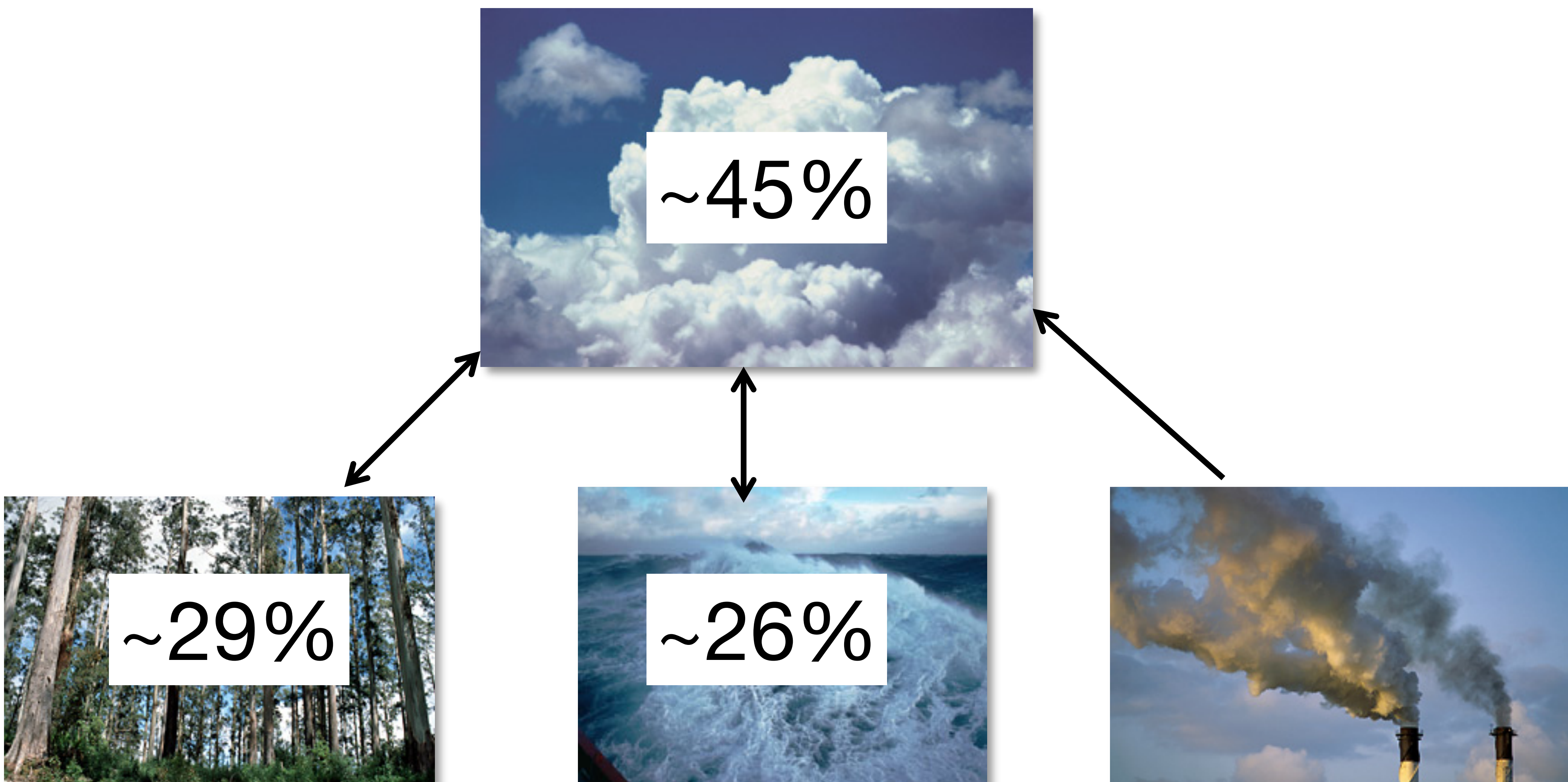

Boreal forests


Temperate forests

Early successional
tropical forests

Why Earth System Models?

- Goal: Predict the allowable emissions that avoid exceeding a temperature target



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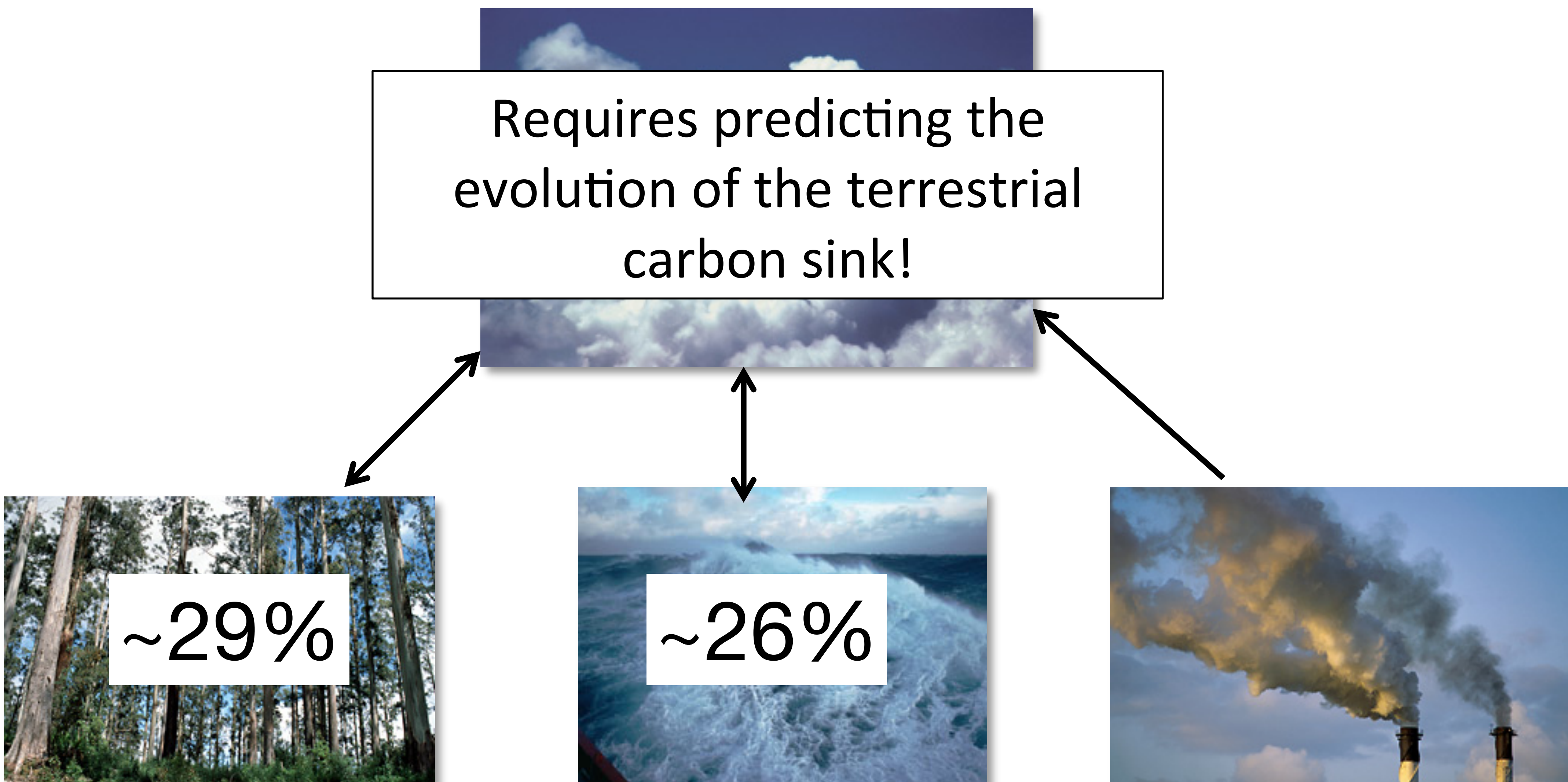


Carbon cycle feedbacks

Atmospheric CO_2

\+ ↓ Stabilizing Feedback ↑ -

Land C sink

Temperature

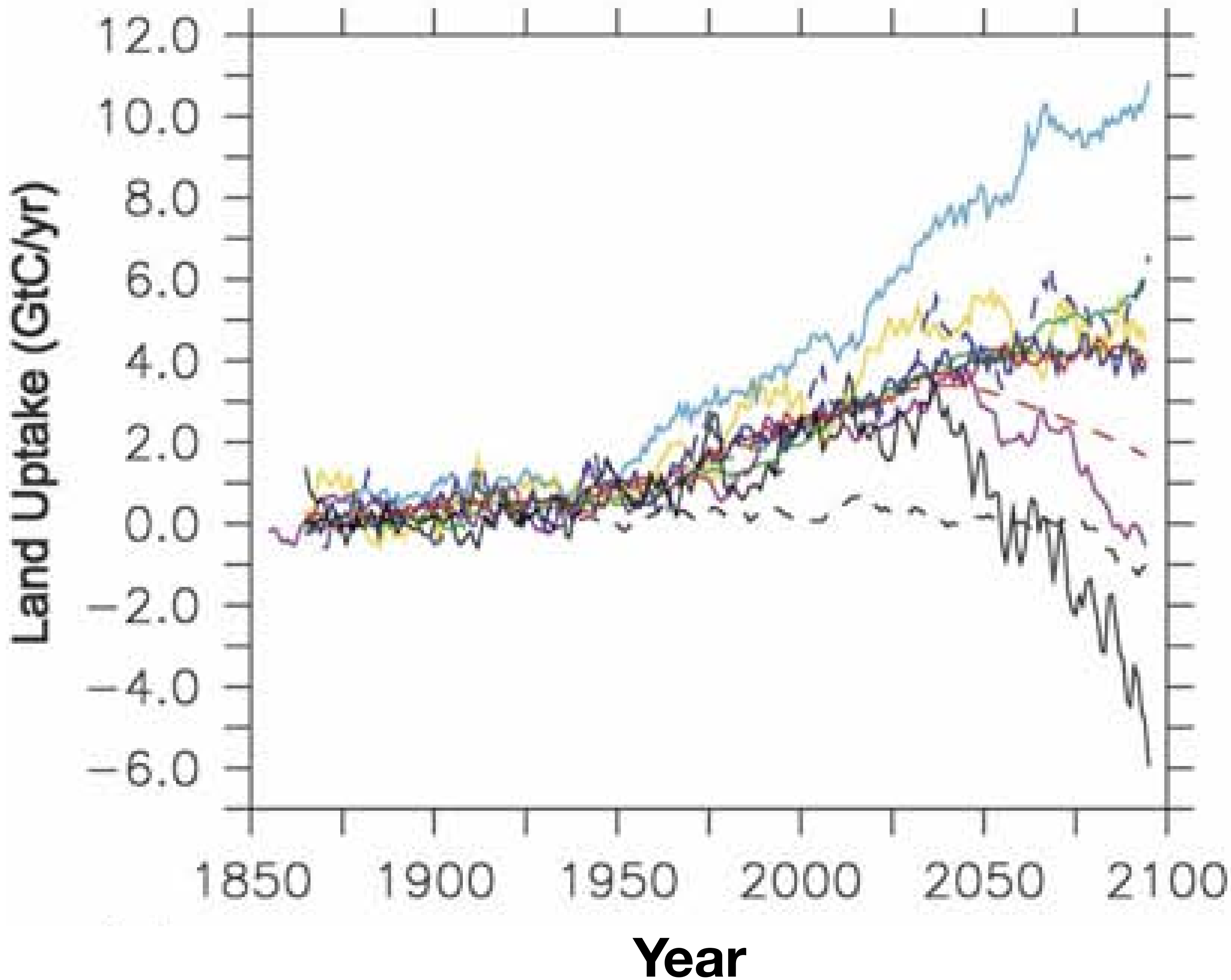
\- ↓ Amplifying Feedback ↑ +

Land C sink

Carbon concentration feedback

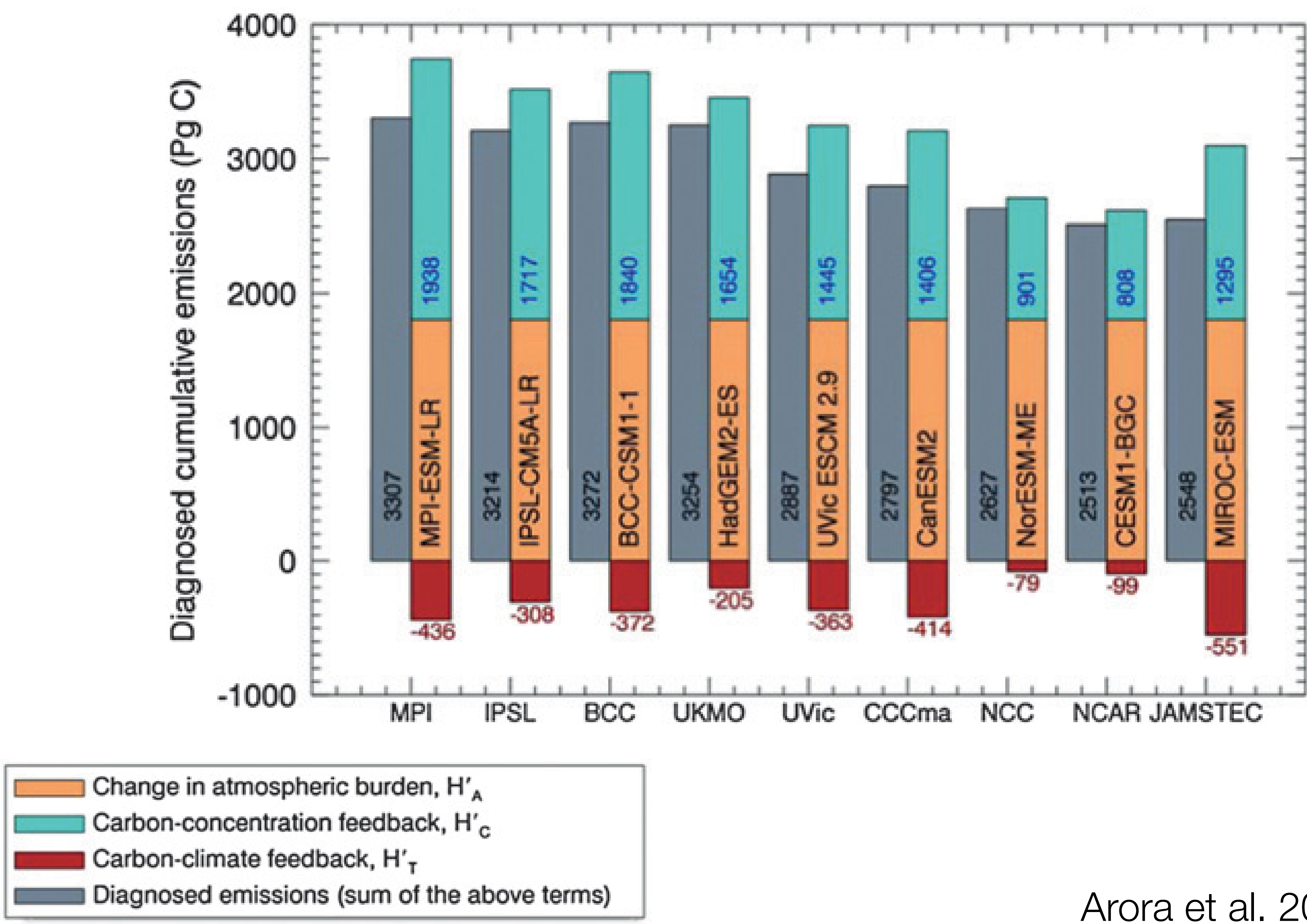
Carbon climate feedback

Wide range of predictions for future carbon sink



Friedlingstein et al. 2006 J of Climate

Carbon feedbacks impact effective emissions

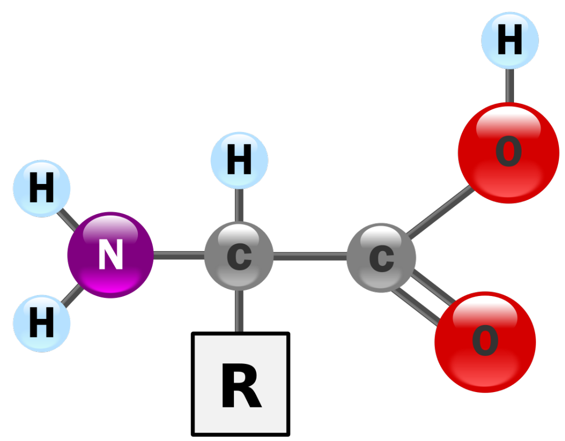


Arora et al. 2013 J of Climate

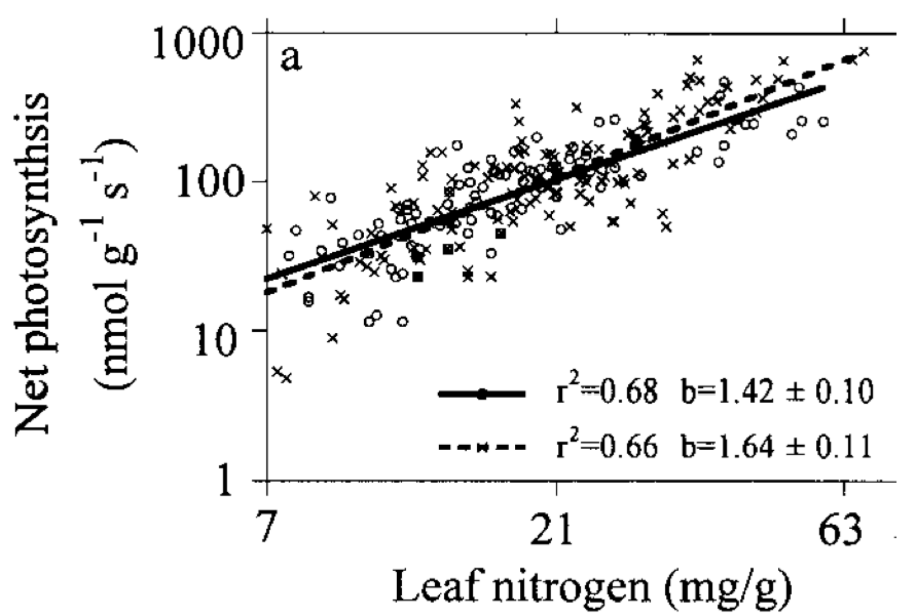
Components of the land carbon sink

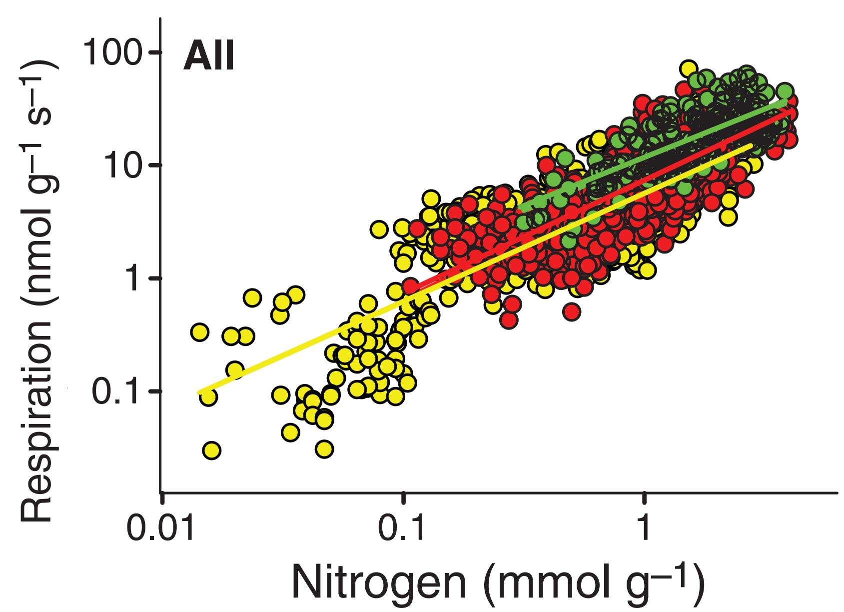
C sink =

Plant C uptake - C release by decomposition



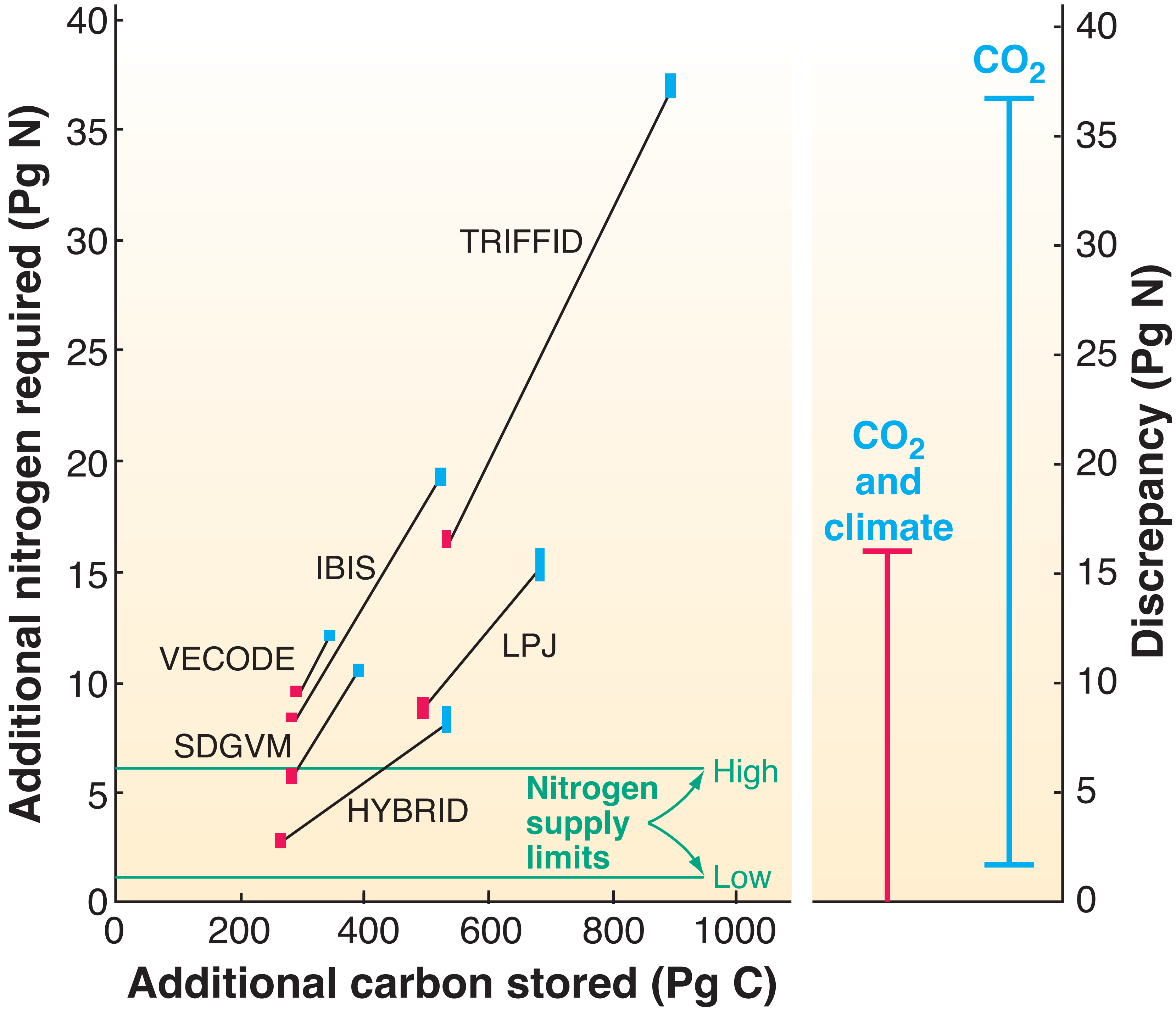
Tissue	C:N
Leaves	16-60
Woody tissue	212-1400
Fine roots	20-70
Microbes	5-17





Reich et al. 1997 PNAS, Reich etal. 2008 Ecol. Letters, White et al. 2005 Earth Interactions

Overly optimistic CO_2 fertilization?



Hungate et al. 2003 Science; Norby et al. 2010 PNAS

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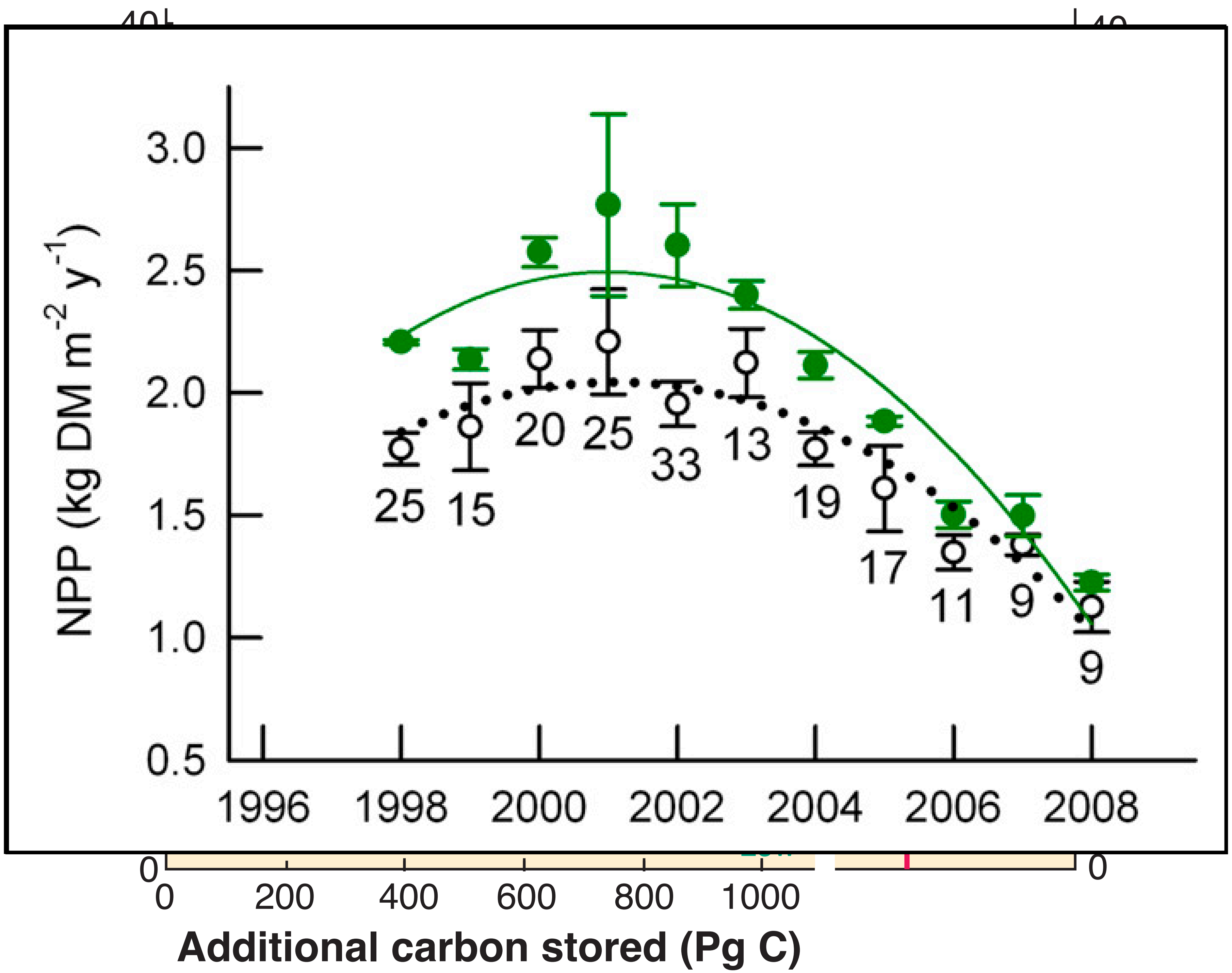

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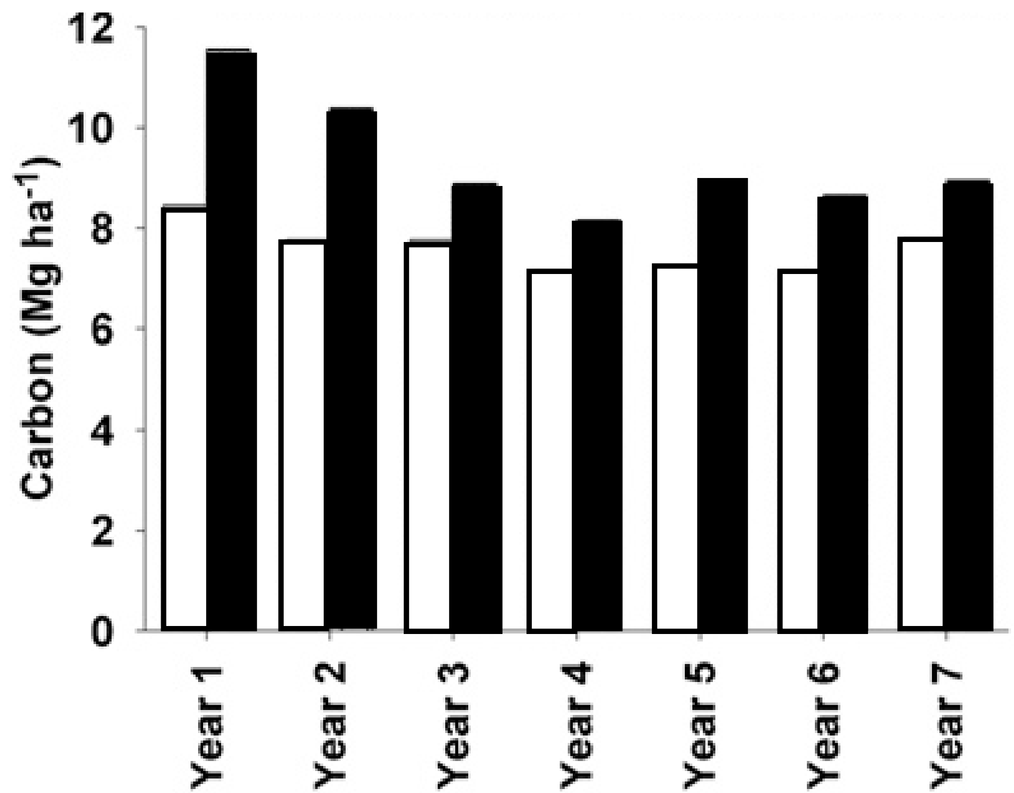
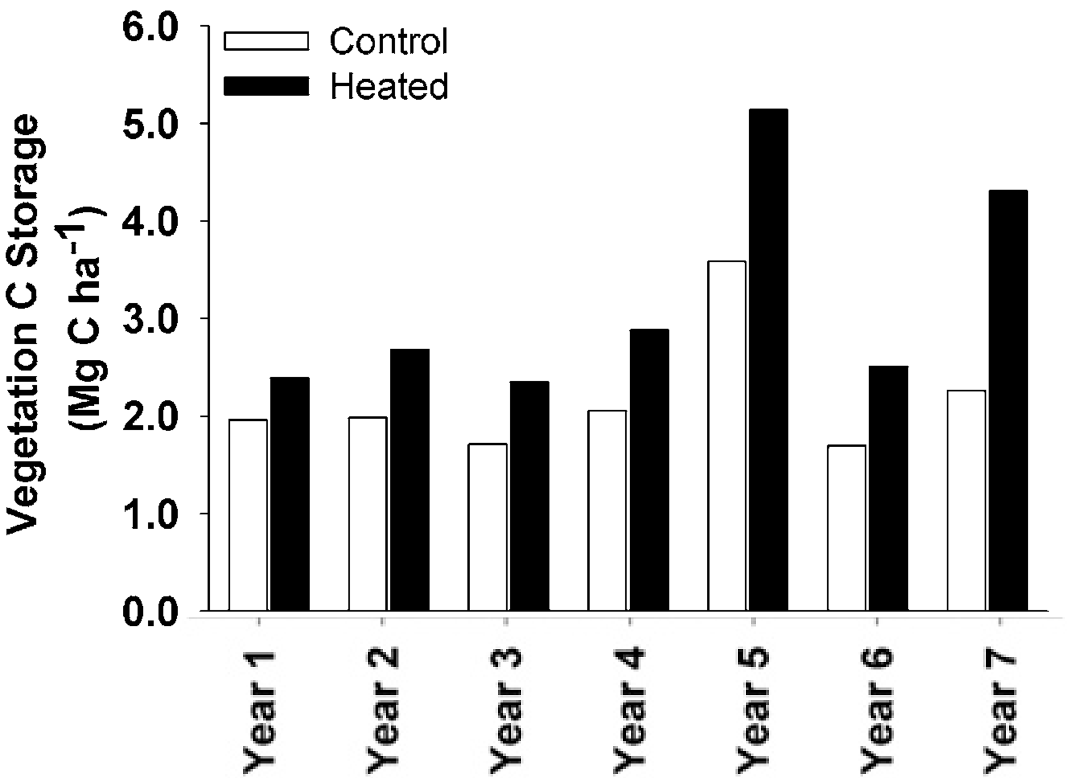
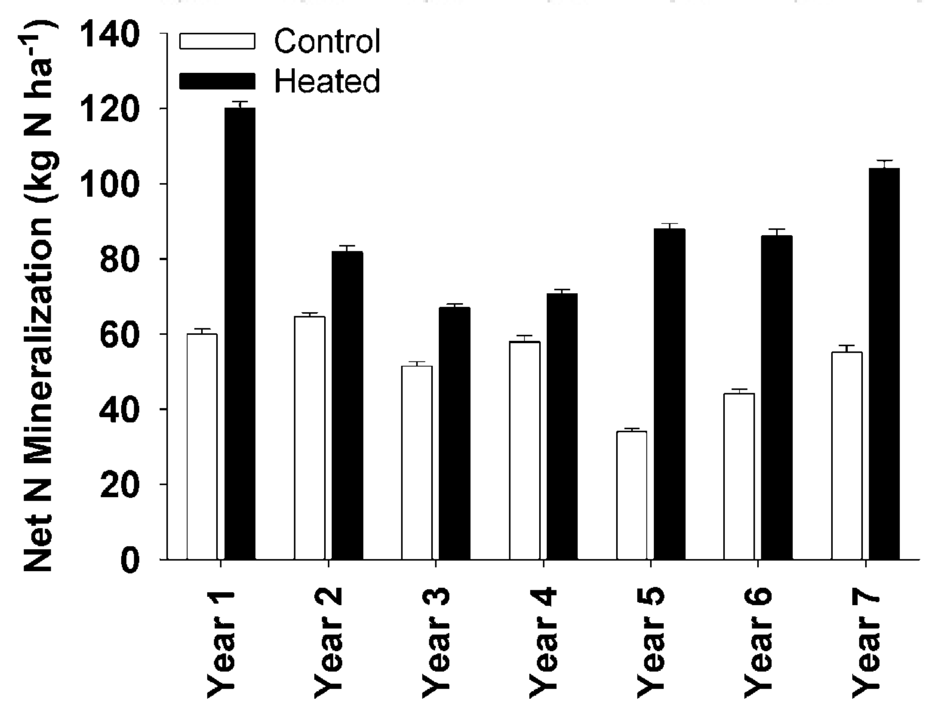
Overly negative carbon loss?







Melillo et al. 2011 PNAS

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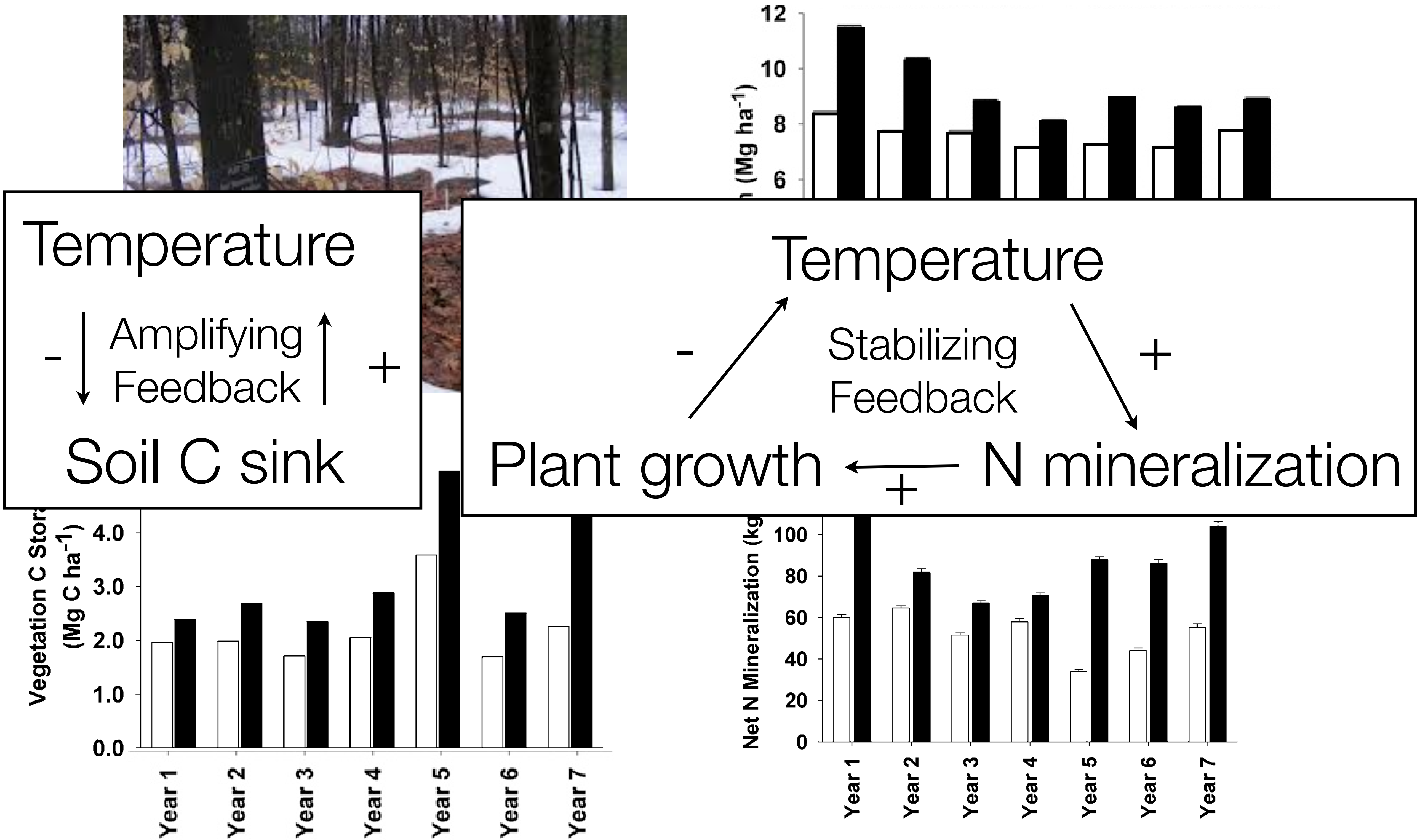

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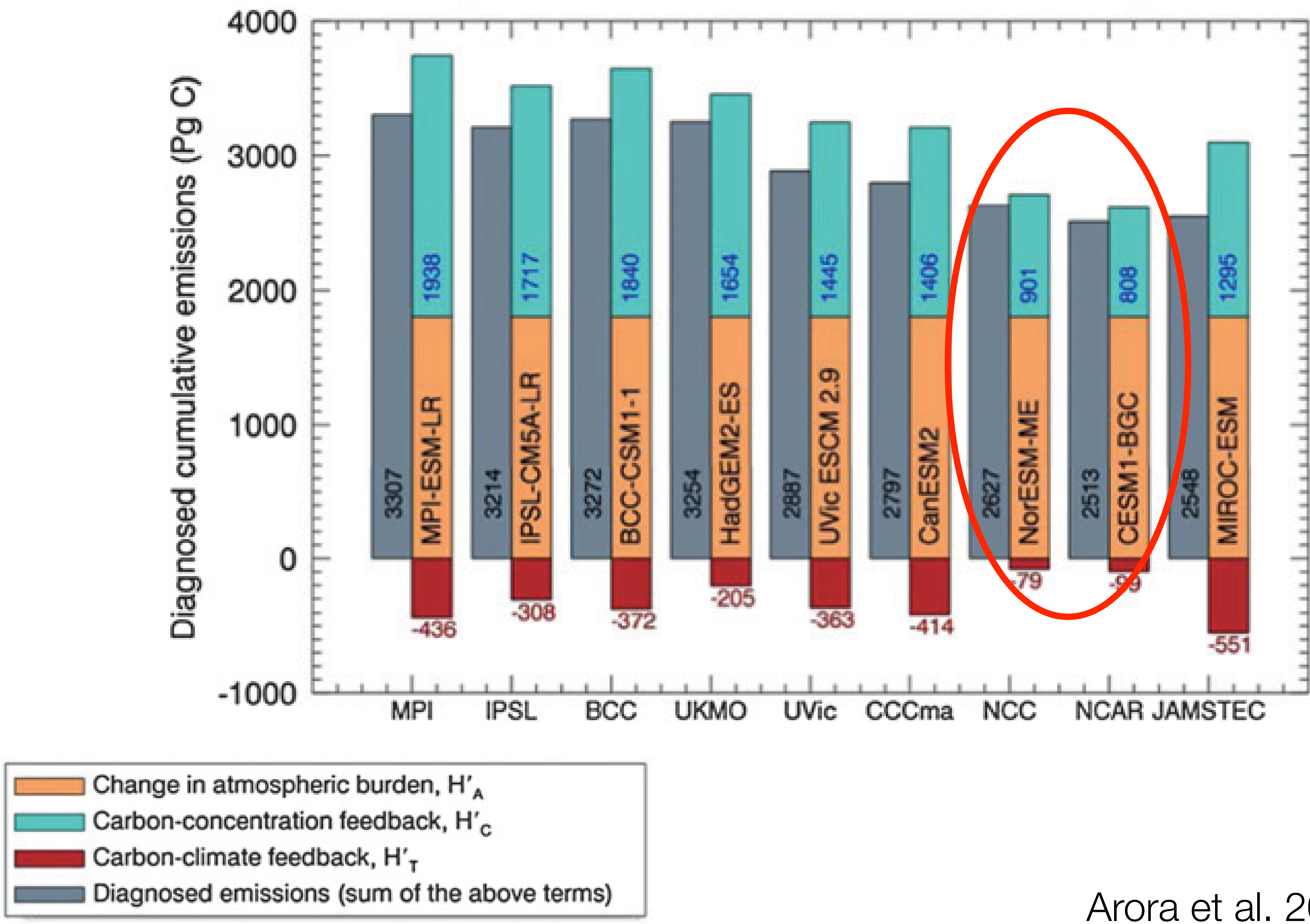
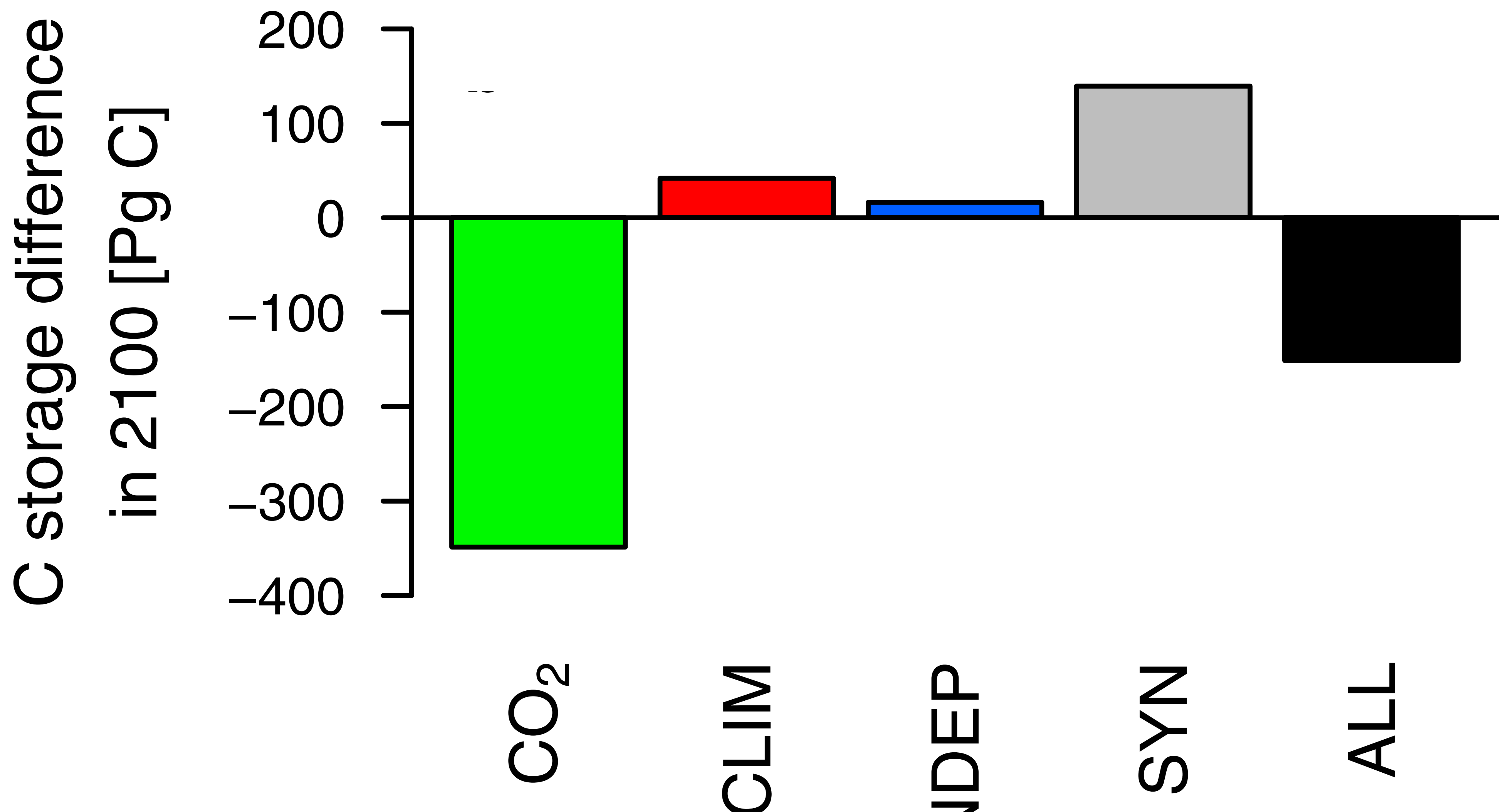


Arora et al. 2013 J of Climate

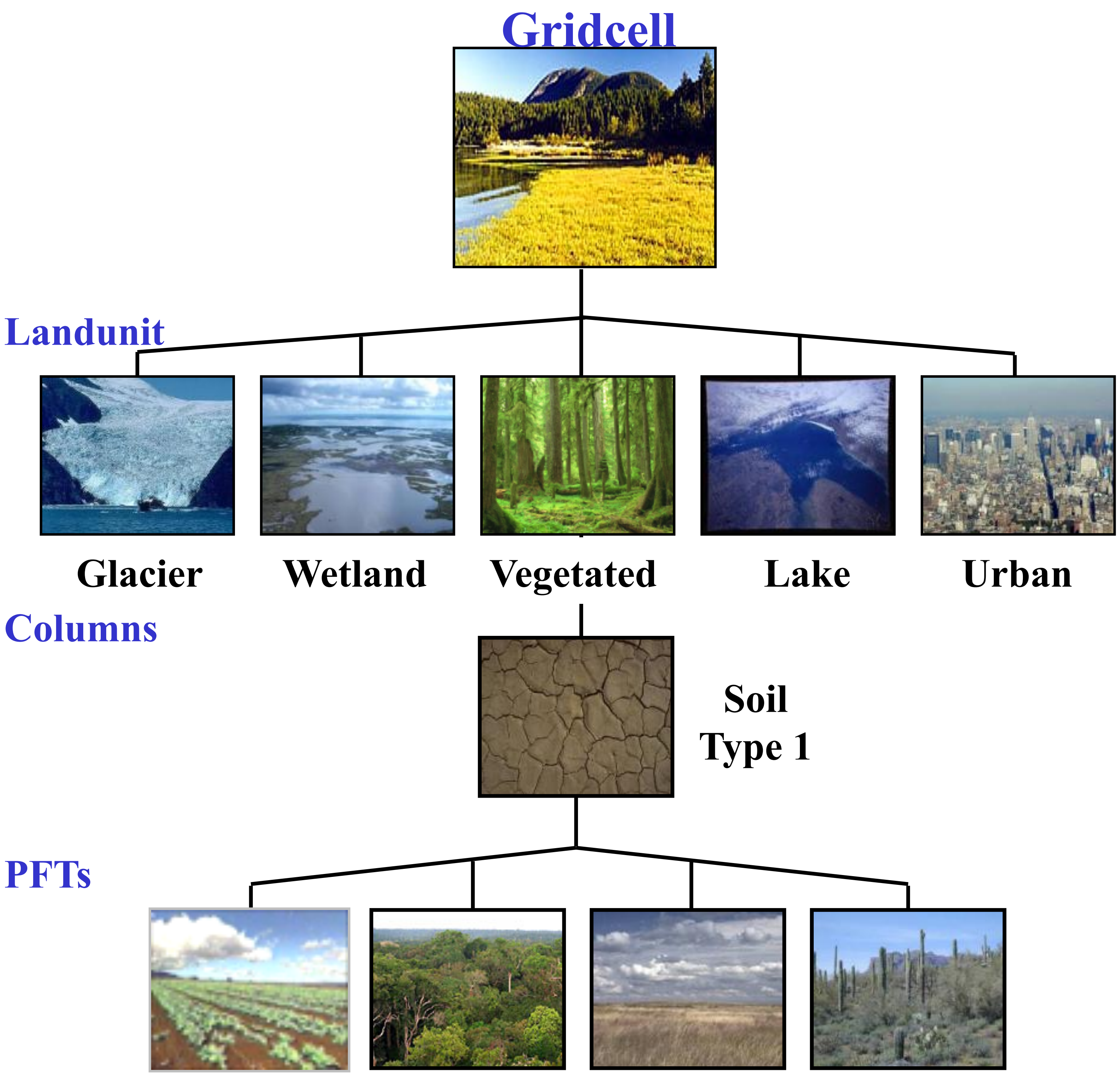
Typical result from Earth System models with carbon and nitrogen interactions

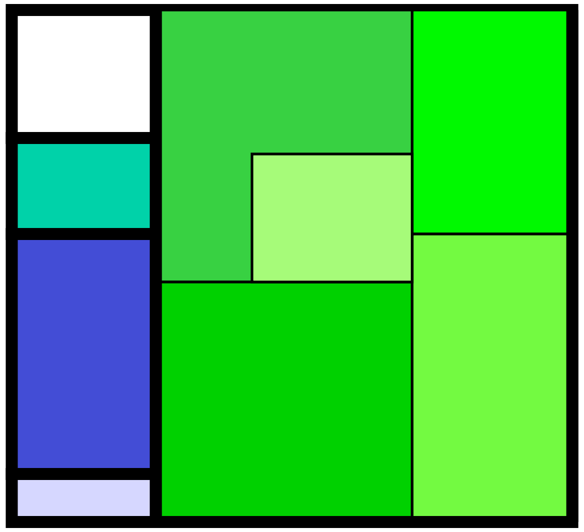
Simulation with carbon and nitrogen coupled cycles	-	Simulation with only carbon cycle



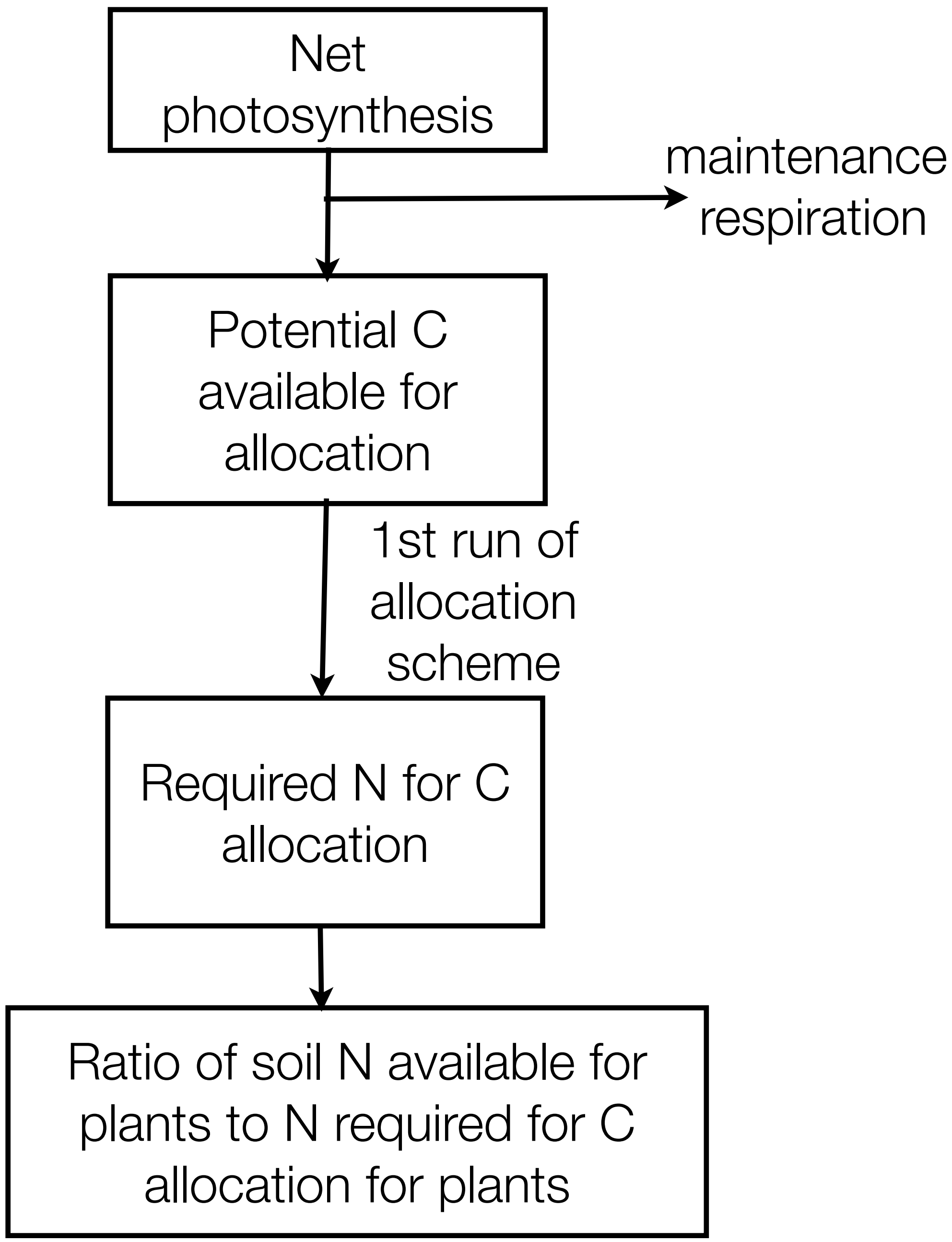
Zaehle et al. 2010 GRL

N cycle is resolved at the landunit scale





How do we model coupled C & N cycles: CLM-CN: Allocation and Plant N limitation



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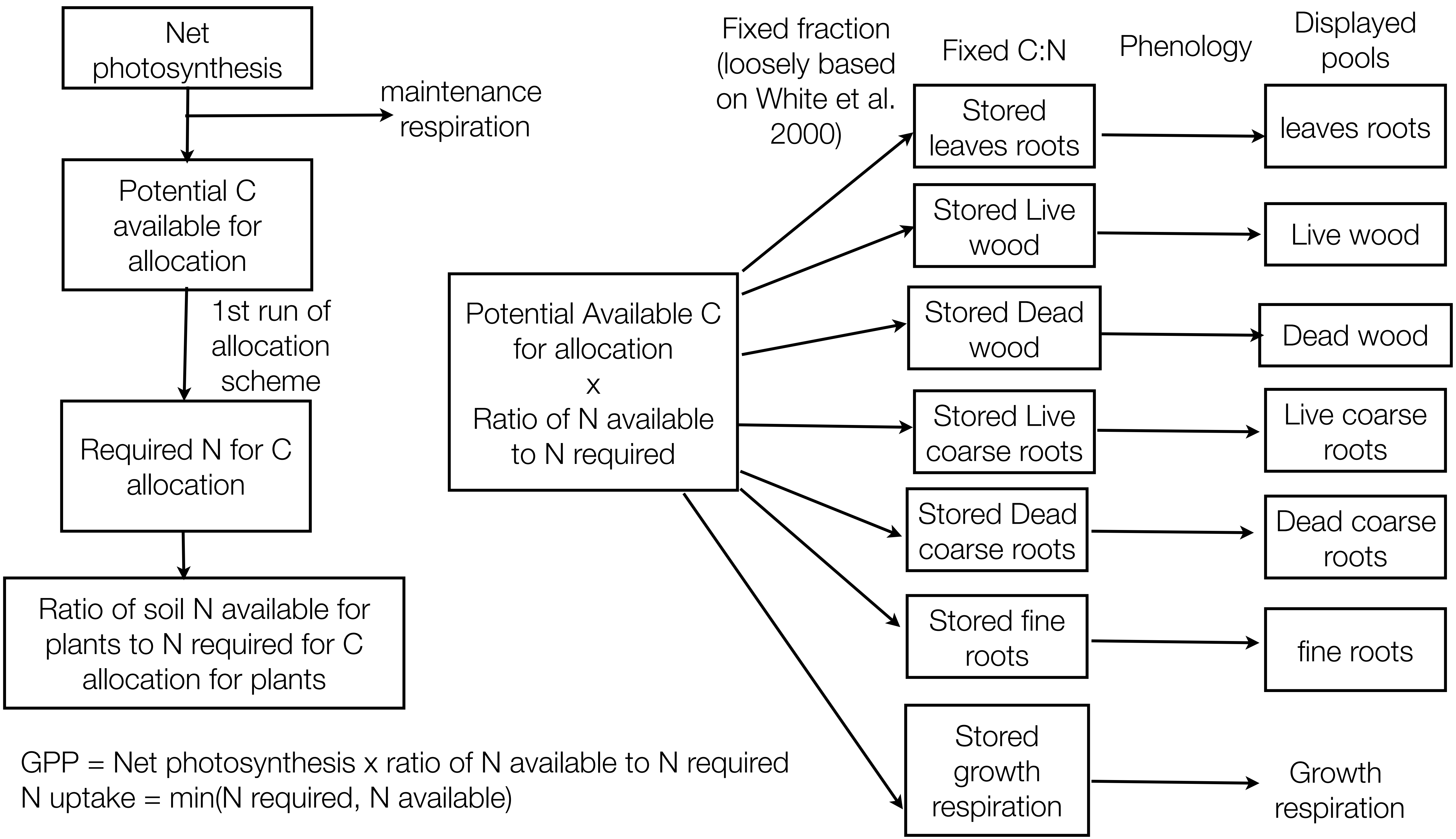

GPP = Net photosynthesis x ratio of N available to N required
N uptake = min(N required, N available)

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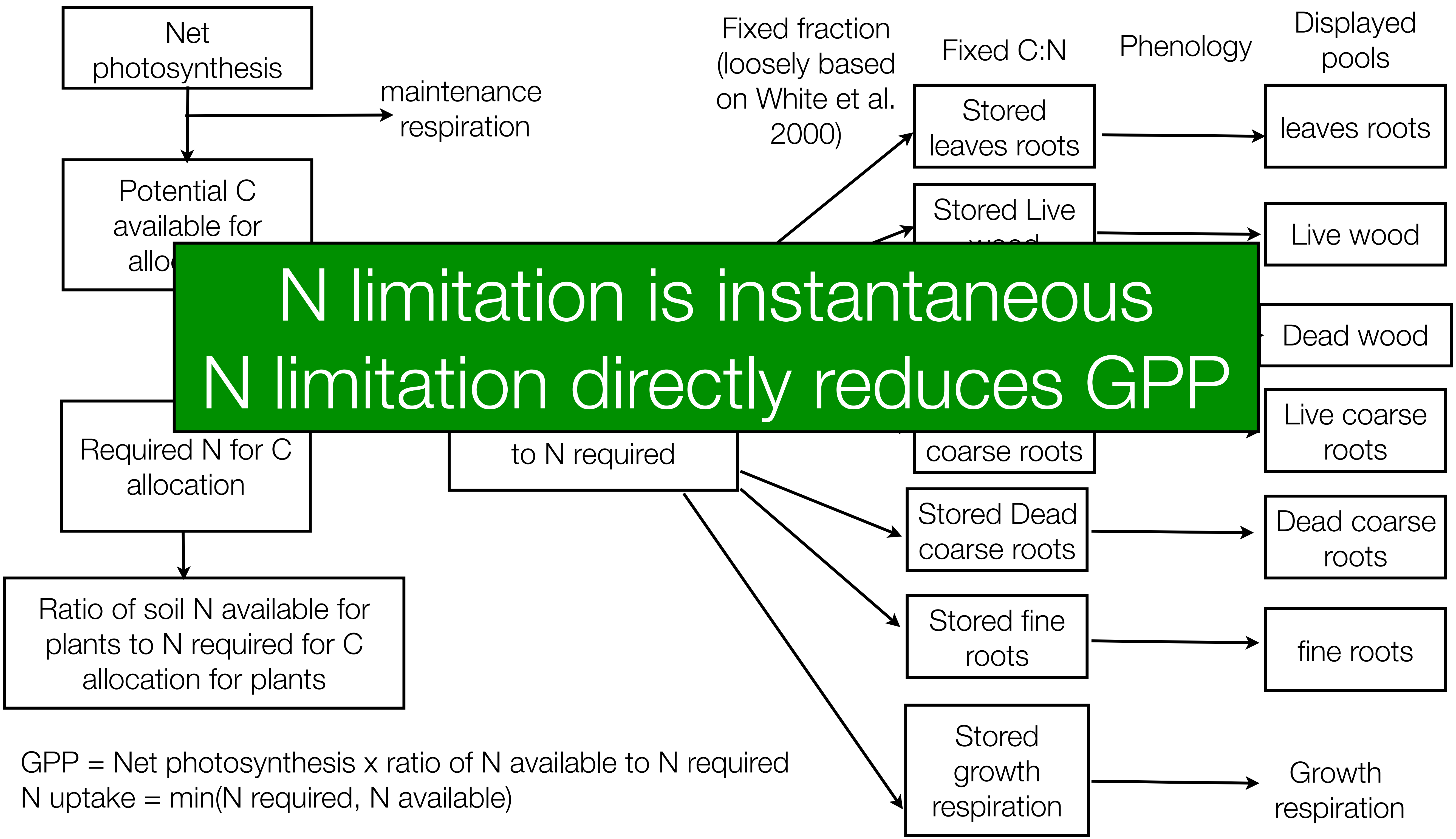


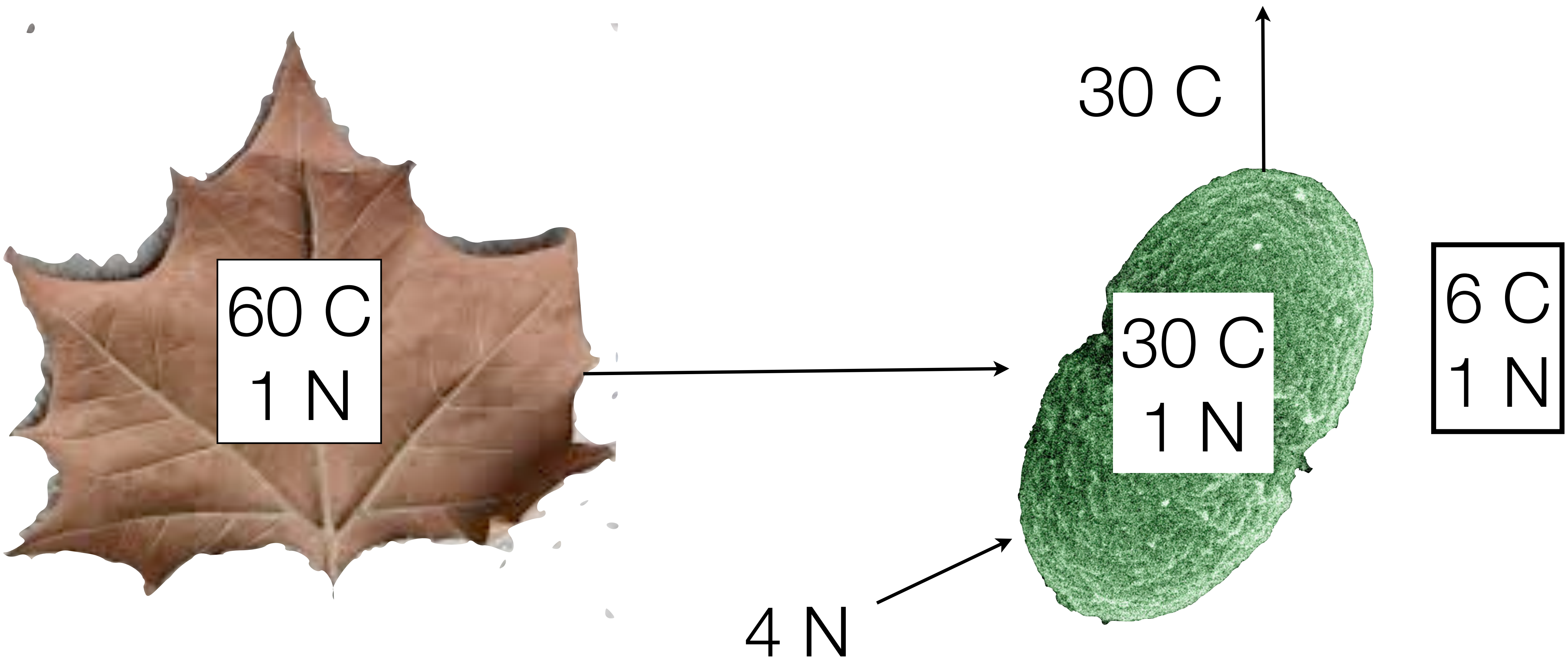
N limitation is instantaneous

N limitation directly reduces GPP

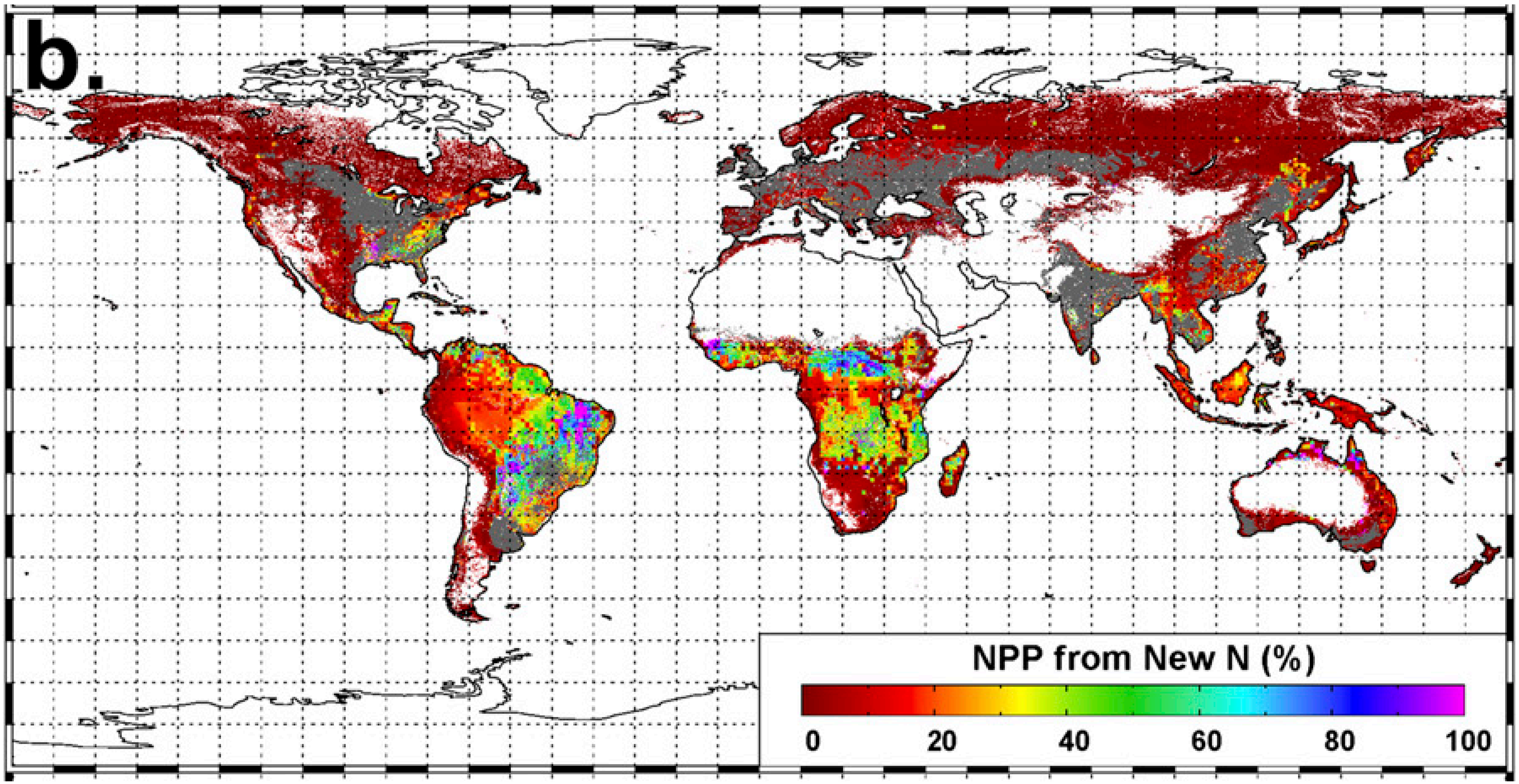
GPP = Net photosynthesis x ratio of N available to N required

N uptake = min(N required, N available)

How do we model coupled C & N cycles: Microbial example

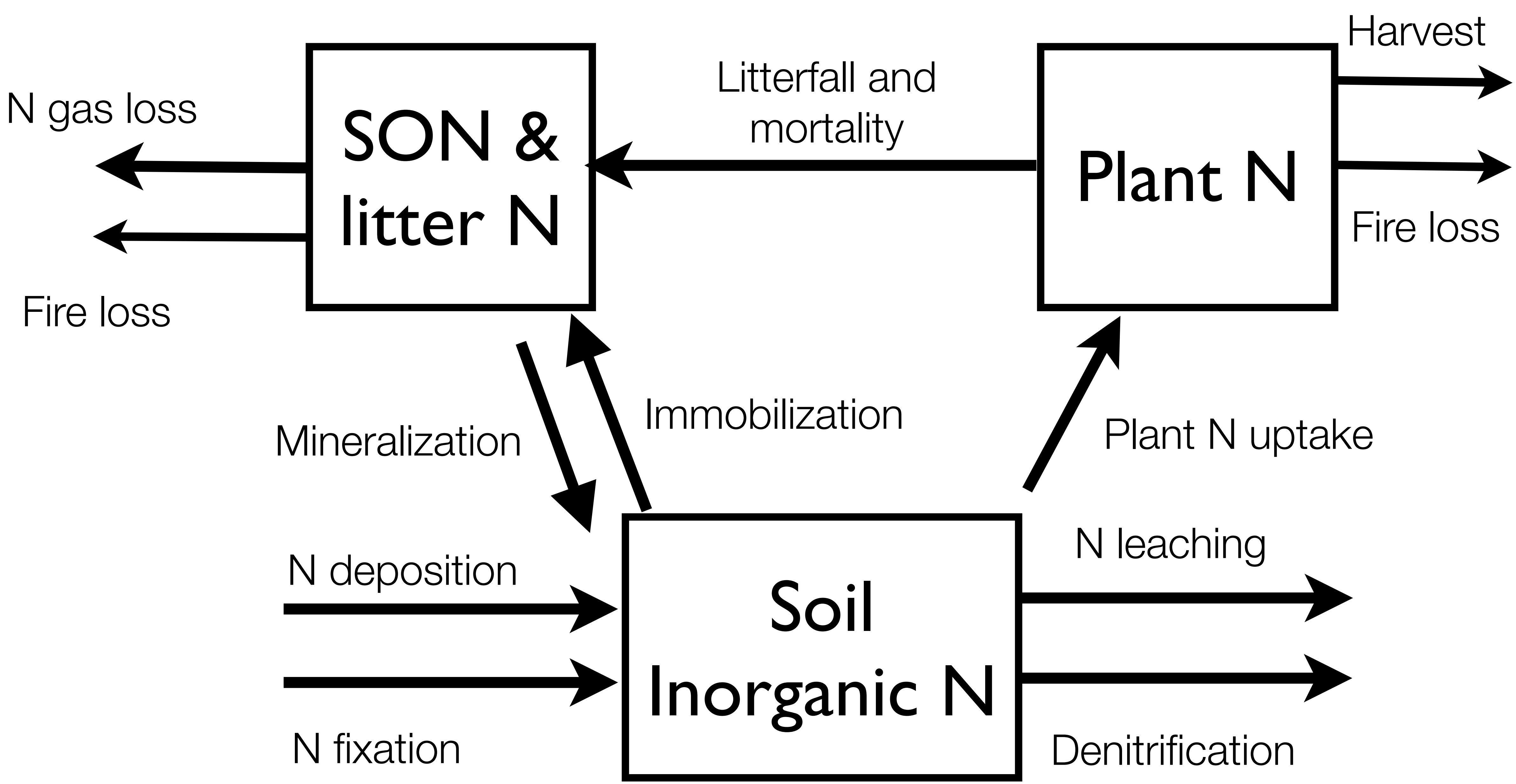


Most nitrogen is recycled



Cleveland et al. 2013 PNAS

CLM-CN 4.0: General N cycle structure



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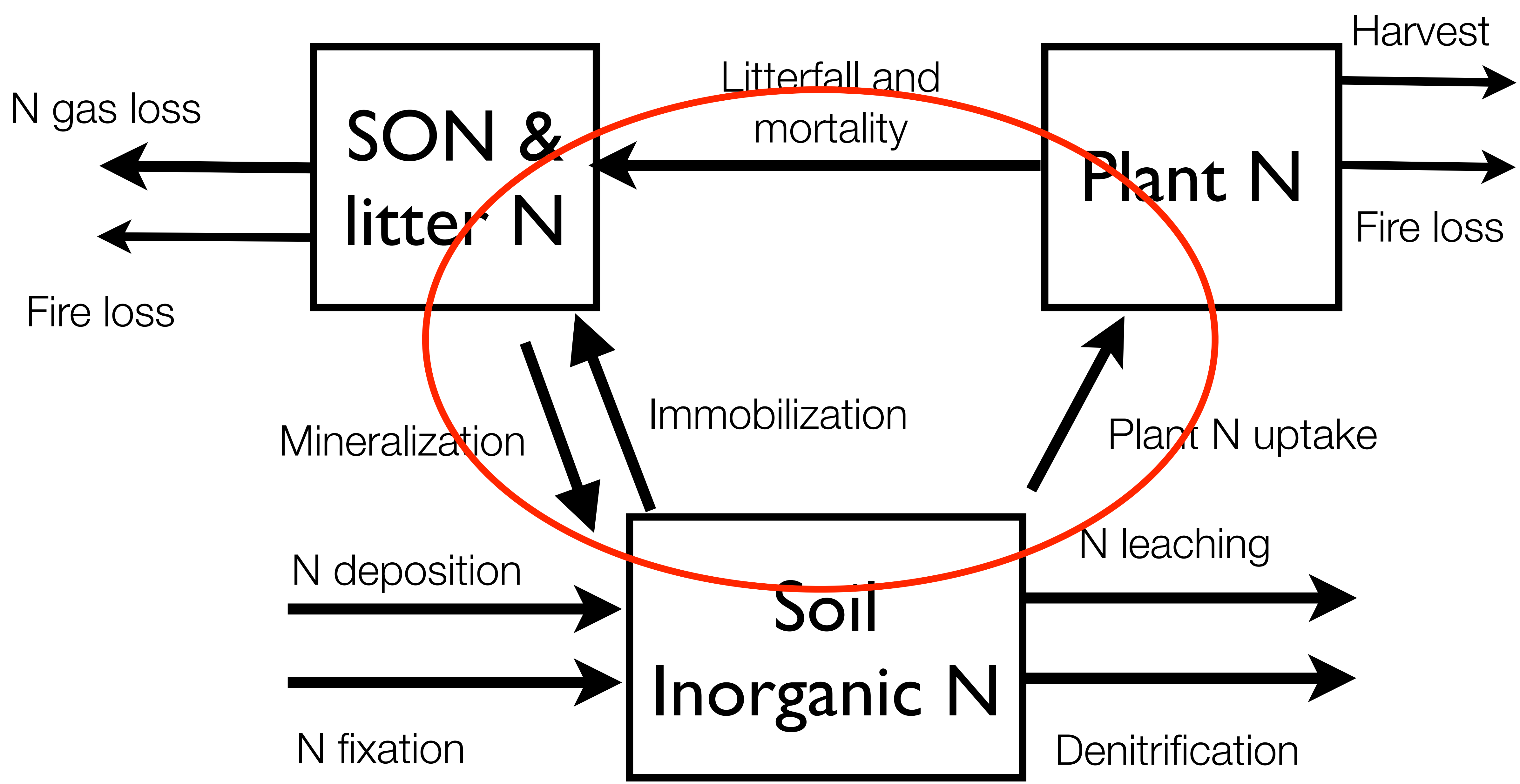

Mechanisms that govern N limitation

Steady-state and transient processes

Pathway	Mechanism
Demand-independent losses	losses of combined N that organisms cannot prevent, including leaching of DON, post- disturbance losses, some gaseous pathways
Constraints to biological N fixation	biological N fixation is slow or absent even when N is limiting; could be due to energetic costs, differential grazing, demands for P, Mo, or other essential elements
Transactional	slow release of N from complex organic into soluble forms, relative to the supply of other resources
Sink driven	sequestration of available N in an accumulating pool within ecosystems

Sources: Vitousek and Howarth (1991), Vitousek and Field (1999), and Vitousek (2004).

Transient-only processes

Vitousek et al. 2010 Ecol. Applications

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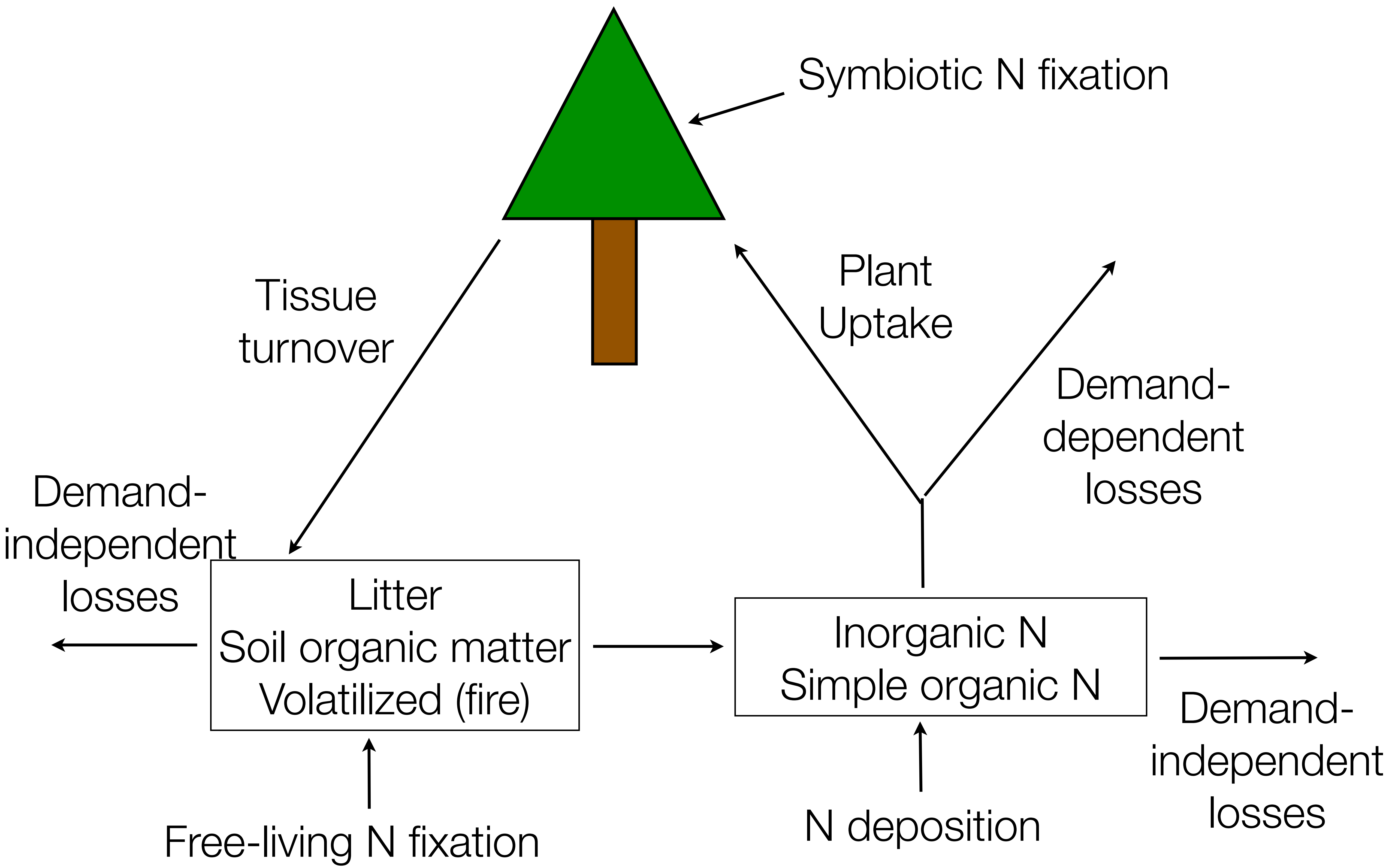

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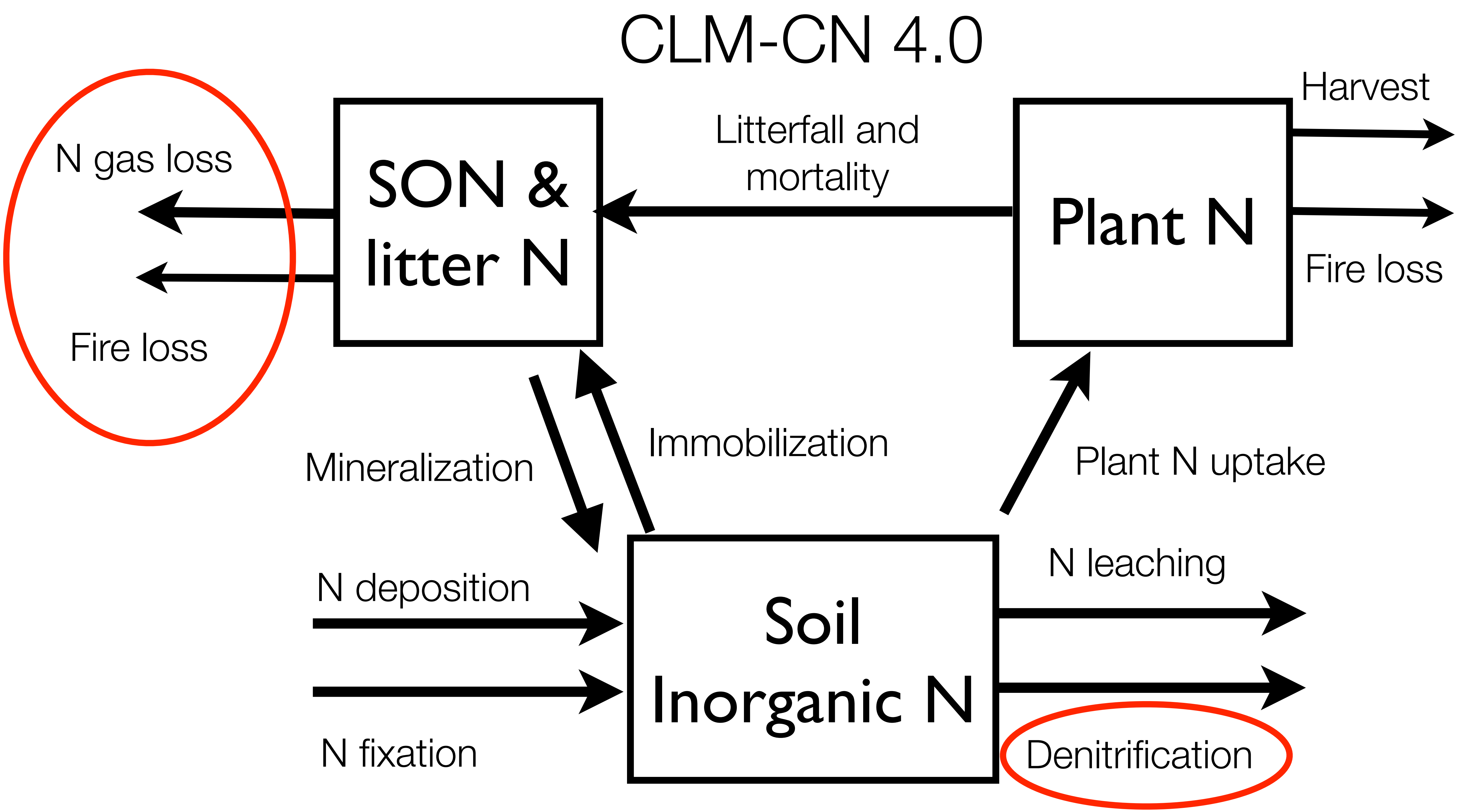

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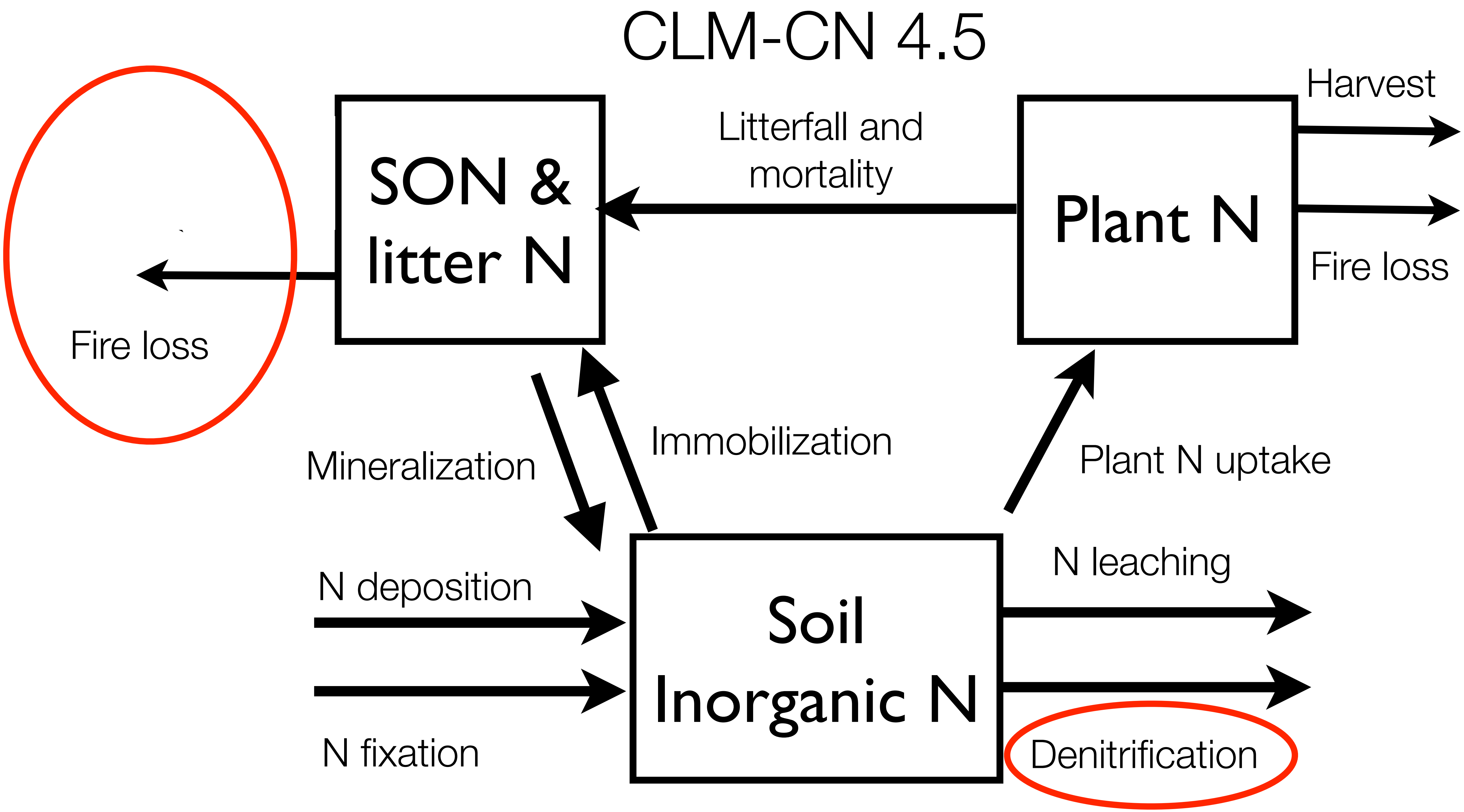

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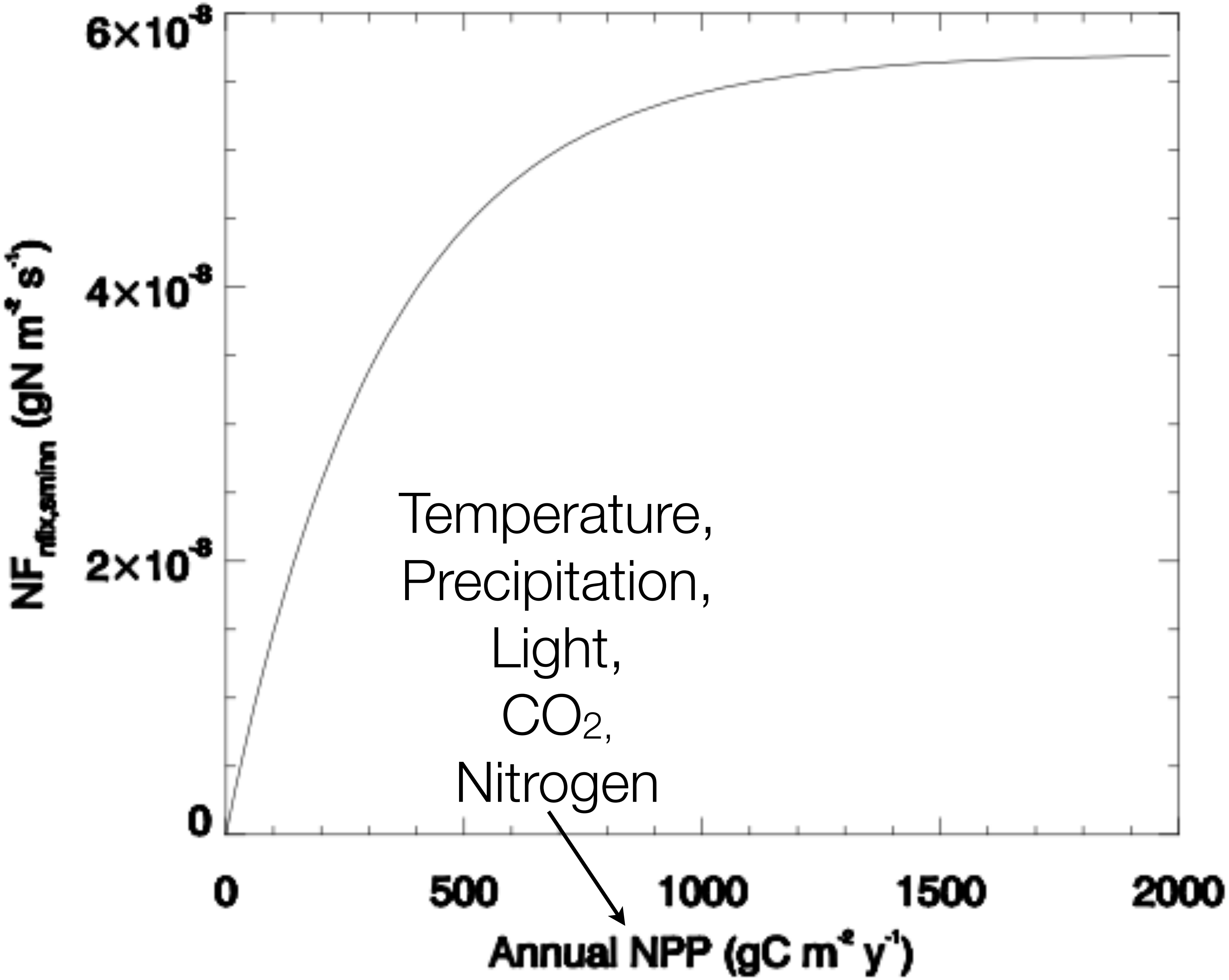

Cleveland et al. 1999 Global Biogeochemical Cycles

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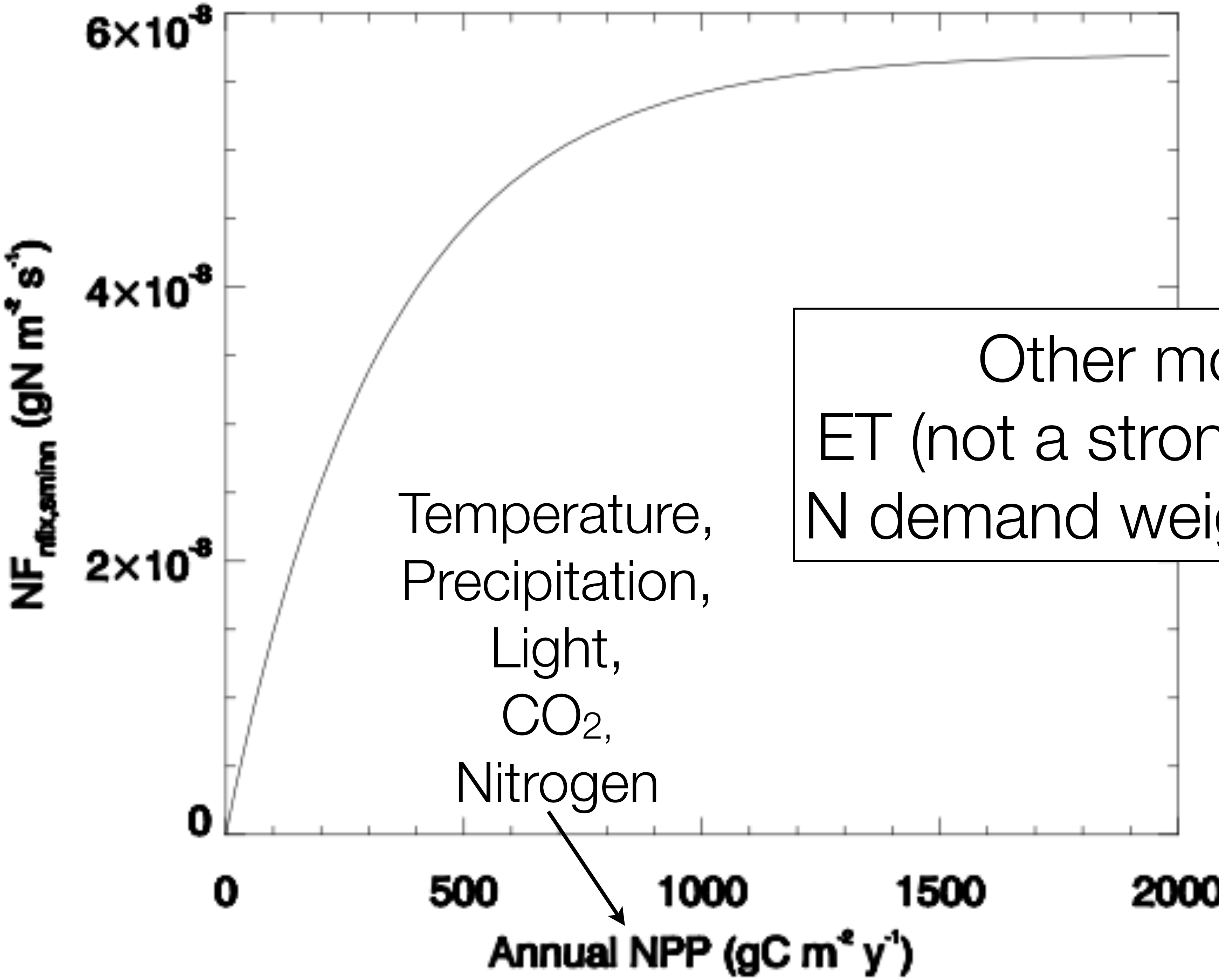
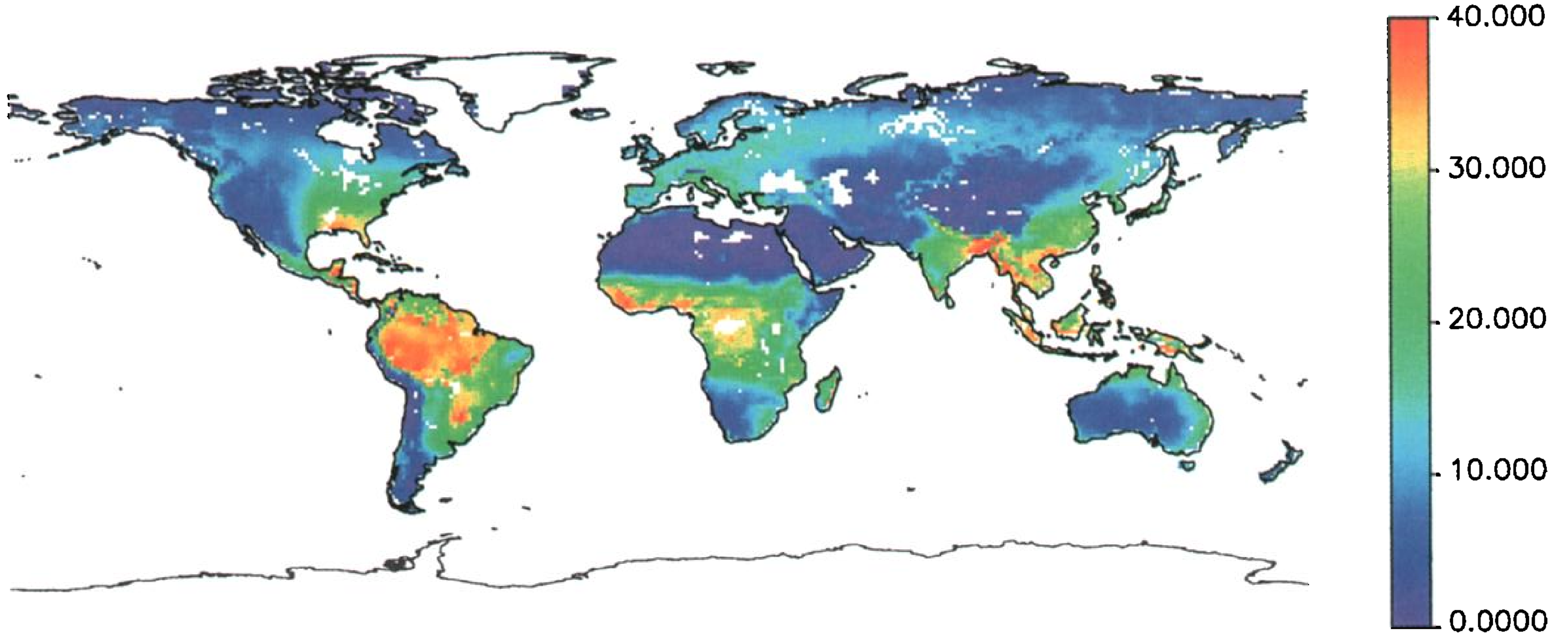


Temperature,
Precipitation,
Light,
CO_2,
Nitrogen

Other models use:
ET (not a strong function of N)
N demand weighted by energy

Cleveland et al. 1999 Global Biogeochemical Cycles

Constraints to Biological Fixation



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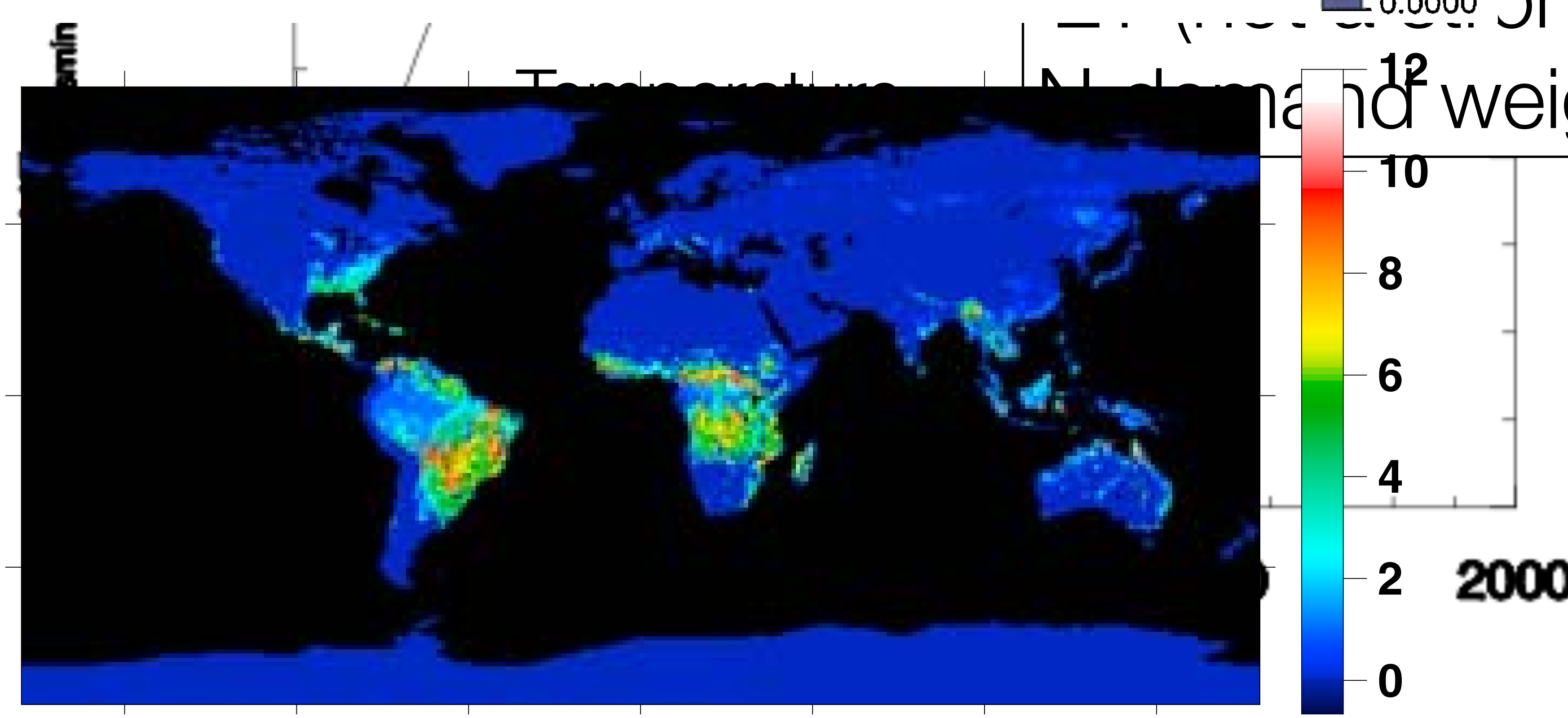

Cleveland et al. 1999 Global Biogeochemical Cycles

N limitation at steady-state

N fixation < Demand-independent losses

How to classify losses
in Earth System Models?

Demand-dependent losses < N deposition

Menge 2011 Ecosystems

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Transient-only processes

Vitousek et al. 2010

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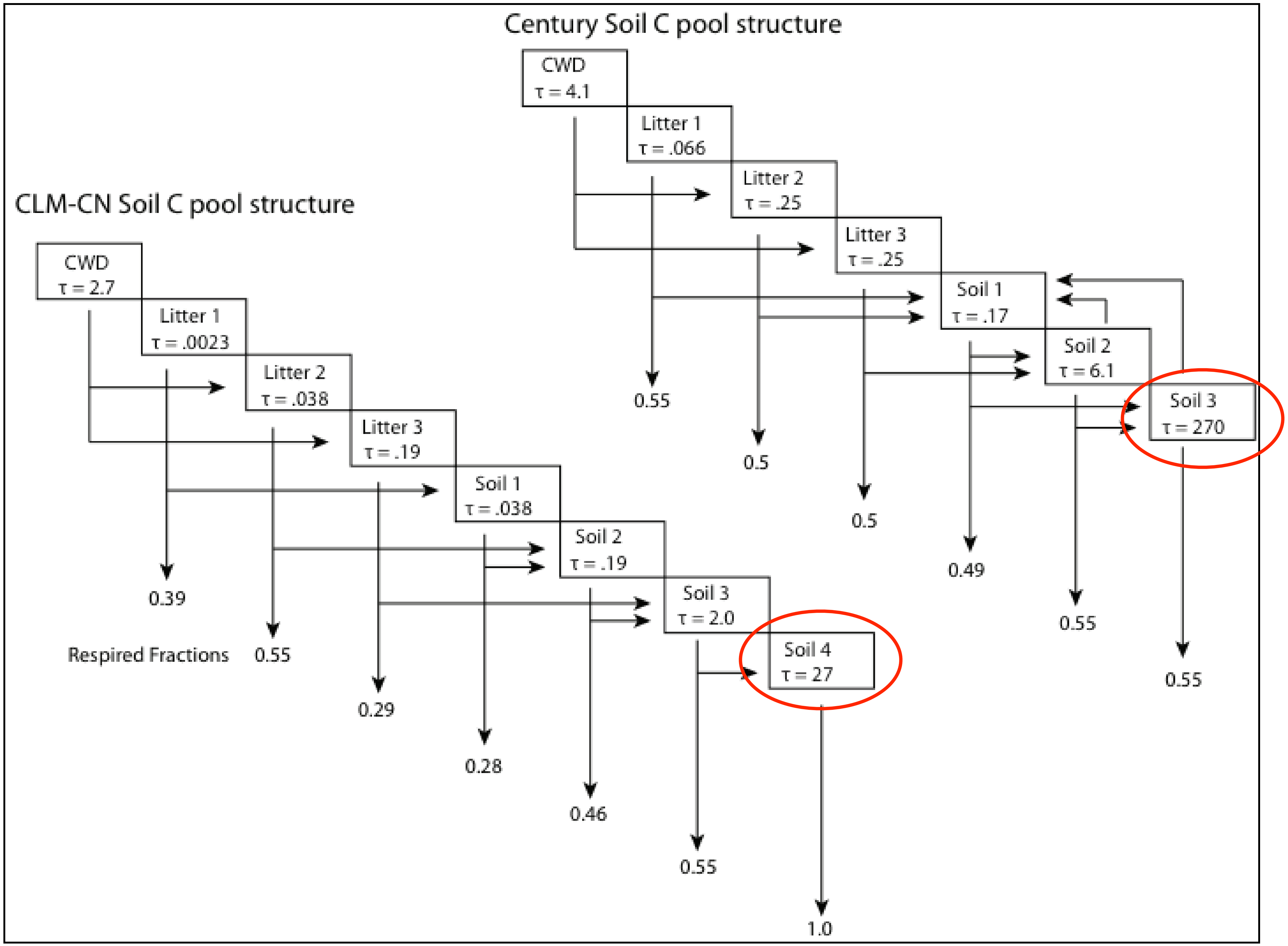

Thornton and Rosenbloom 2005 Ecological Modelling

Parton et al. 1993 Glob. Biogeochemical Cycles

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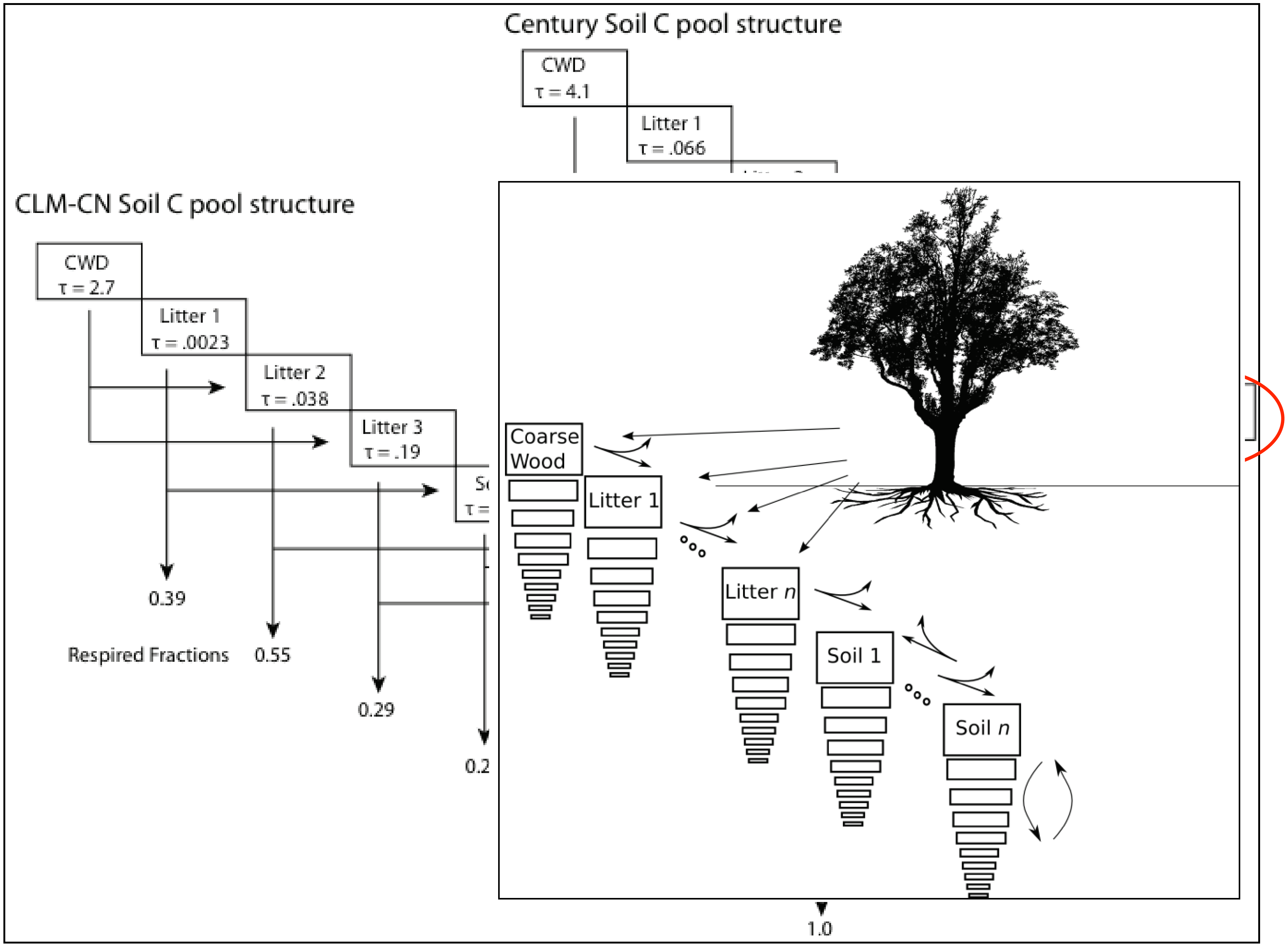

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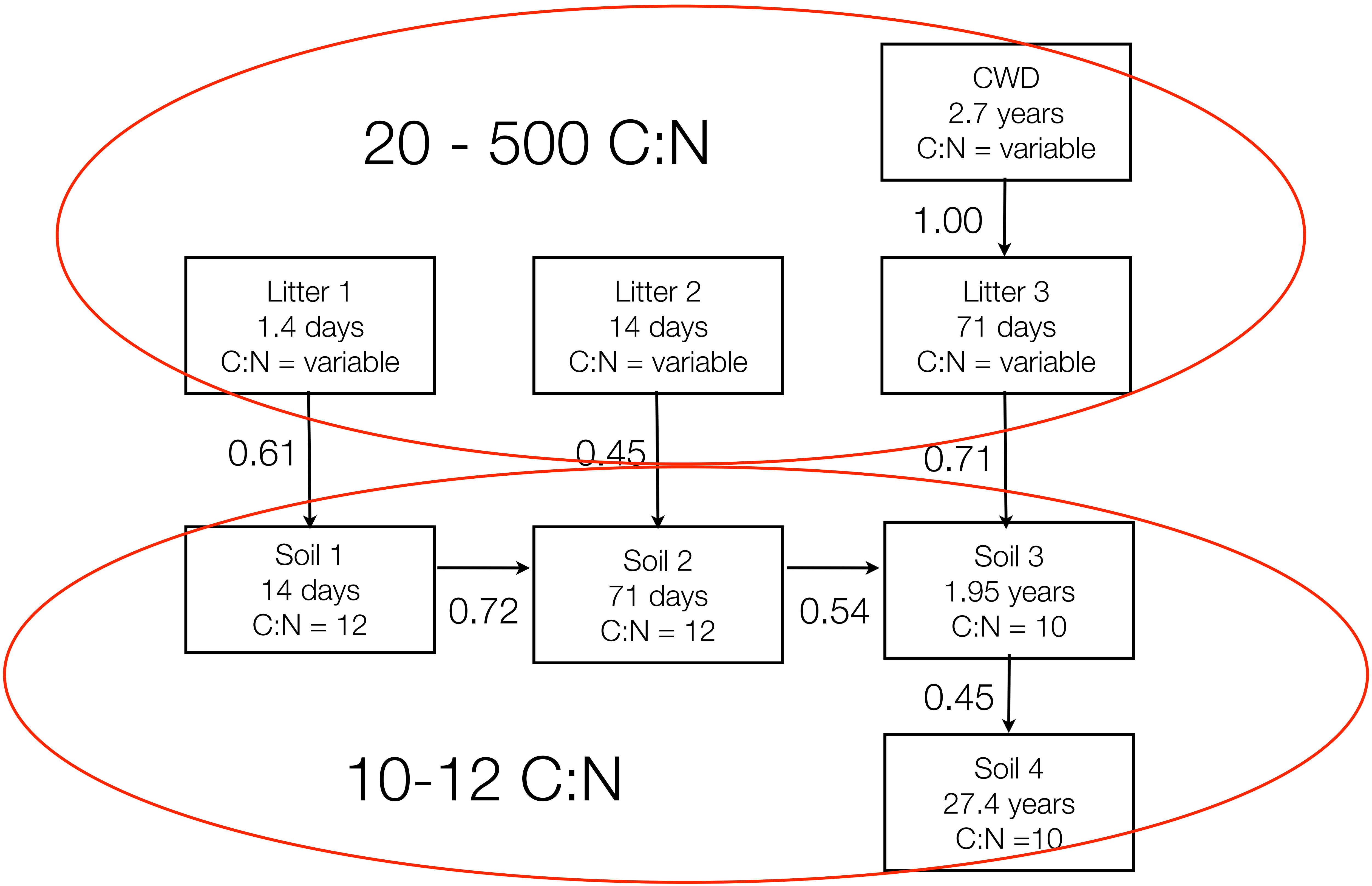
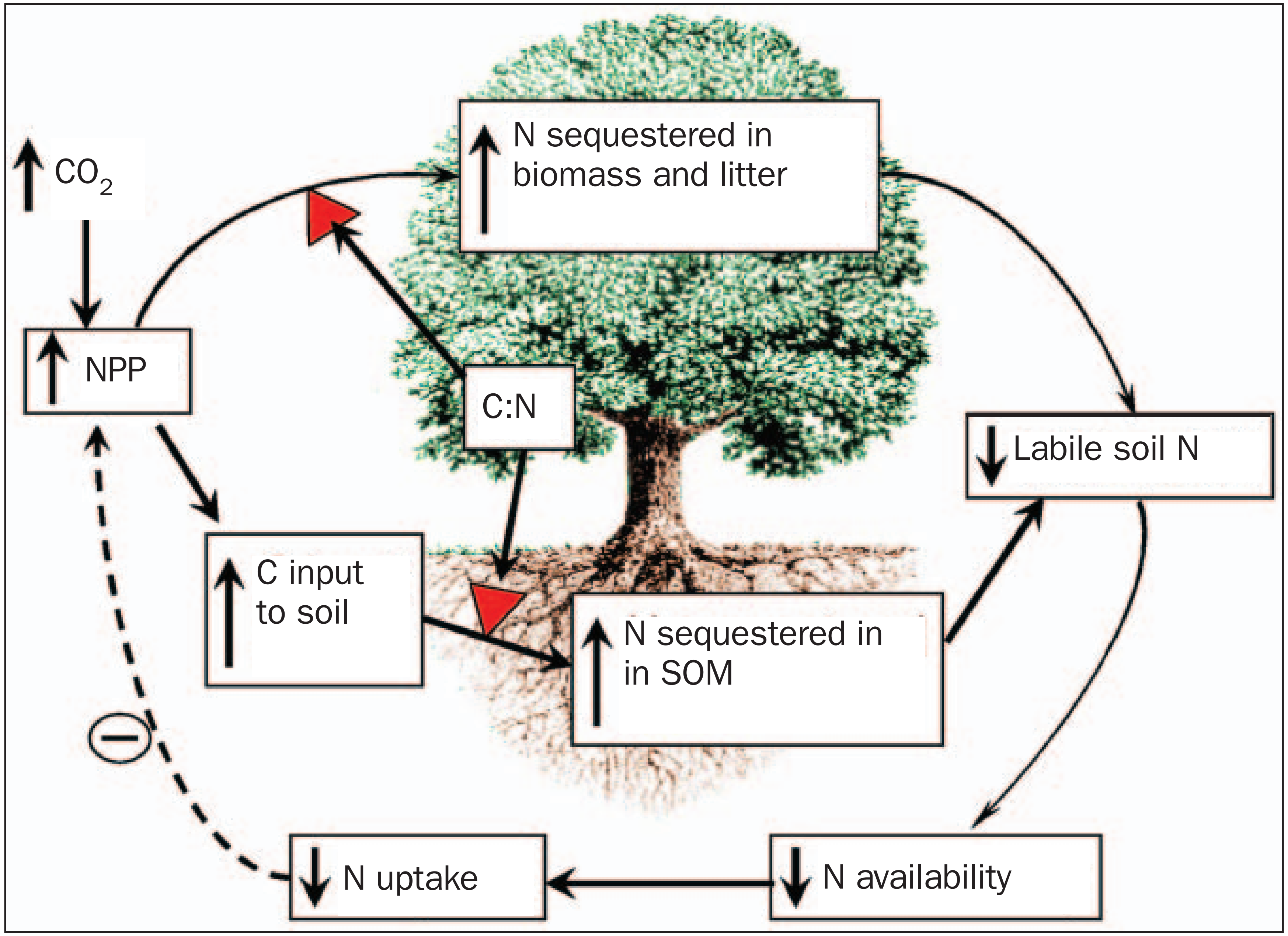
Sink-driven N limitation



Sink-driven N limitation

Progressive N limitation



Luo et al. 2004 Bioscience

How do we measure and evaluate N limitation?

Field

Add N to ecosystem and measure response

Measure inorganic N leaching relative to N deposition

Measure leaf chemistry (N:P ratios)

Measurement of N fixation relative to DON leaching

Model

Instantaneous metric in models (actual NPP/potential NPP)

Coupled simulations with and without N constraints included

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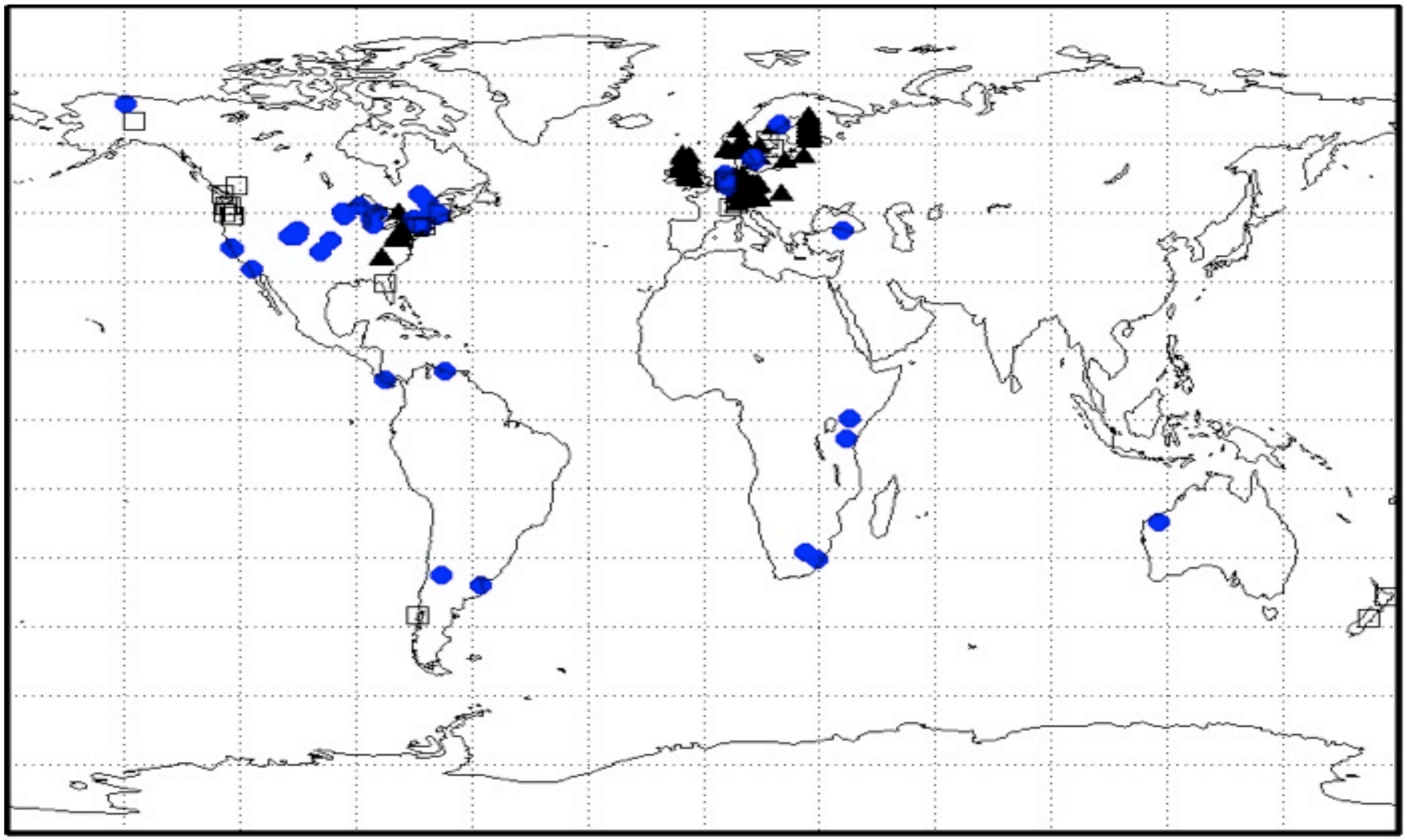
Model comparison to data:
Model response compared to observations



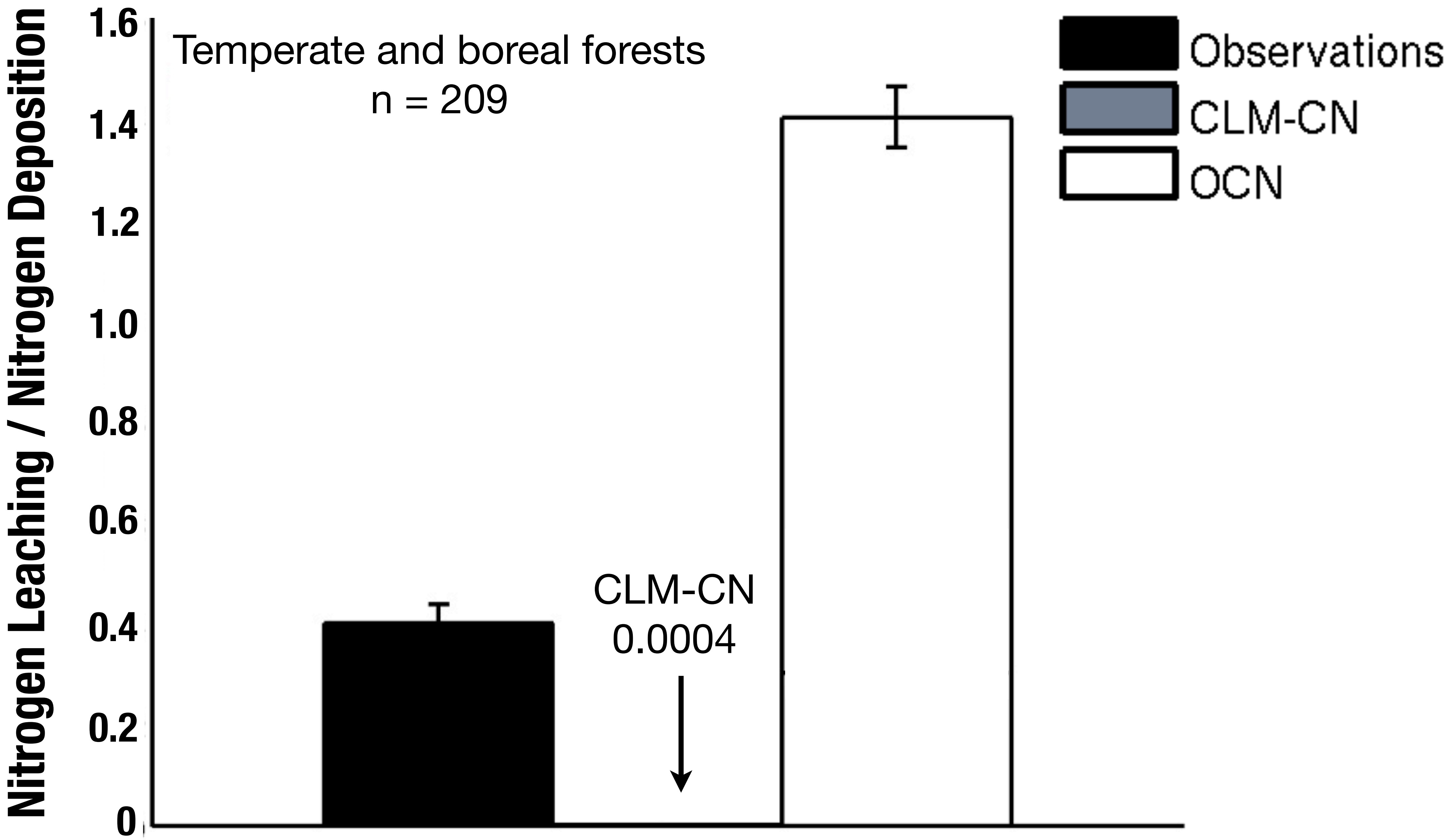
● Nitrogen fertilization experiments

□ ^{15}N tracer studies

▲ Plot/small catchment nitrogen budgets

Thomas et al. 2013 Global Change Biology

Model comparison to data: Plot/Small Catchment Nitrogen Budgets



Thomas et al. 2013 Global Change Biology

Observations from NiRENA project: Goodale *et al.*

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Test of nitrogen limitation in two global biogeochemical models

CLM-CN 4.0	O-CN
(Thornton *et al.* 2009 *Biogeosciences*)	(Zaehle *et al.* 2011 *Nature Geoscience*)

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O-CN

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nature geoscience LETTERS

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O-CN

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Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions

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Test of nitrogen limitation in two global biogeochemical models

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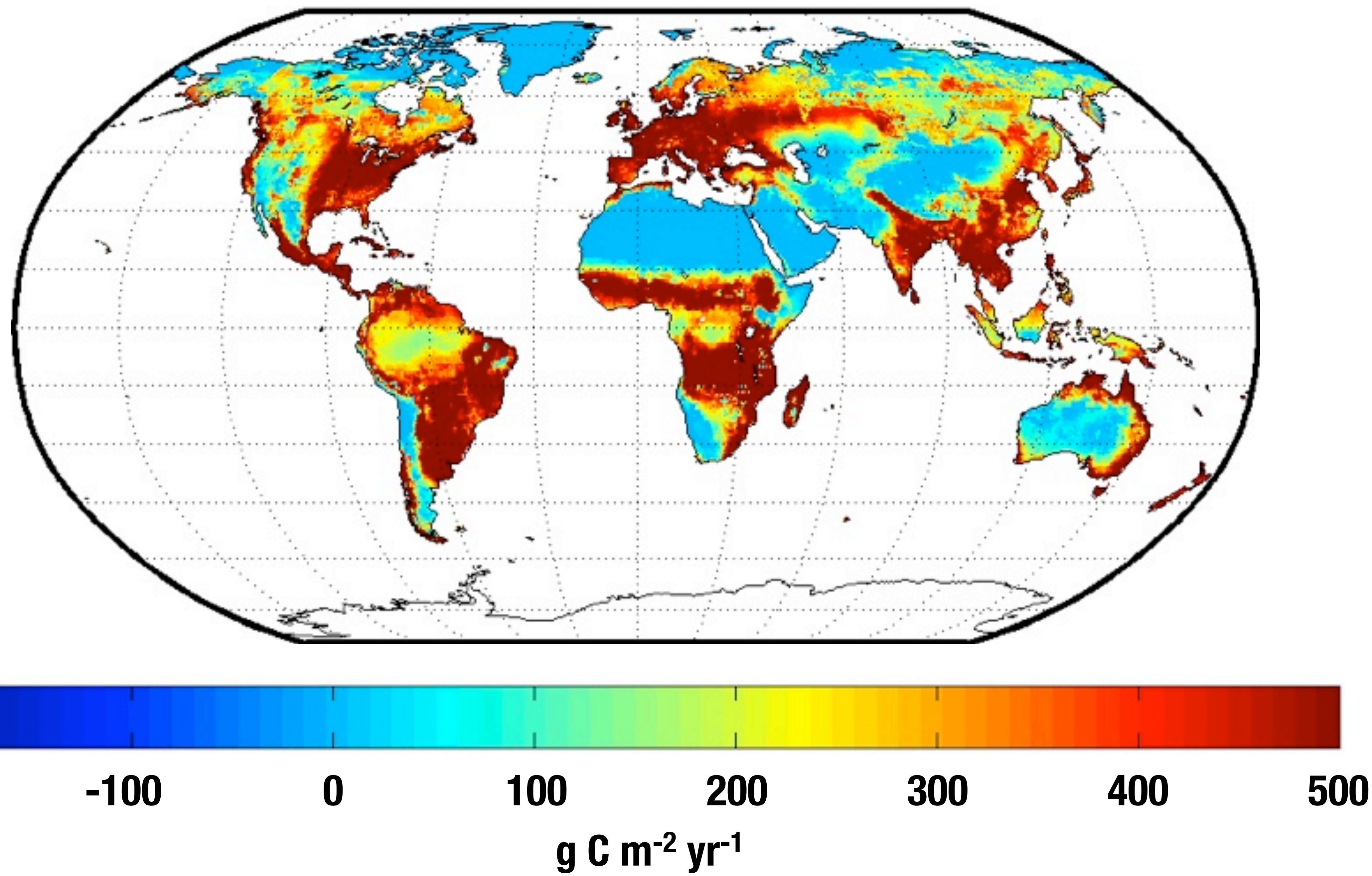
Differing mechanisms governing N loss

Global nitrogen fertilization experiment

- 25 year simulations (1985-2009)
- Nitrogen applied globally at five levels continuously
  - Low application to parallel plausible changes in nitrogen deposition (0.5 g N m^{-2} yr^{-1})
  - Higher applications to parallel field experimental additions of nitrogen fertilizer to terrestrial ecosystems
    (2.0, 4.0, 10.0 g N m^{-2} yr^{-1})
  - High application to test nitrogen saturation (30.0 g N m^{-2} yr^{-1})
- Same climate inputs and land-use history

Global nitrogen fertilization response: High addition (30.0 g N m^{-2} yr^{-1})

CLM-CN ΔNet Primary Productivity



Thomas et al. 2013 Global Change Biology

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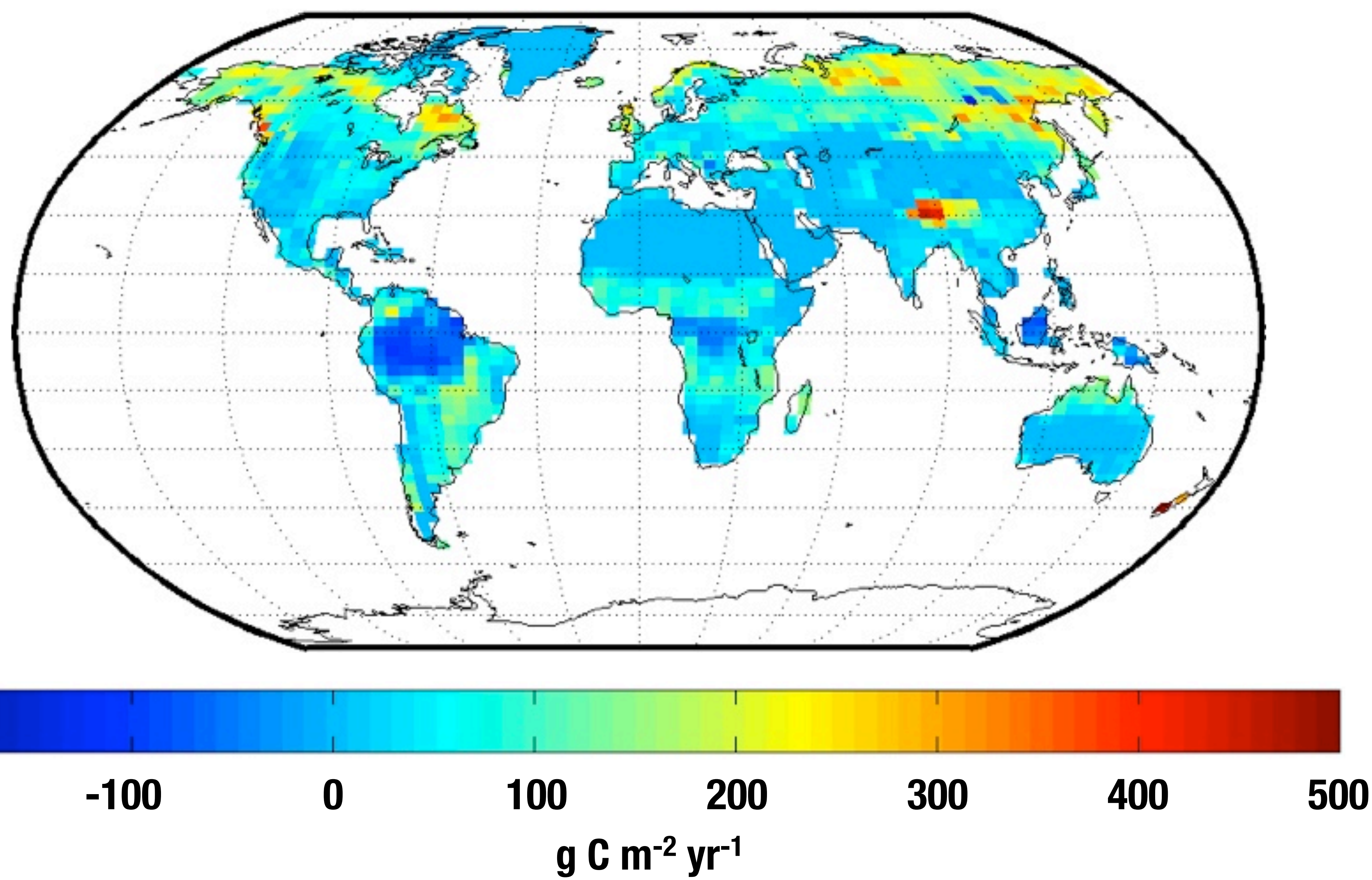

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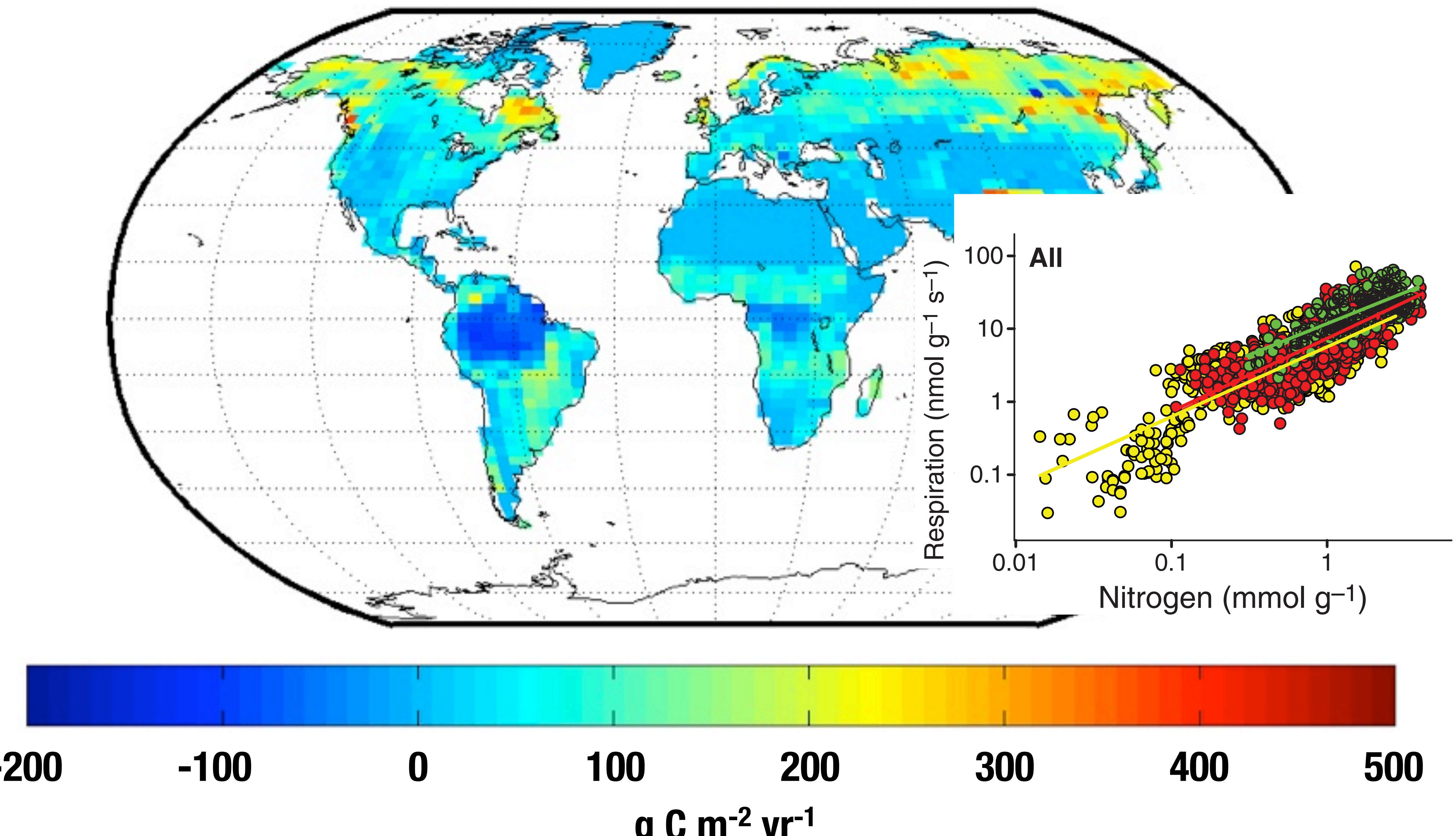

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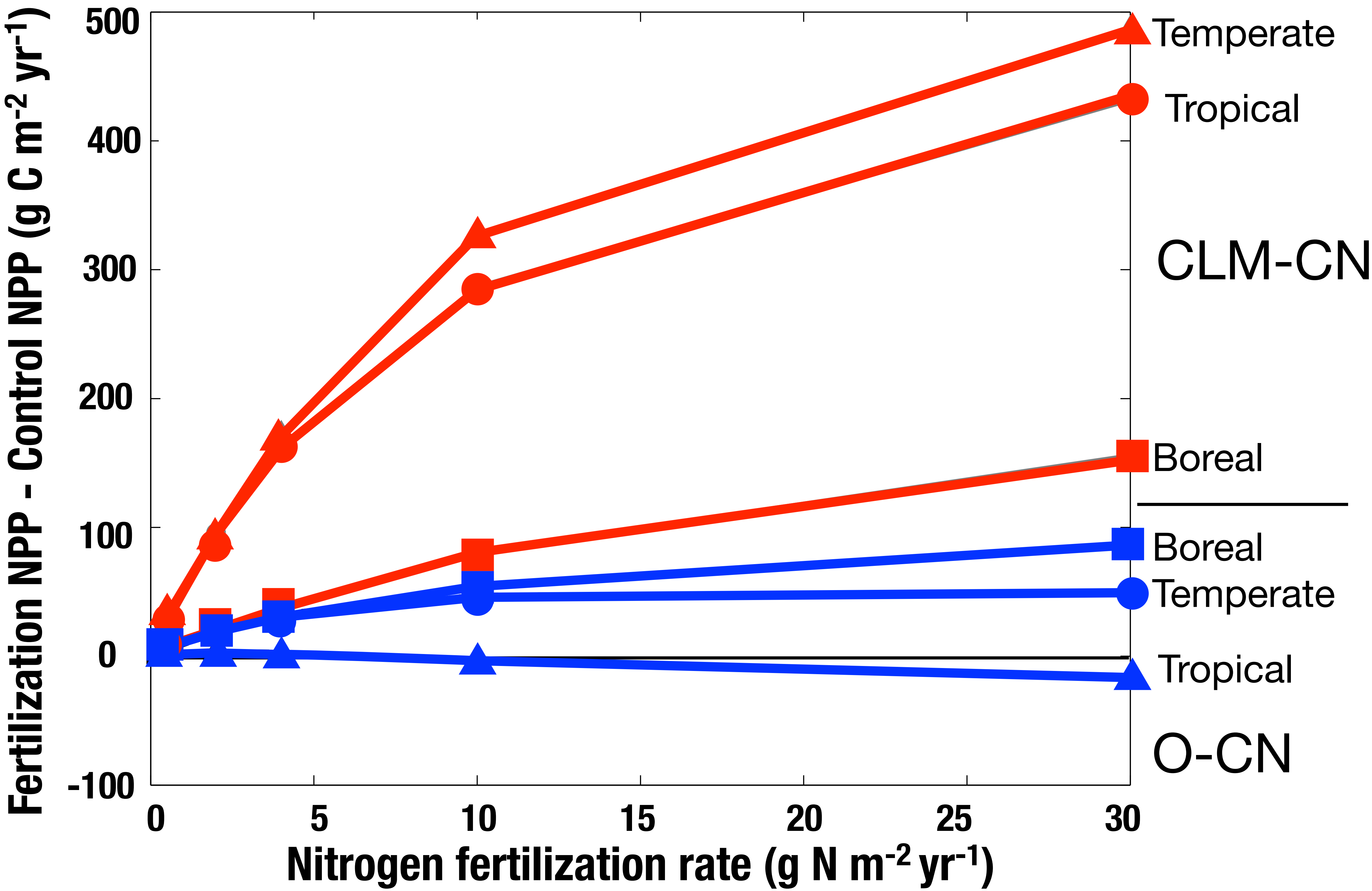
CLM-CN more responsive to nitrogen than O-CN



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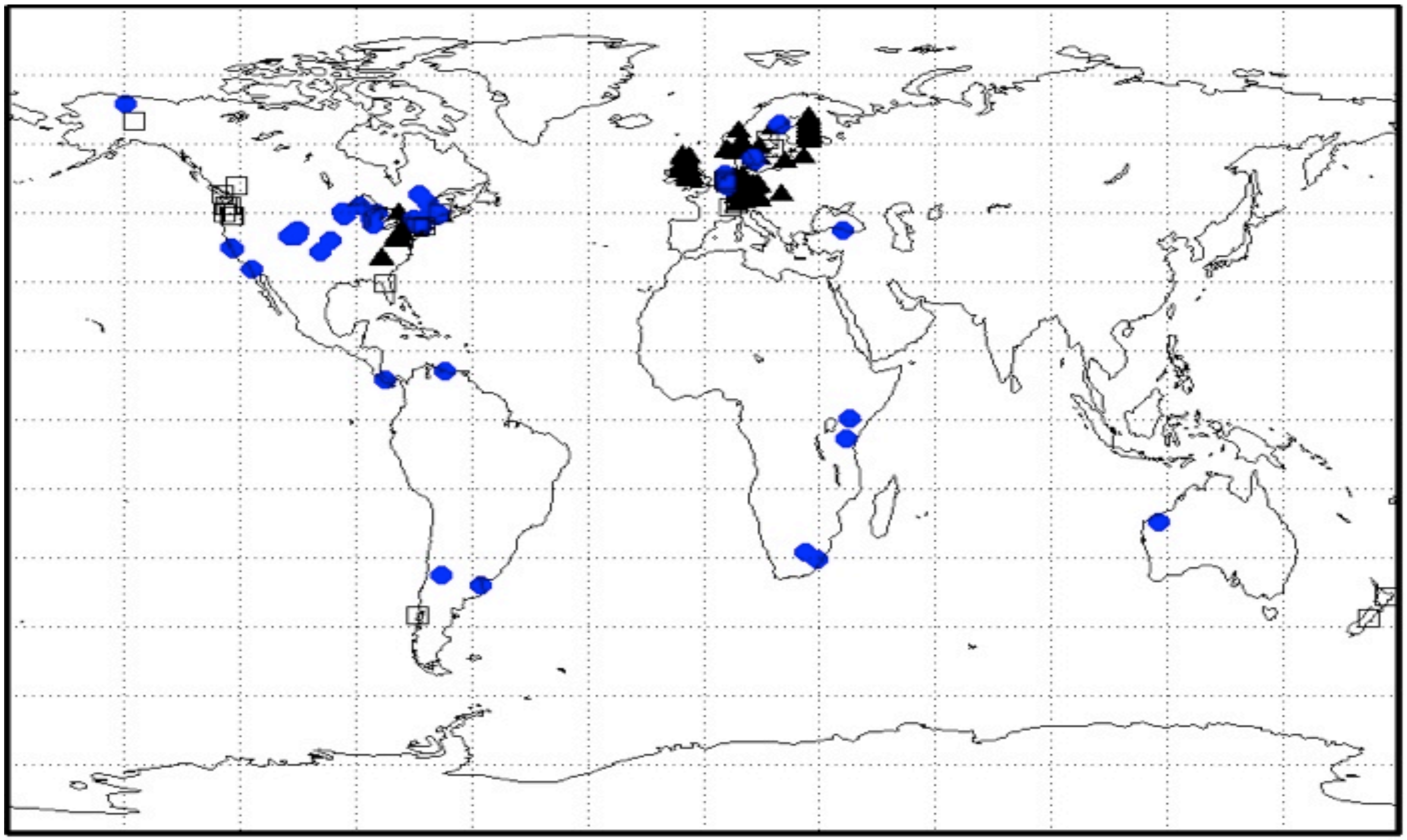
Model comparison to data:
Model response compared to observations



● Nitrogen fertilization experiments

□ ^{15}N tracer studies

▲ Plot/small catchment nitrogen budgets

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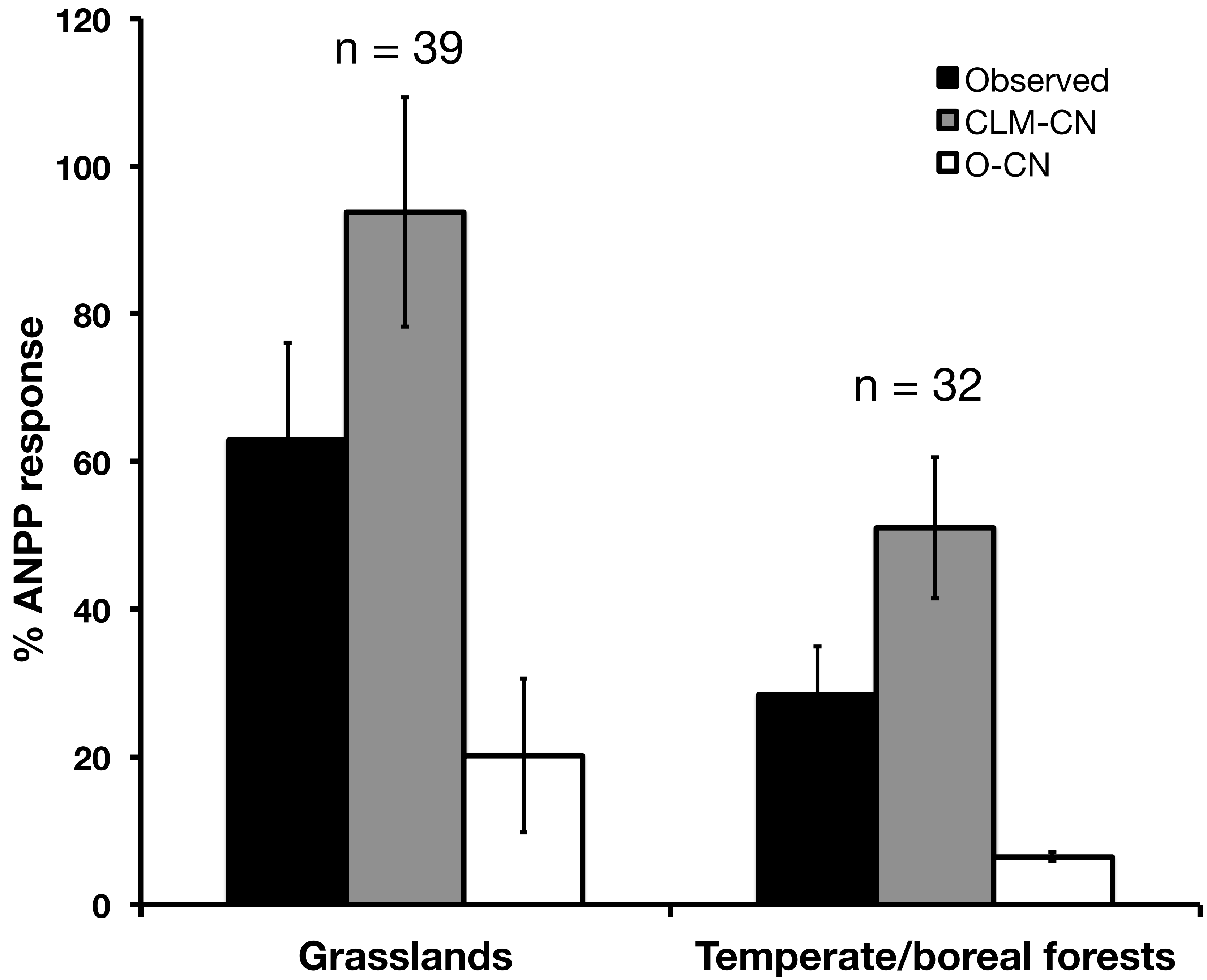
Model comparison to data: NPP response to N fertilization



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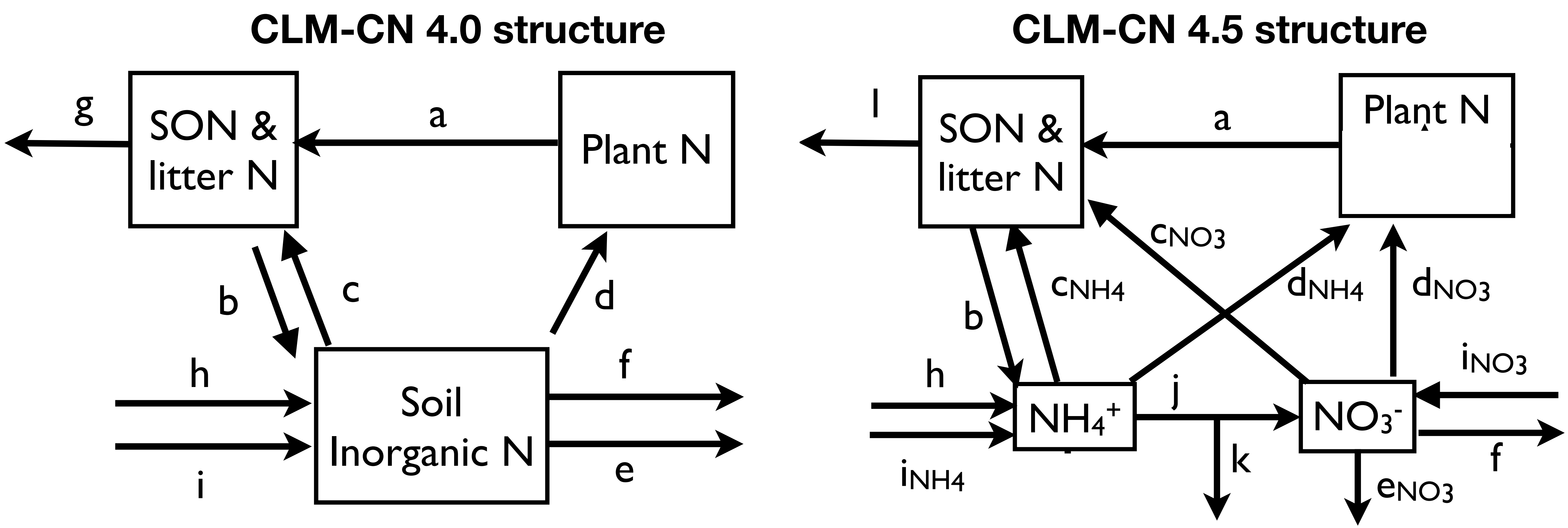
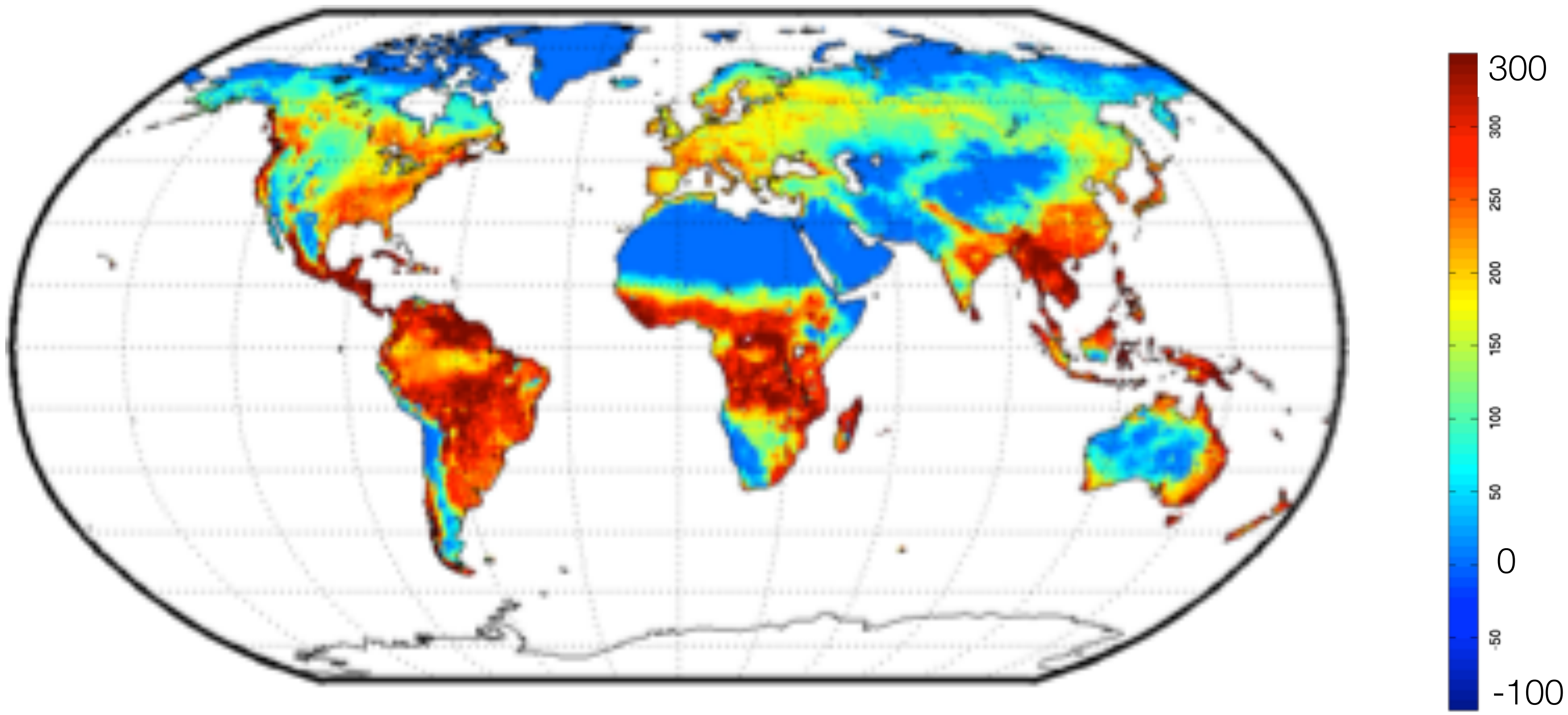
What controls the C cycle response to N additions? Alternative versions of the CLM-CN



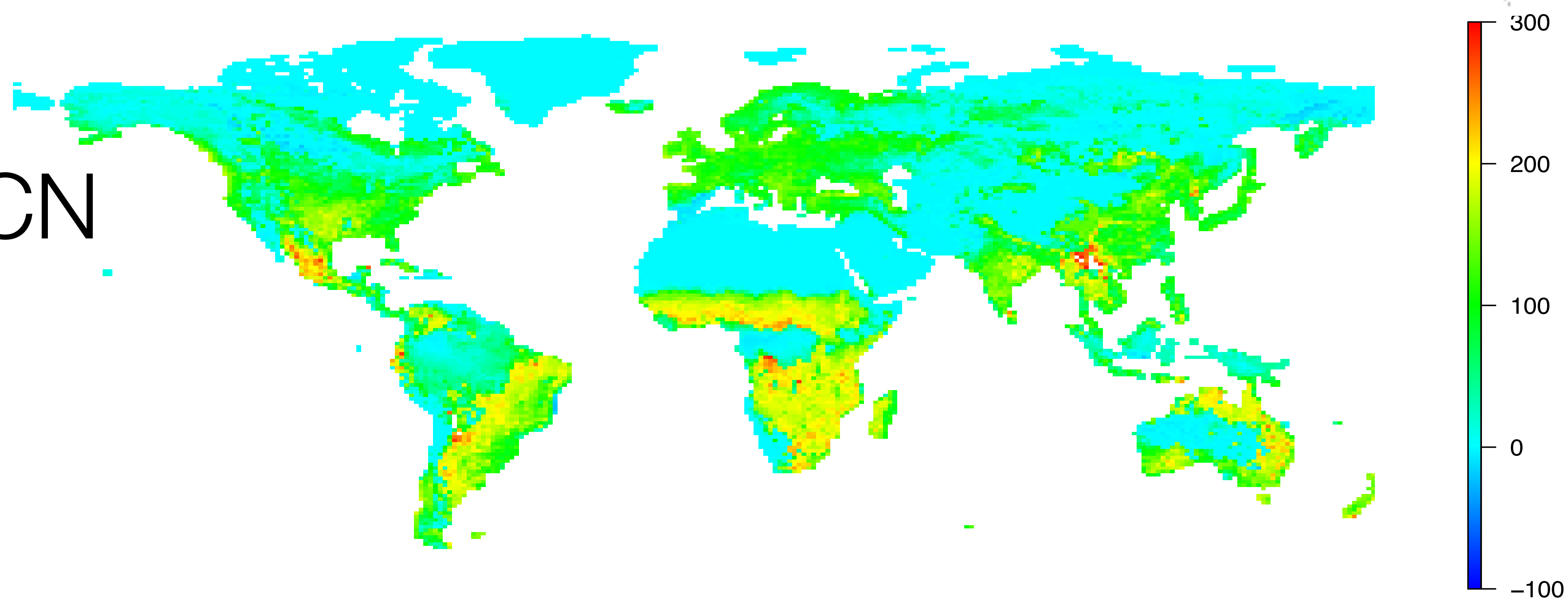
- Removed N gas loss that is 1% of net mineralization
- Denitrification based on environmental conditions
- Soil NH_4^+ and NO_3^- pools
- Reduced light use efficiency (Bonan et al. 2011,2013)
- Vertical soil layers
- Modified the timing of N fixation in high latitudes

NPP response to N fertilization: CLM-CN 4.0 vs. CLM-CN 4.5

CLM-CN 4.0



CLM-CN 4.5



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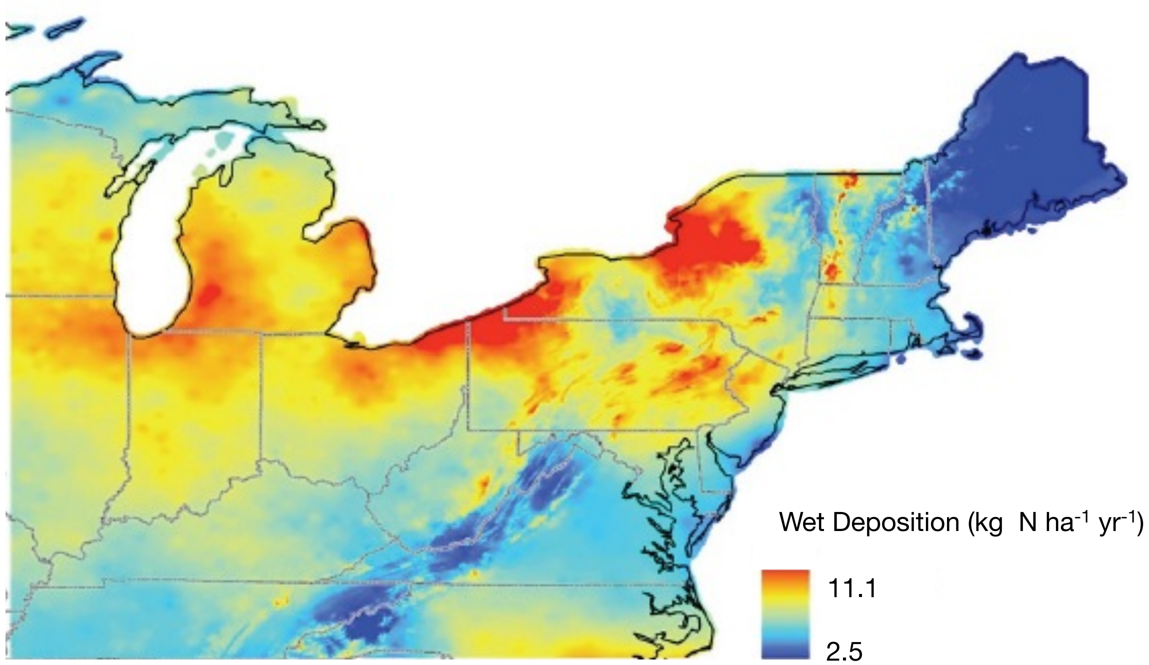
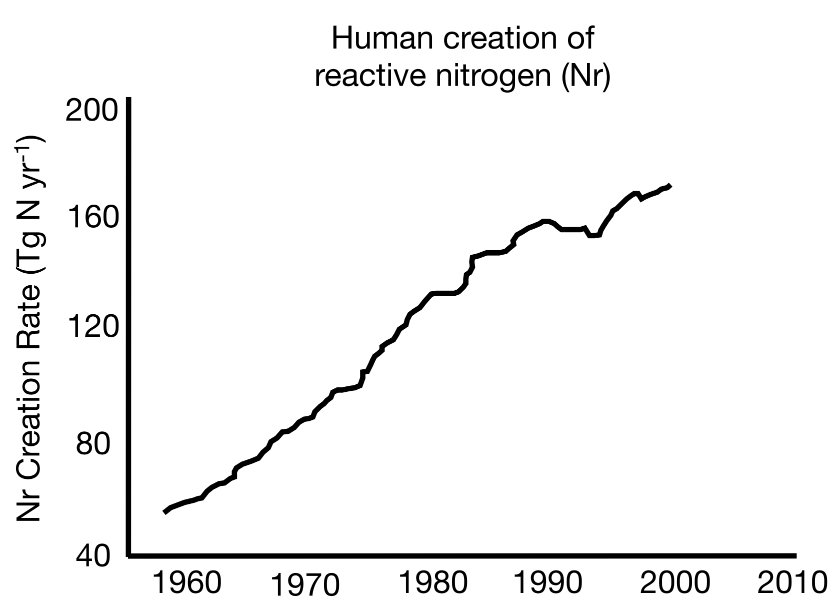
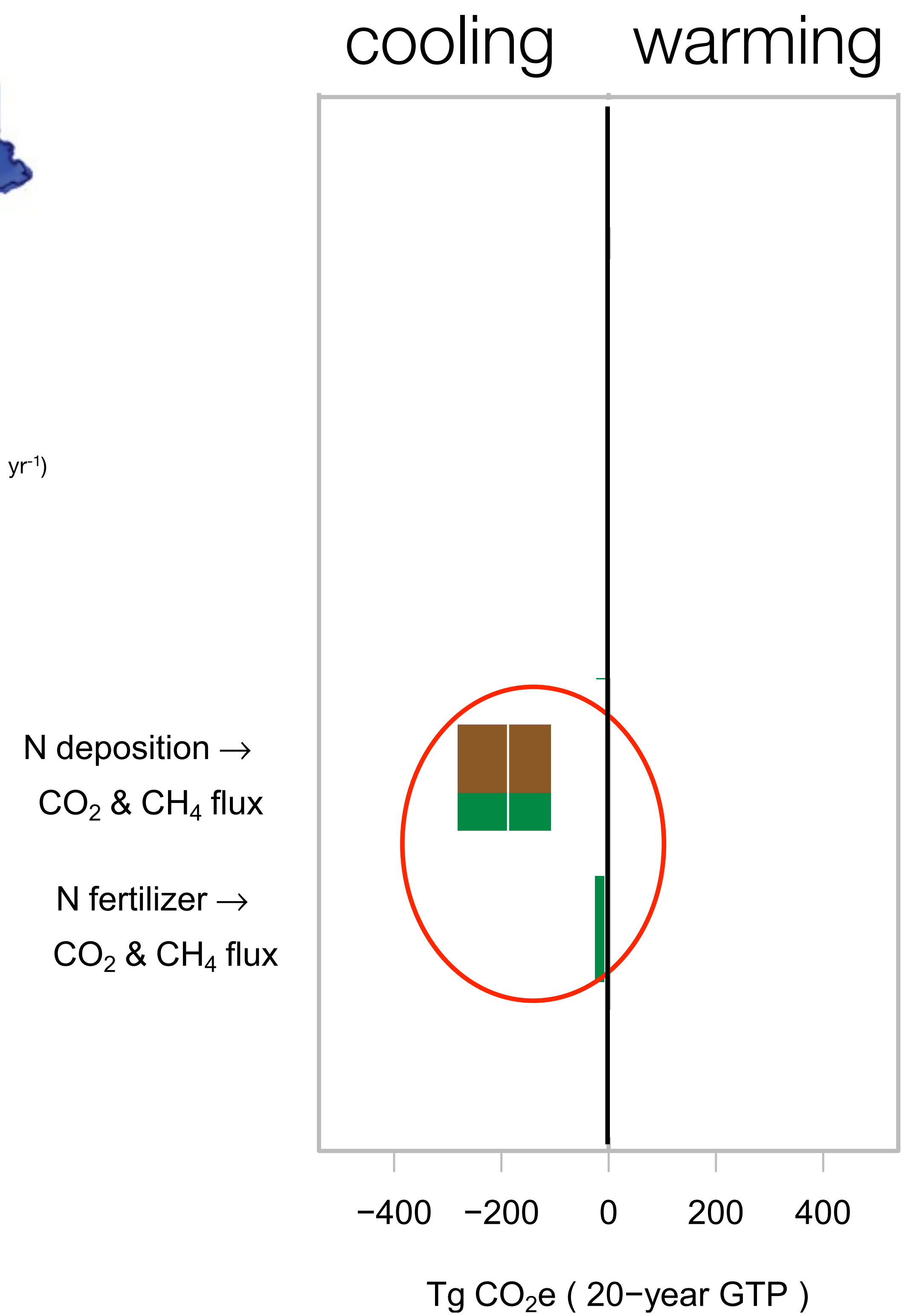
- Involves coarsely representing fine-scale non-linear processes.

Many other pathways that N influences climate: What happens when adding N?







Pinder et al. 2012 PNAS

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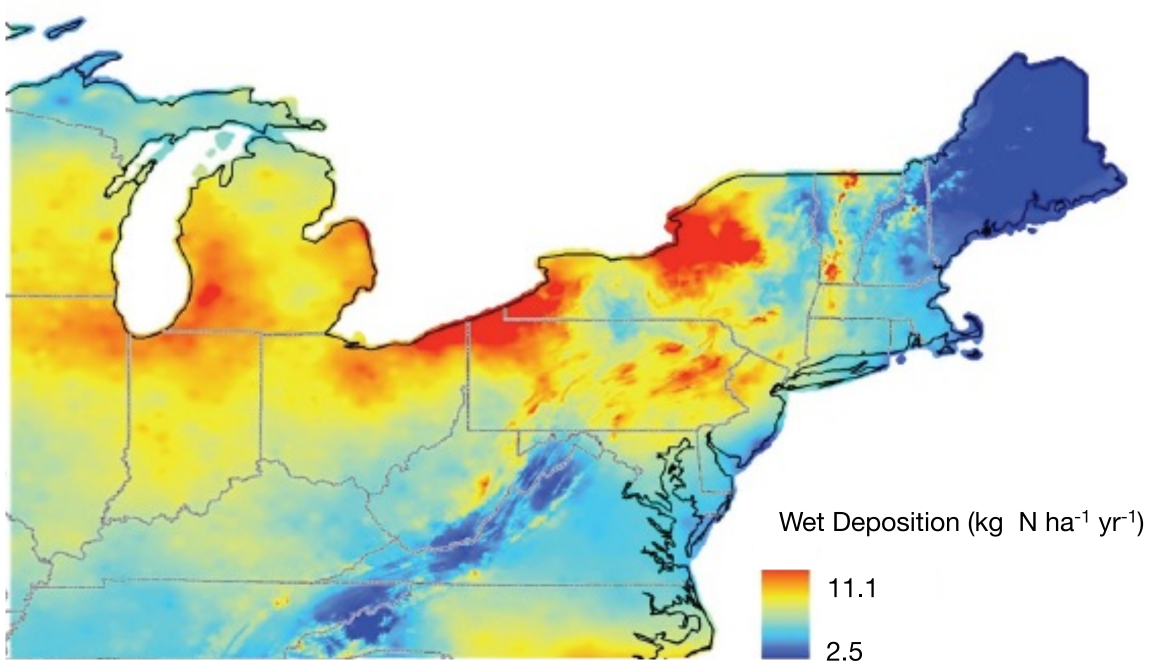

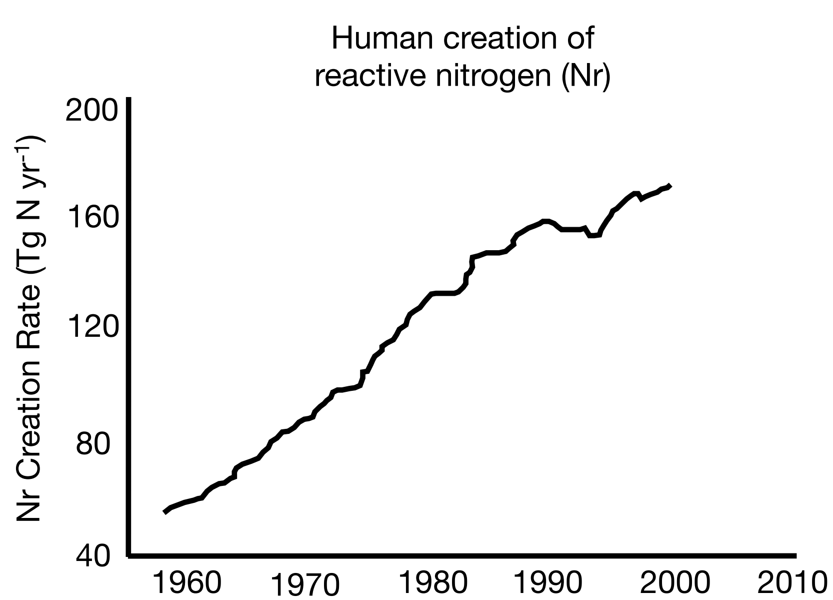

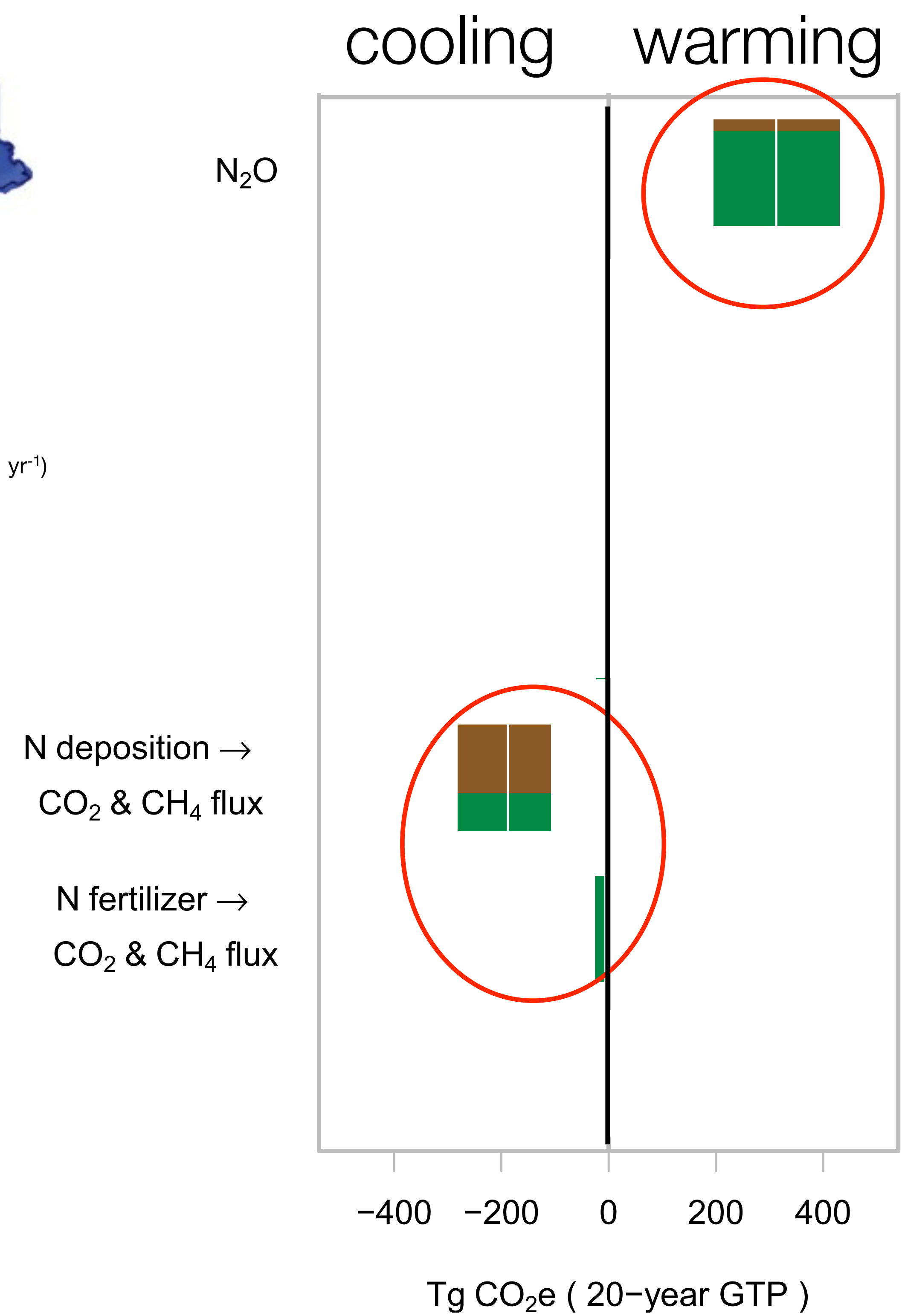

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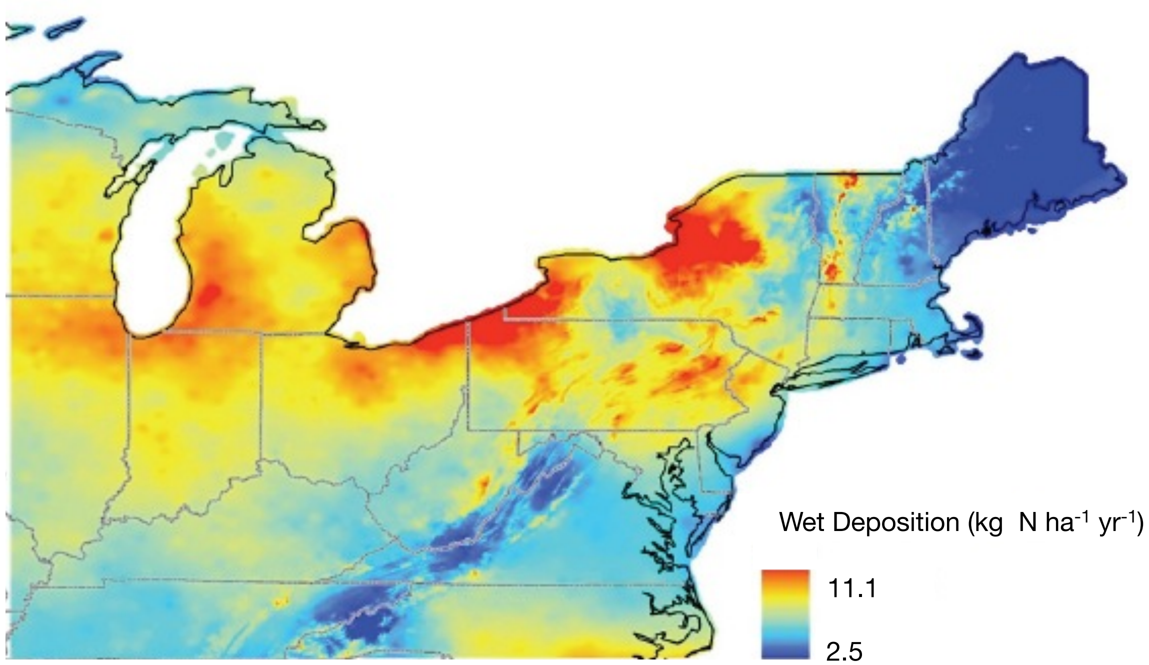

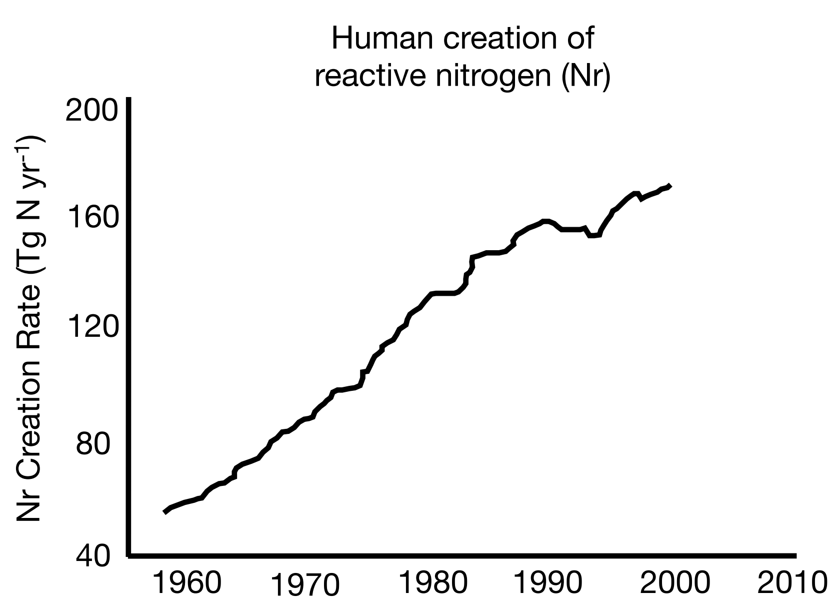

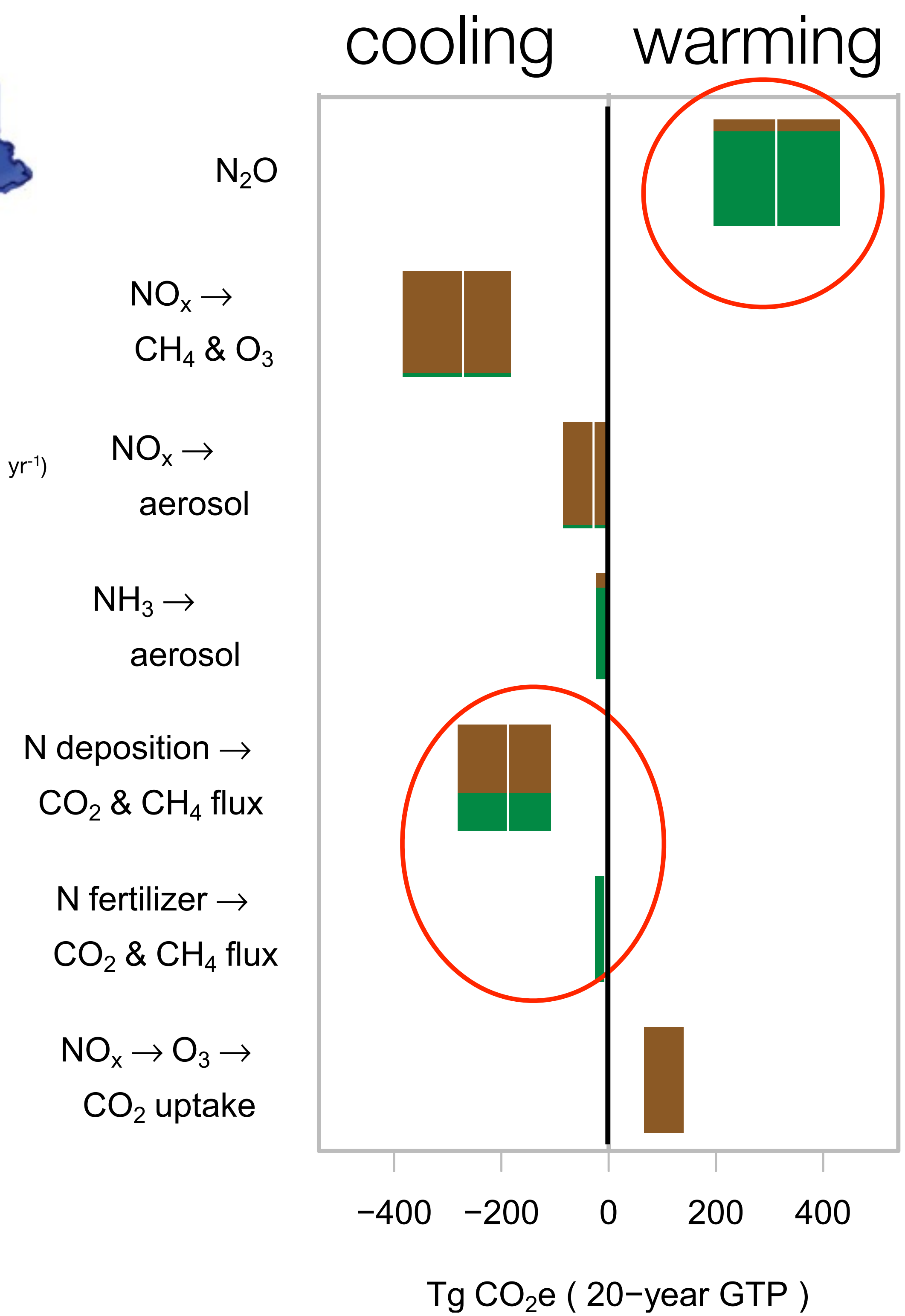

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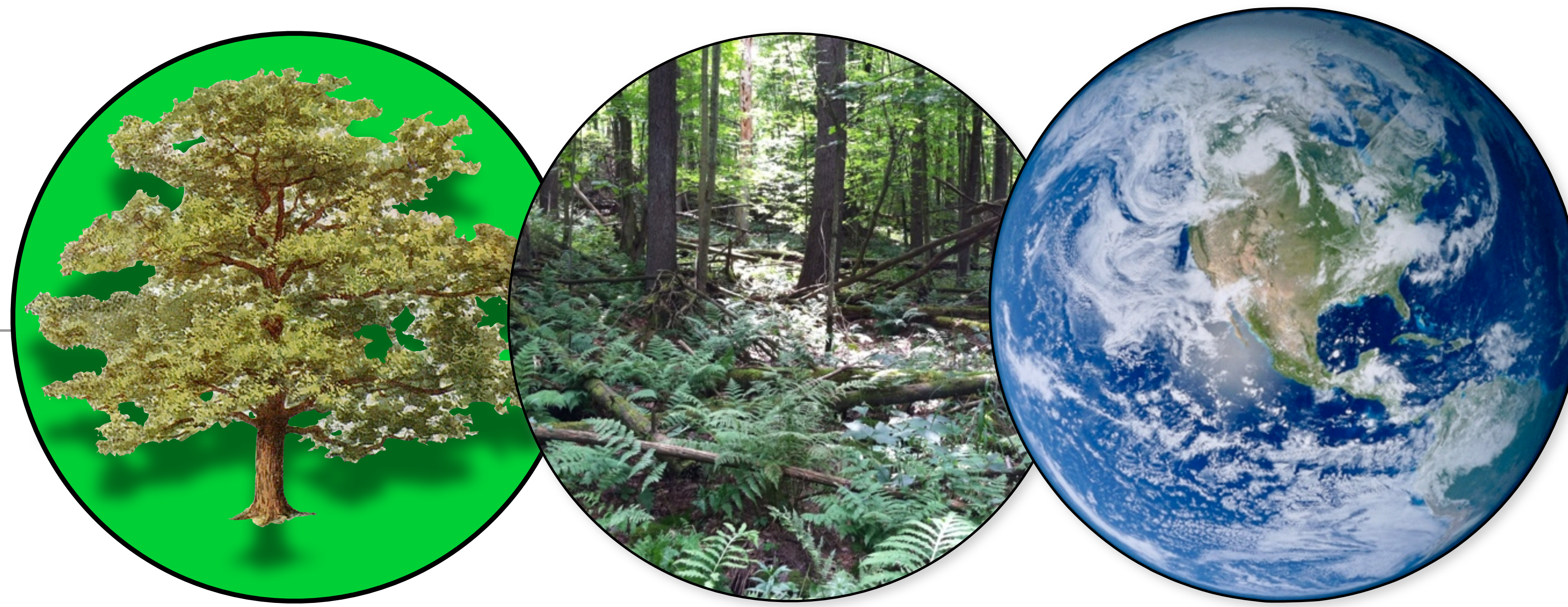
Questions?



R. Quinn Thomas
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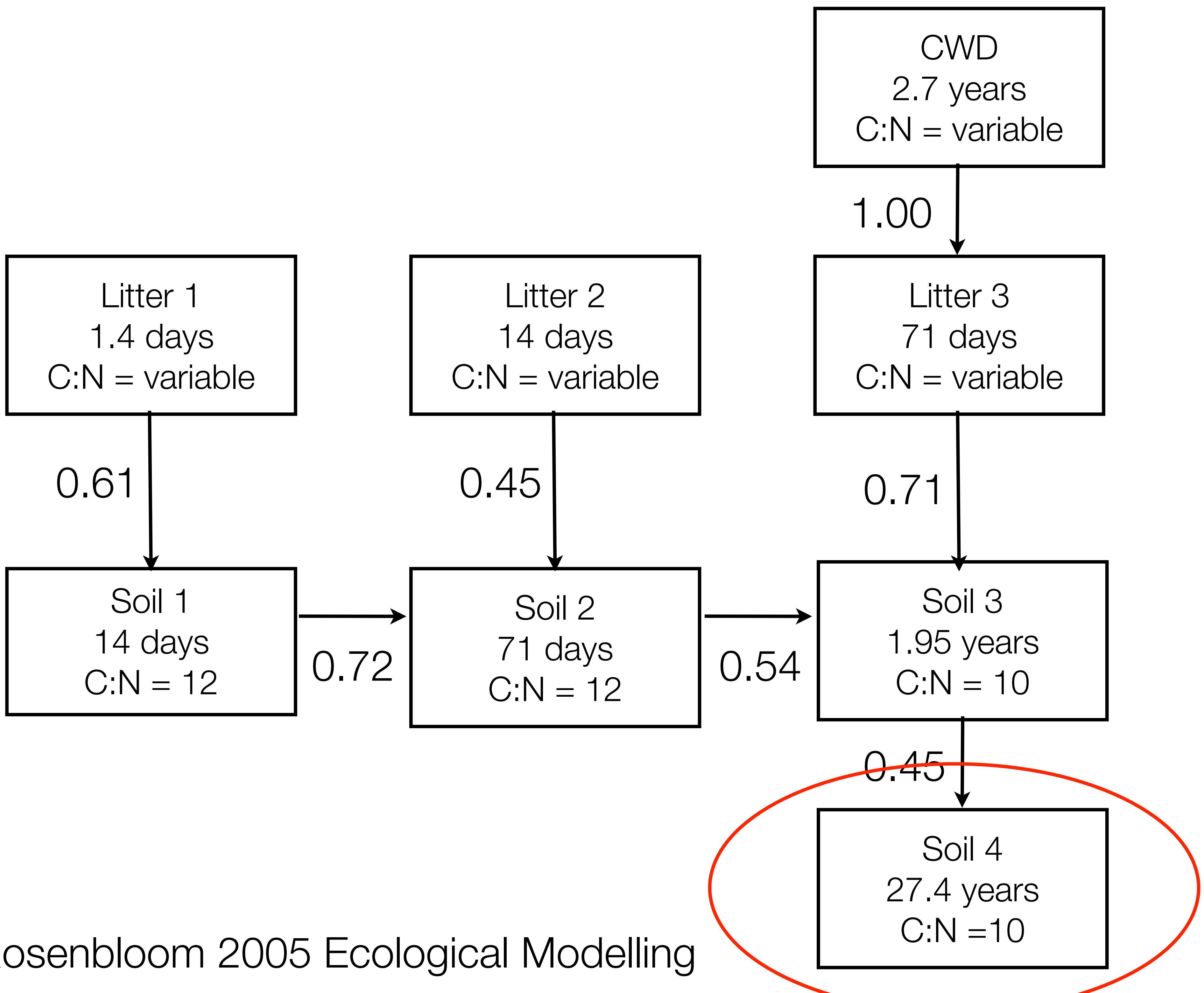
VirginiaTech
Invent the Future

Transactional N limitation



Thornton and Rosenbloom 2005 Ecological Modelling

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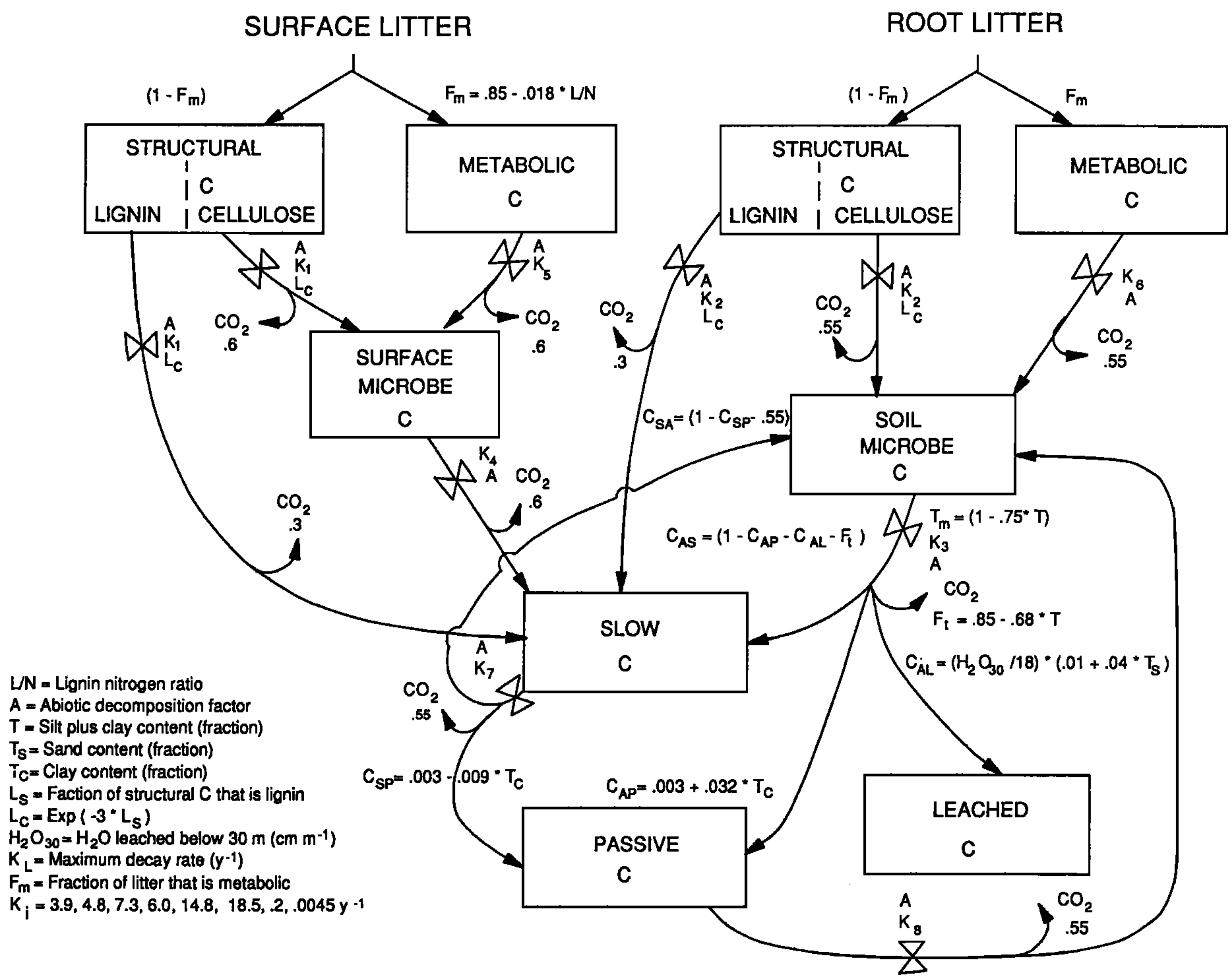

X

Parton et al. 1993 Glob. Biogeochemical Cycles

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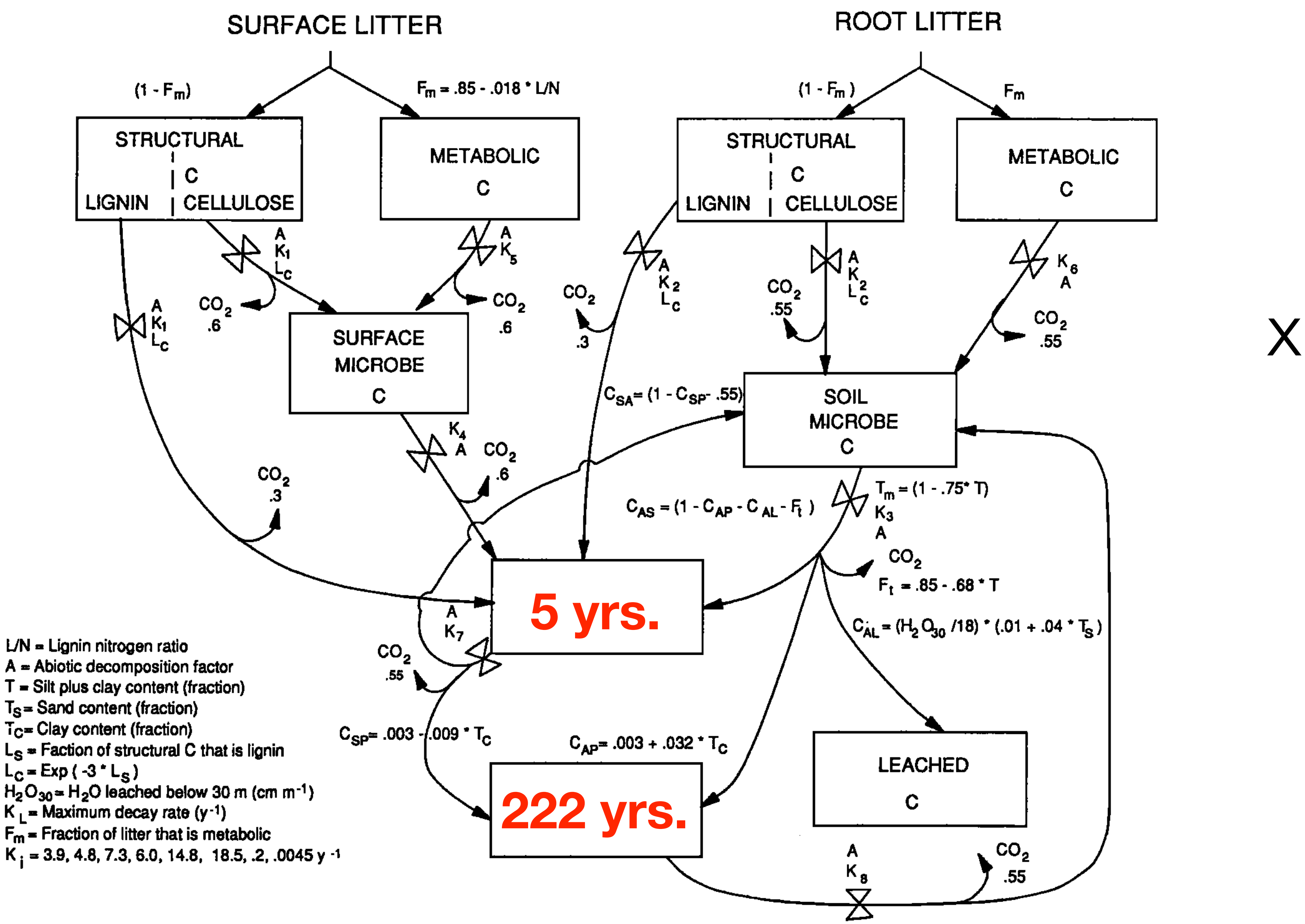

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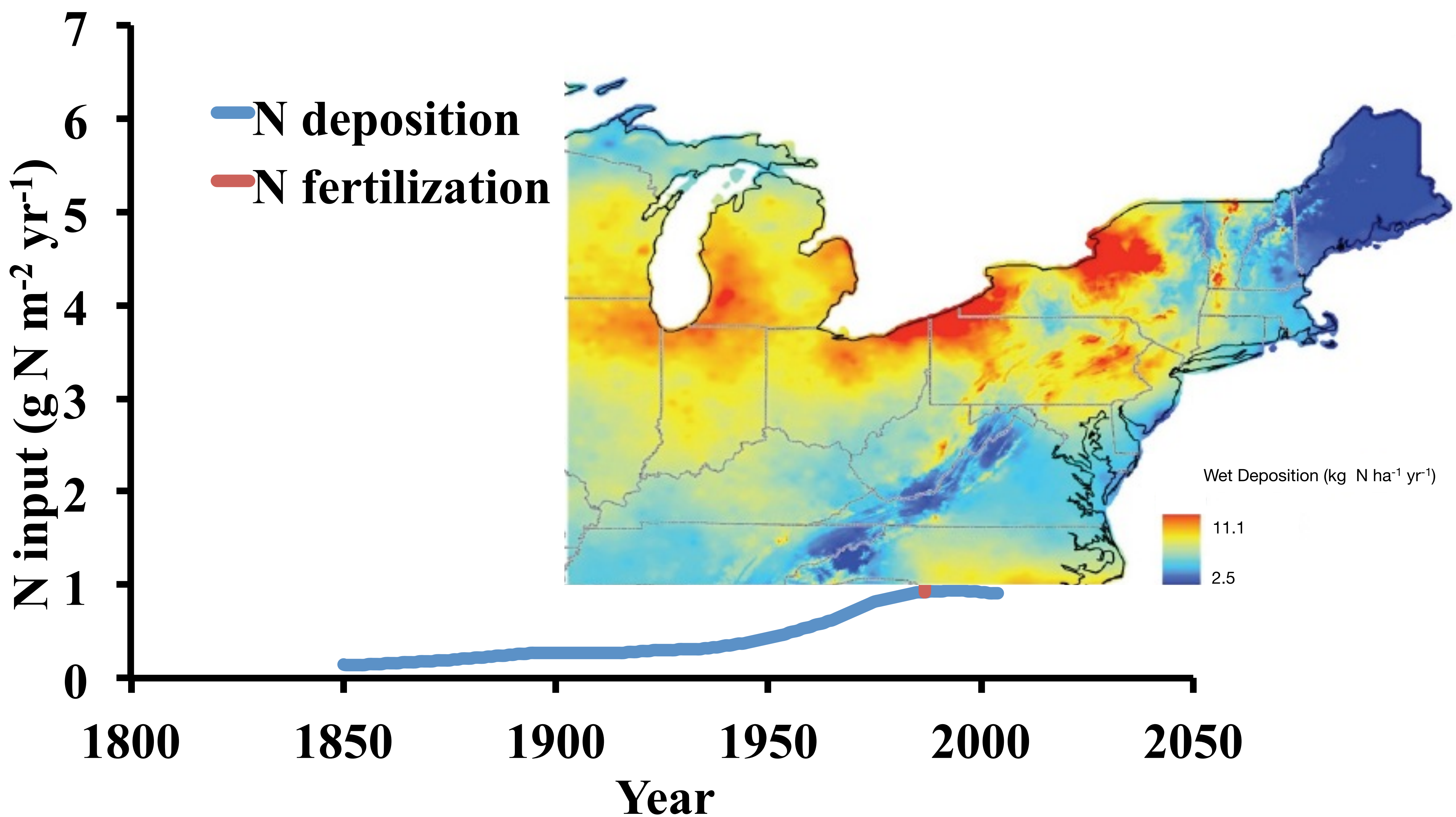
Carbon response to N addition:
Nitrogen deposition vs. nitrogen fertilization



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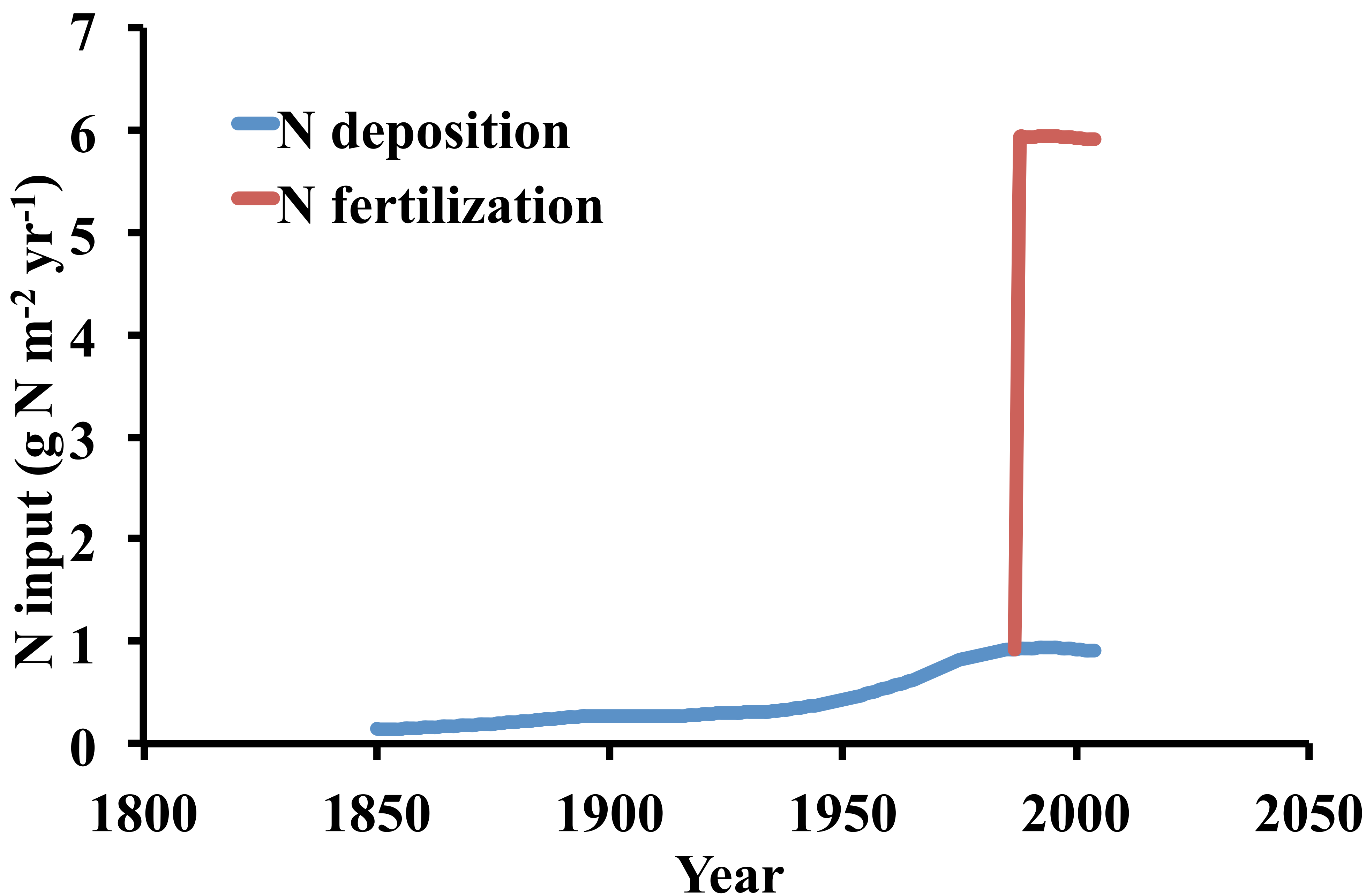

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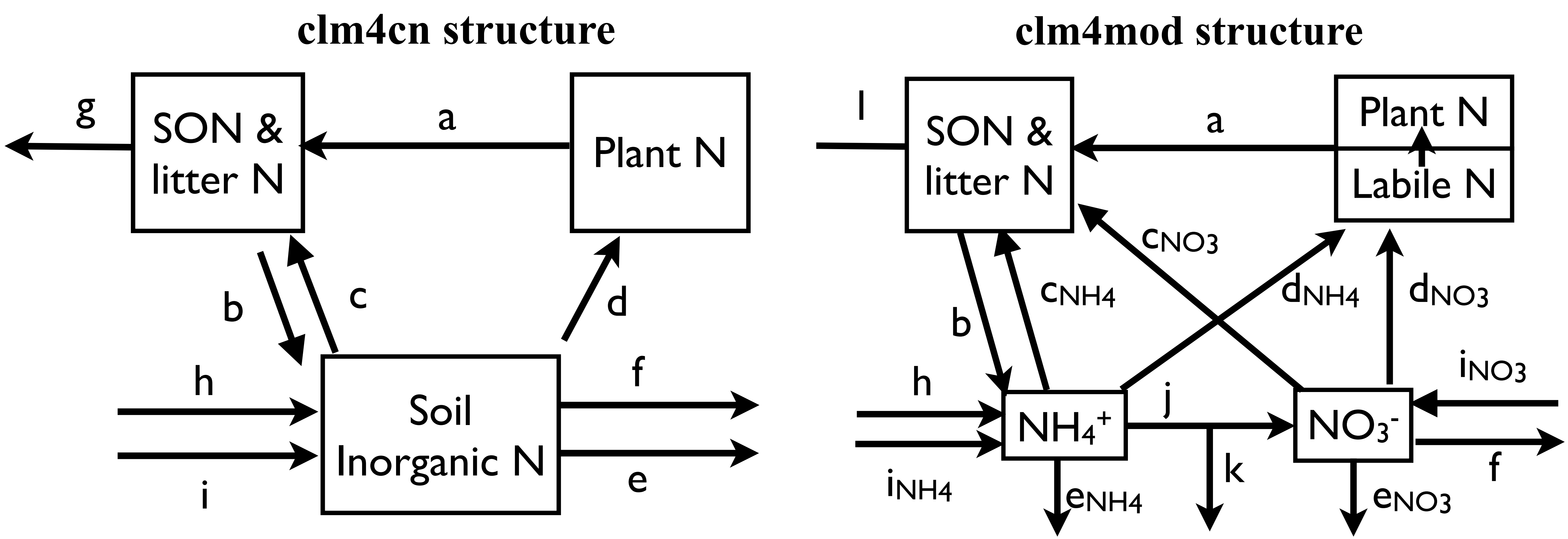

- Michaelis-Menten plant N uptake
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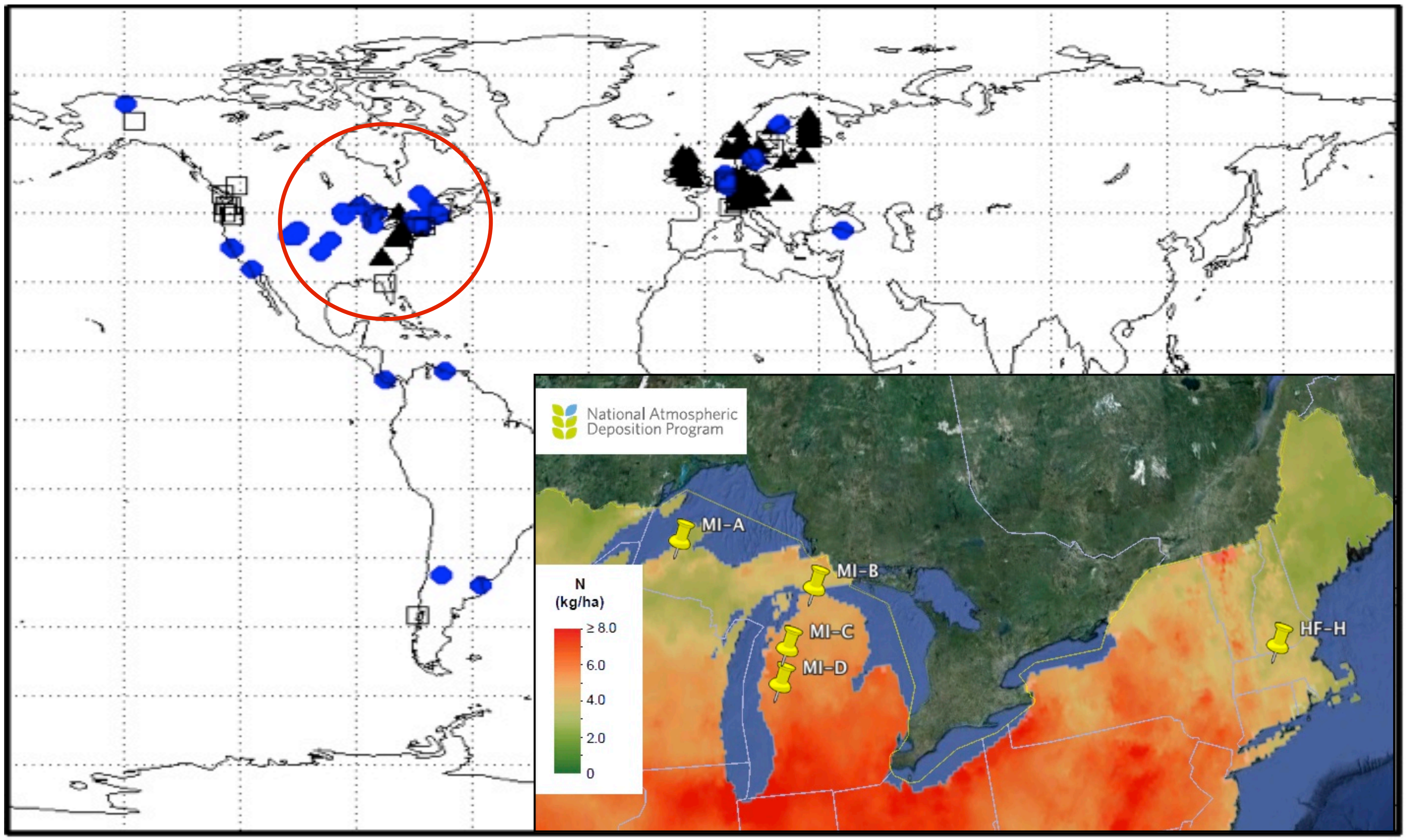
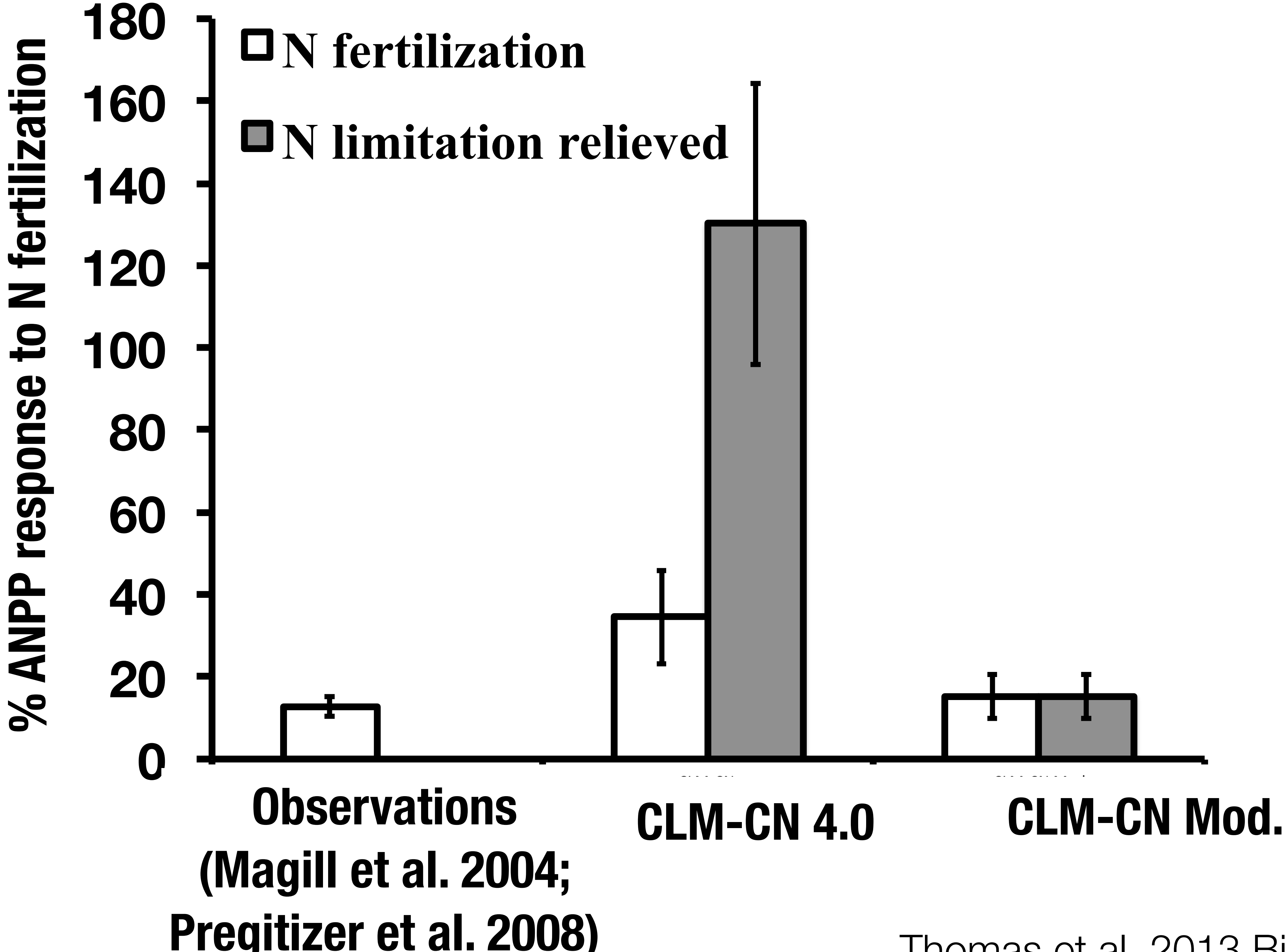


5 sites, 6 fertilization experiments
(4 in Michigan, 1 in Massachusetts)
10+ years of observations

Model comparison to data: NPP response to N fertilization



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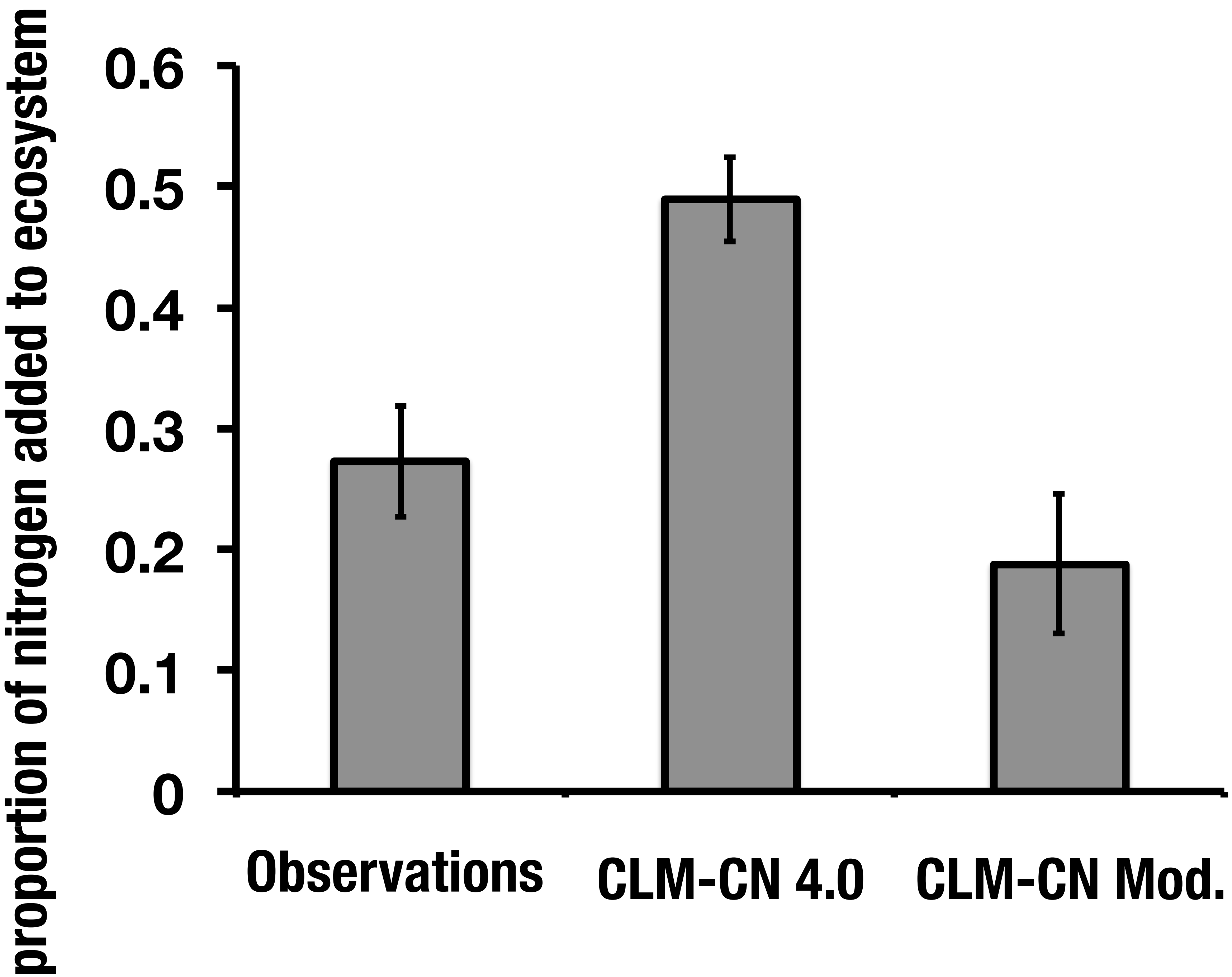
Model comparison to data: ^{15}N Tracer studies



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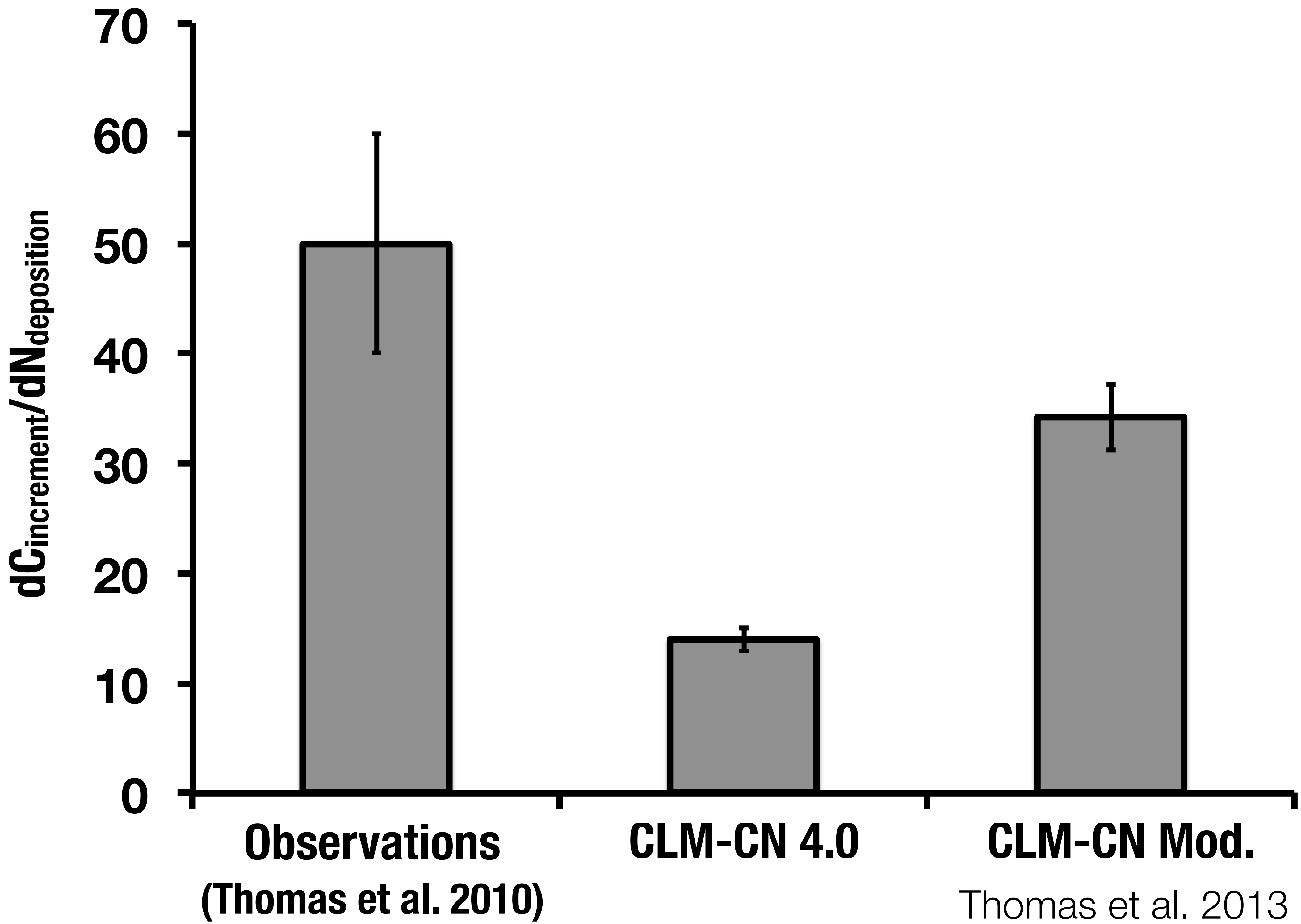
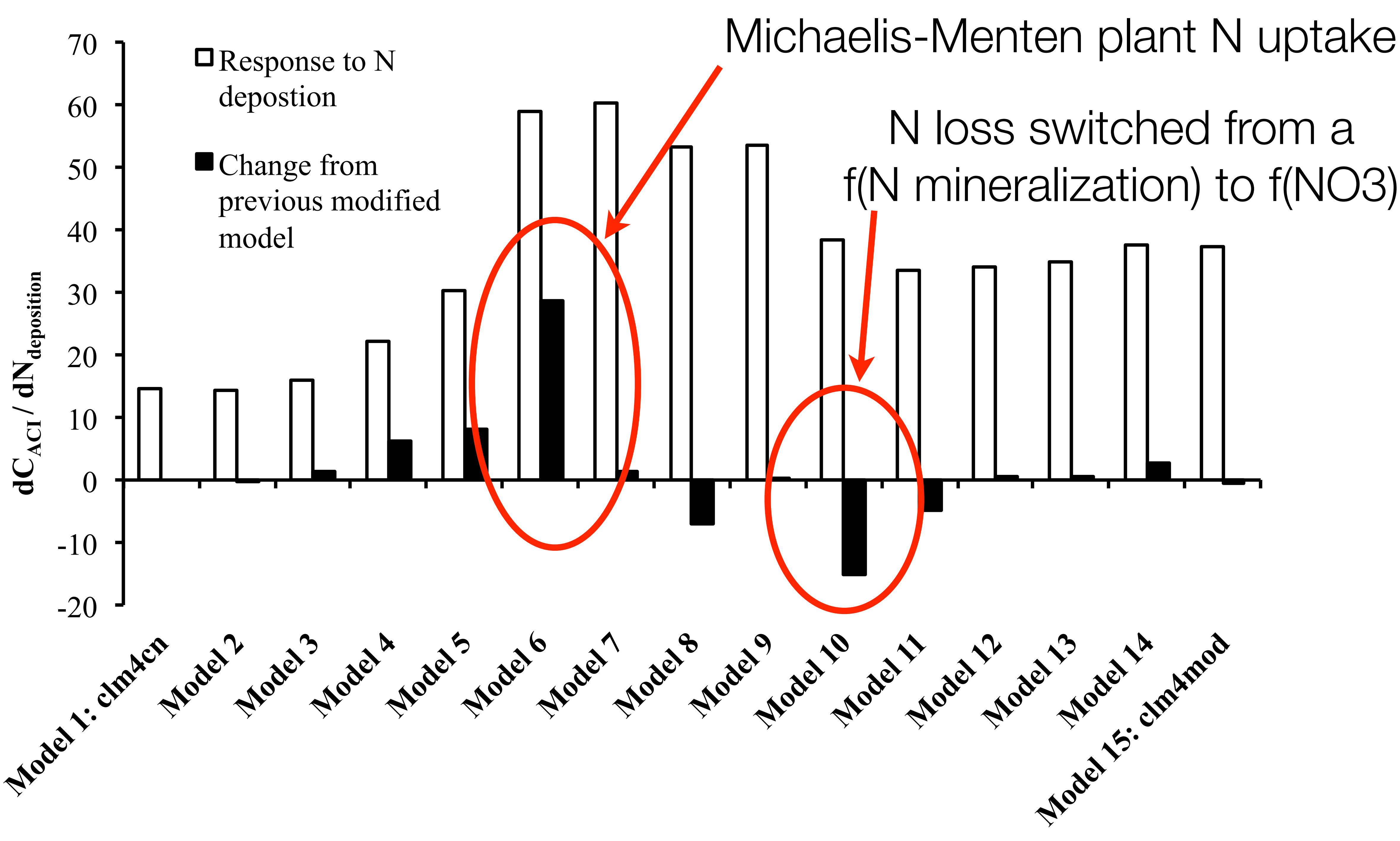
Model comparison to data:
C increment response to N deposition



Thomas et al. 2013 Biogeosciences
Thomas et al. 2010 Nature Geoscience

Implications of alternative approaches to modeling N cycling



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