Nitrogen and phosphorous cycles in terrestrial ecosystems

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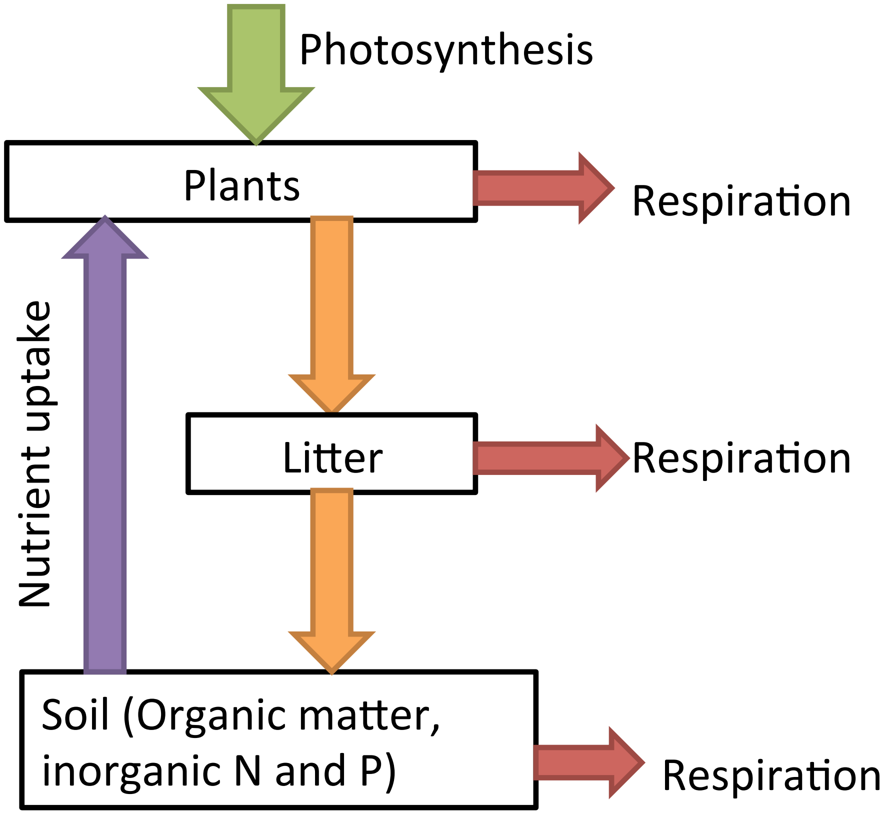
Outline

- Carbon-nutrient interaction and human influences on N and P cycles
- nitrogen cycle
- phosphorus cycles
- Effects of nutrient limitation of carbon production in land biosphere
- Global pattern of nutrient limitation
- Global models of terrestrial C, N and P cycles
- Summary

Interaction of carbon and nutrients



Photosynthesis

Plants

Respiration

Litter

Respiration

Nutrient uptake

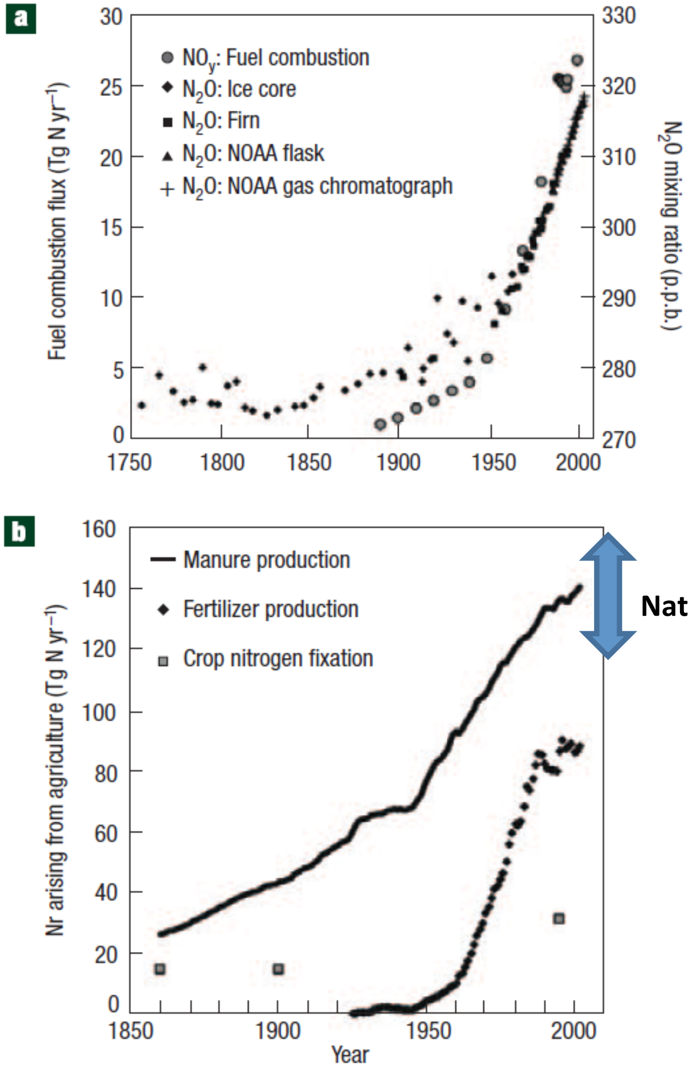
Soil (Organic matter, inorganic N and P)

Respiration

Nutrients (N and P) affects

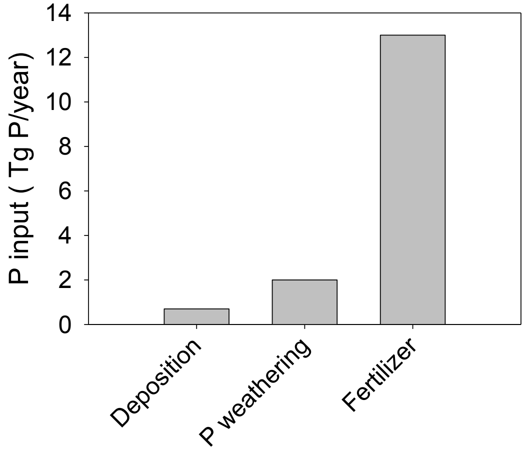
- photosynthesis, respiration
- litter and SOM decomposition, therefore soil nutrient availability, carbon allocation, plant growth

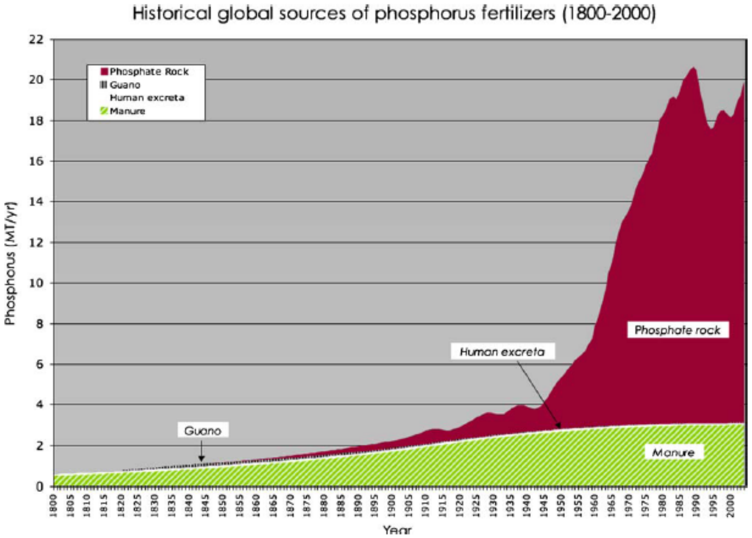
Human influences of N and P cycles



Natural N fixation

Source: Reay et al. 2009





Cordell 2010

Global simulations of NxC interactions

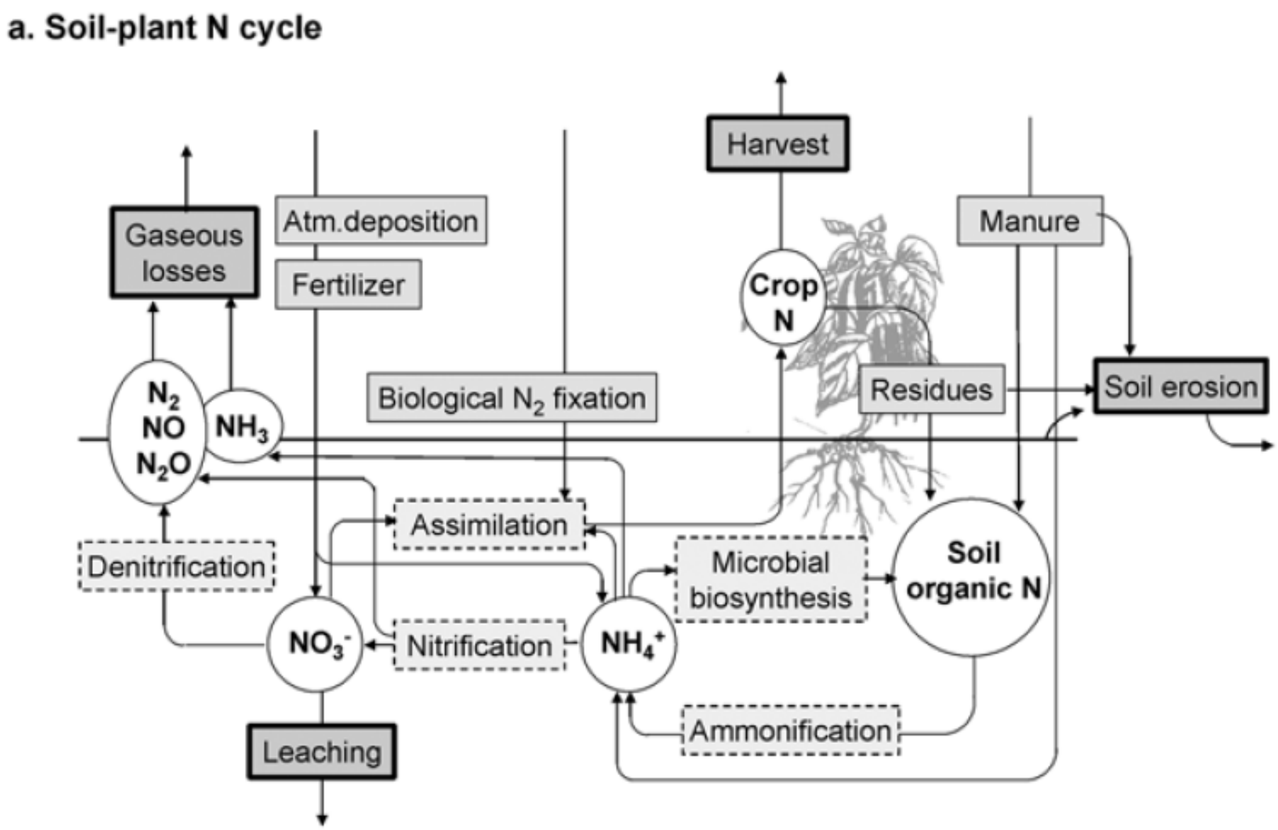
1993. Melillo et al. published their estimate of NPP response to climate change and CO2;

1993. Schindler et al. showed N deposition could contribute to a carbon of 0.6 to 2 Gt C/yr; and that estimate was refined by Townsend et al. (**1996**) to 0.4 to 0.8 Gt C/yr in 1990's.

Hungate et al. (**2003**), Wang & Houlton (**2009**) showed global models without N overestimated land C uptake and underestimated global warming

2008, Sokolov et al. conducted the first fully coupled CN simulation using a simple earth system model;

2013. AR5, only an ESM with N cycle, and its land C uptake sensitivity to CO_2 was about 25% of the mean of other models without N

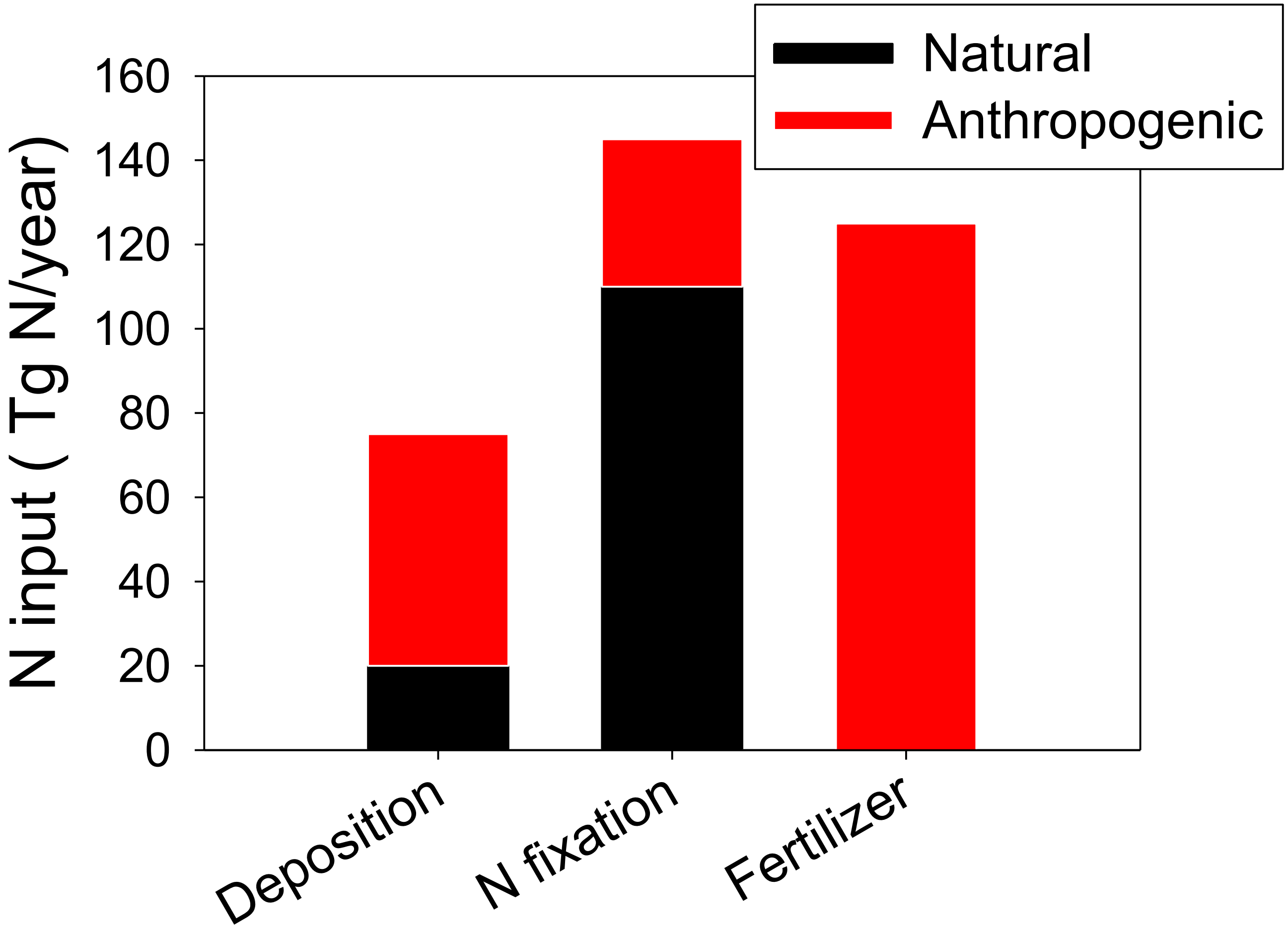


Forms: Organic, *inorganic*(*NH_4, NH_3, NO_3, NO_2, NO, N_2O, N_2*)
Inputs: *Lightning*
Biological N fixation
Anthropogenic N input
Outputs: *Leaching, Gaseous loss*

Source: Bouwman et al. 2009

Internal cycling:
assimilation (soil to plant)
resorption (plant)
litter fall (plant to litter)
ammonification: organic N to NH_4
nitrification: NH_4-> NO_3
denitrification: NO_3->N_2O-N_2

Nitrogen input



Data source: Gruber and Galloway 2008

Natural N fixation

Cleveland et al. 1999

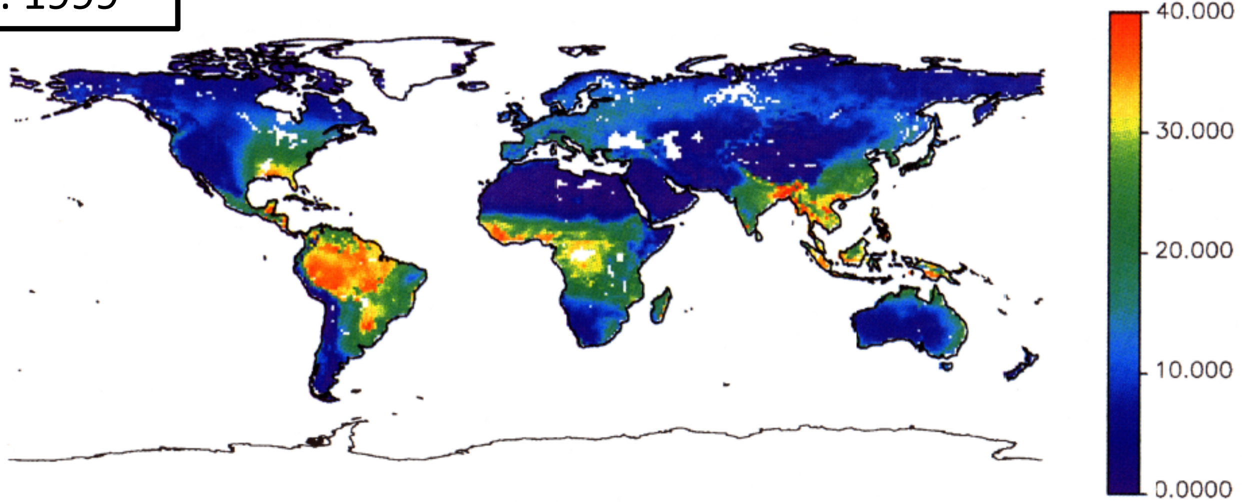
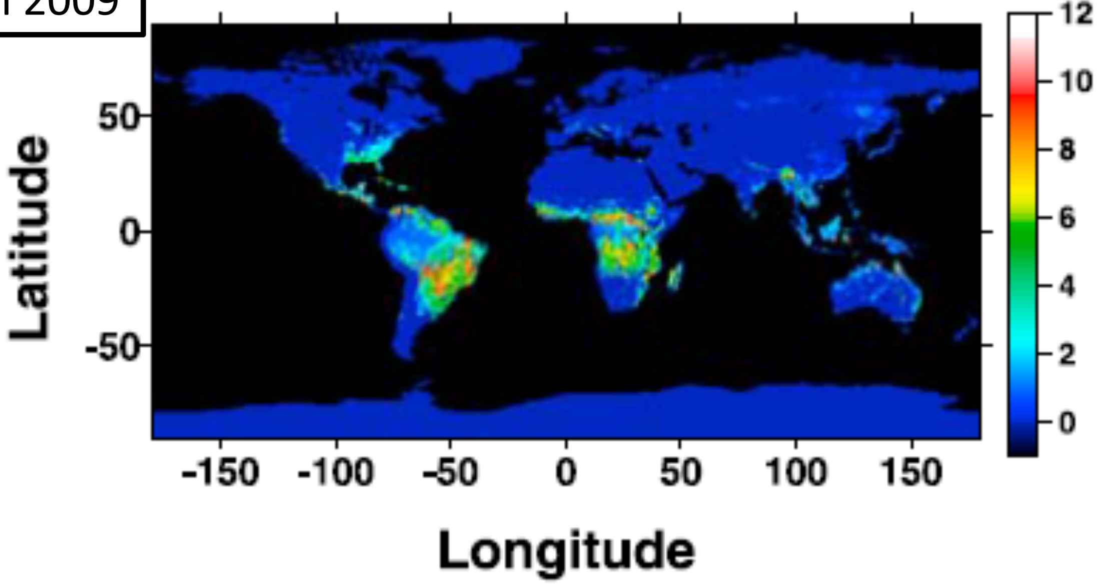


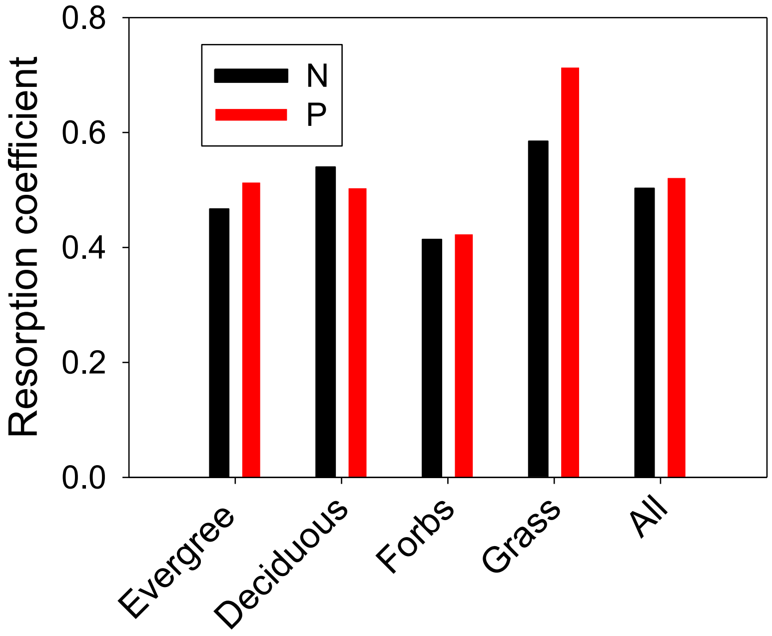
Plate 2. Mapped potential annual BNF by natural ecosystems based on the relationship between the central estimates of BNF (N fixation = 0.234(ET) - 0.172) and ecosystem ET. Values are kg N ha^{-1} yr^{-1}. White areas represent regions where modeled ET values are unavailable.

Wang and Houlton 2009



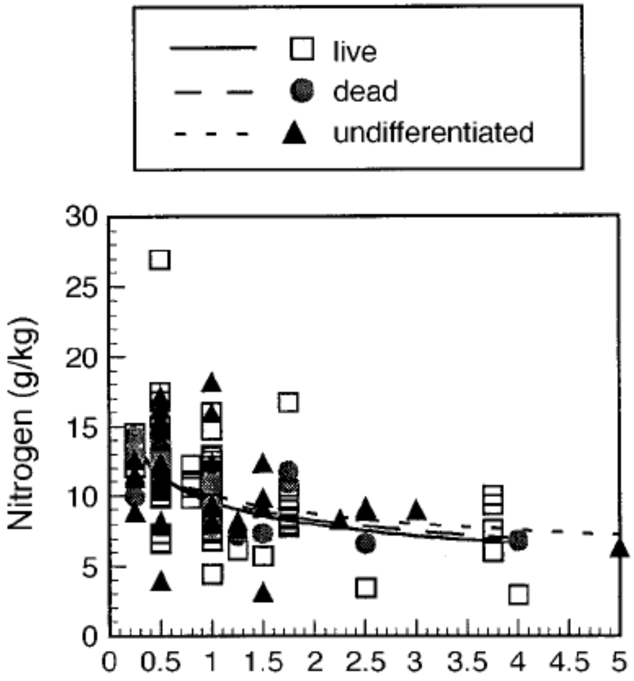
Internal N process: Resorption

Leaf litter



Source: Aerts 1995

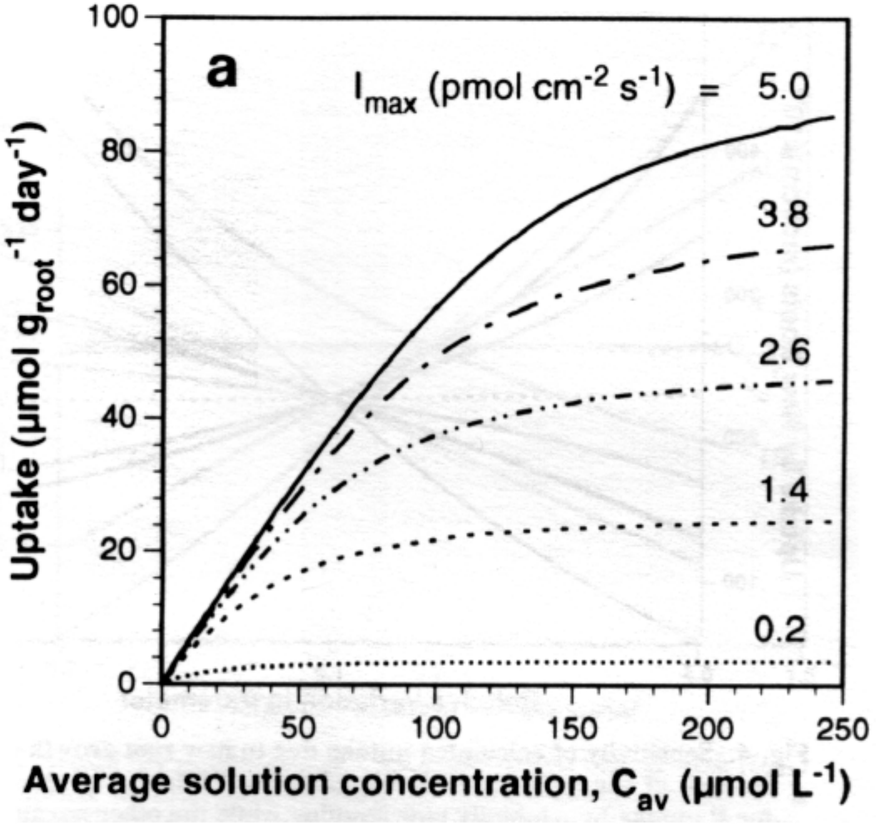
Fine roots



Source: Gordon and Jackson 2000

Internal processes: plant uptake

Plant N uptake: Plant can take up both NH4 and NO3 and dissolved organic N. Plant N uptake rate depends on the rate of soil supply, root length and root activities.



However, nutrient diffusion is not explicitly represented in global models. Nutrient uptake is usually modeled as the smaller value of available nutrient and plant demand.

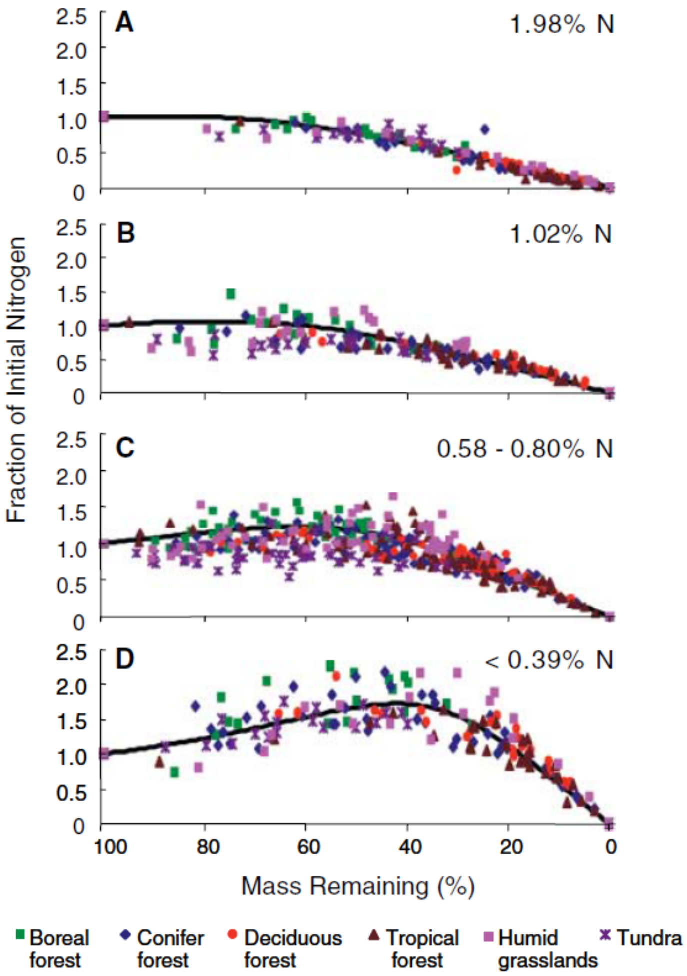
Source: Yanai 1994

Internal N process: Mineralization/ immobilization

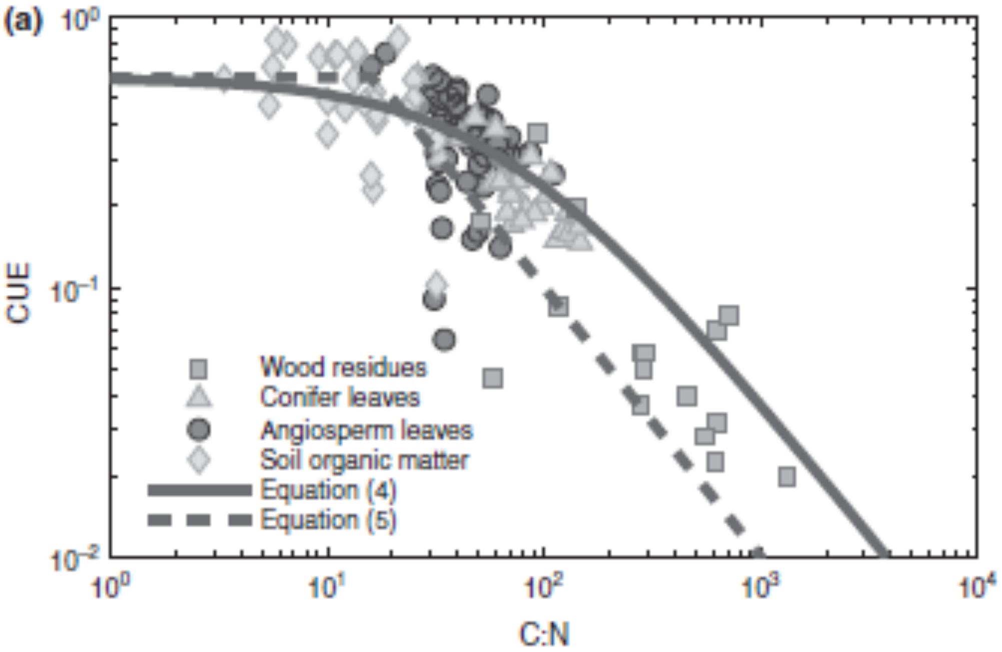
Gross mineralization (G): the rate of total amount of N released via mineralization
Immobilization (I): uptake of N by soil microbes and used for their growth
Net mineralization (N) = gross mineralization- immobilization
Microbial carbon use efficiency (e): the fraction of carbon uptake that is used for growth. Theoretical max: 0.6 for soil microbes (see Sinsbaugh et al. 2013).

The critical C:N ratio of substrate
Assuming C:N of soil microbes of 10:1 with e= 0.4;
BY decomposing 100 g litter C, soil microbes increase their body mass by 40 g C and requires 4 g N (immobilization).
Gross mineralization rate =100/(C:N ratio of litter)
If litter C:N ratio is higher than 25:1, N <0
If litter C:N ratio lower than 25:1, N>0,
25:1 is the critical C:N ratio of decomposing substrate.

N mineralization and carbon use efficiency



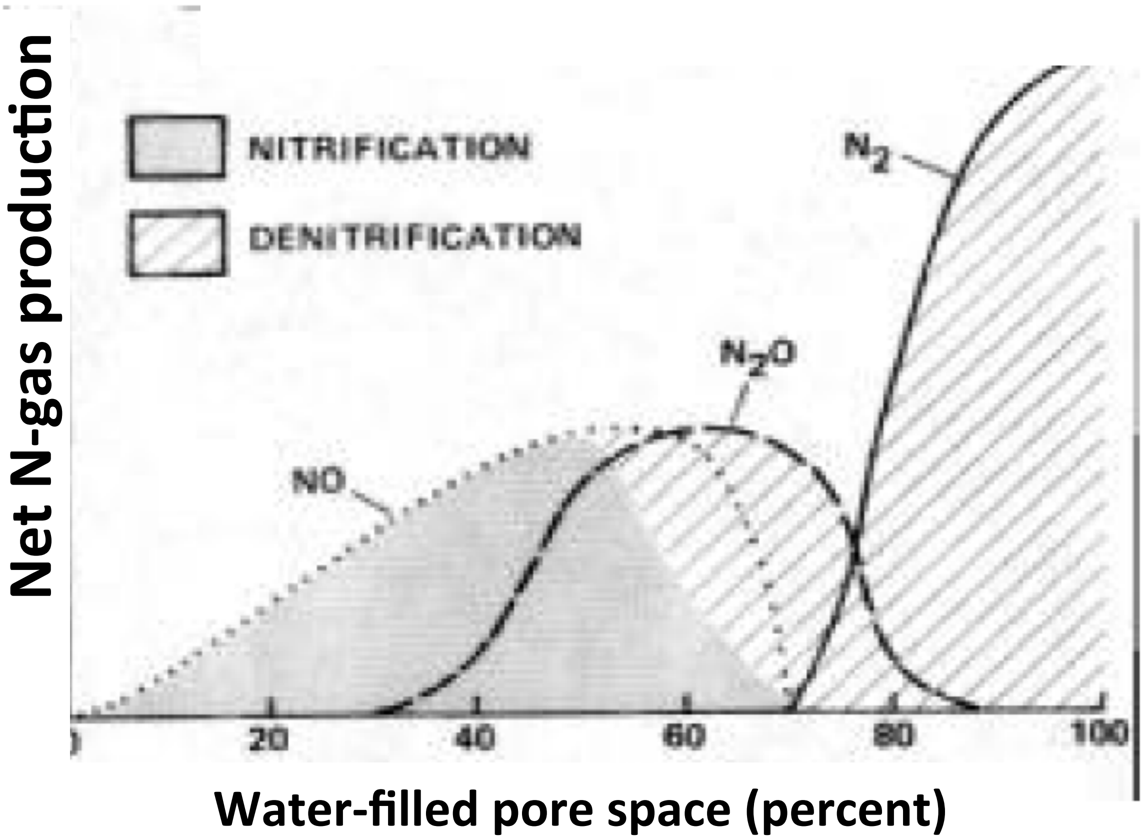
Parton et al. 2008



Sinsbaugh et al. 2013

Internal processes: nitrification and denitrifcation

Nitrification (aeorbic): conversion of NH_4^+ to NO_3^-.
Denitrification(anaerobic, or low oxygen): NO_3->NO_2->NO->N_2O->N_2



Source: Davidson et al. 2000

Denitrifcation: interactive effects of temperature and moisture

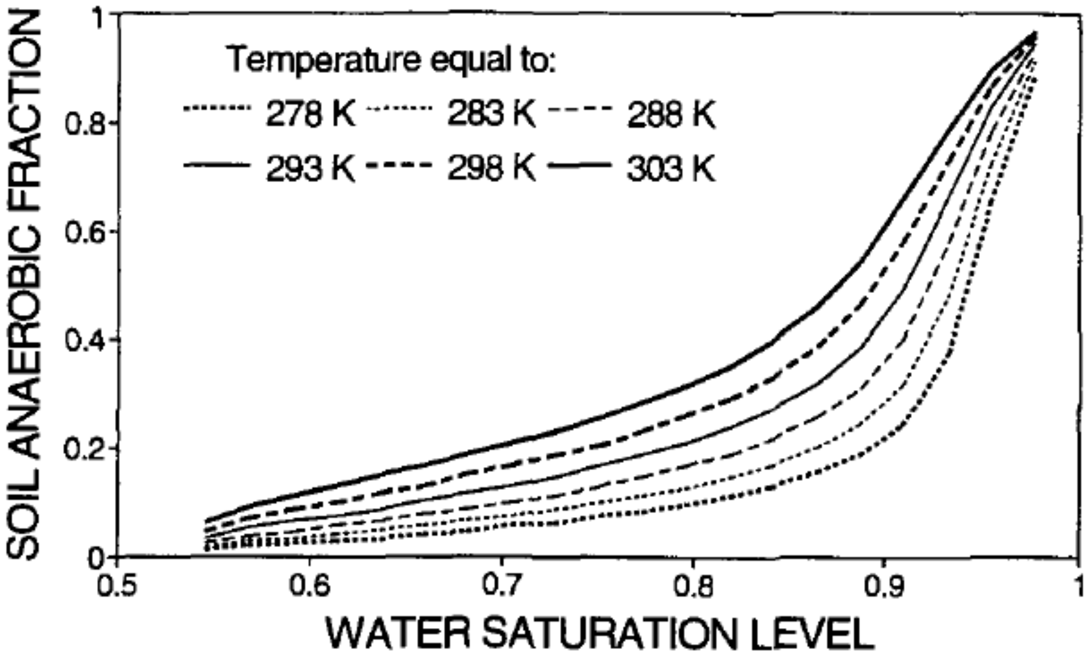


Fig. 8. Influence of the temperature on the anaerobic fraction of the aggregates for a soil having a bulk density of 1.1 and a mean aggregate radius of 0.0025 m and for a real Q_{10} of O_2 consumption of 2.

Source: Renault and Sierra 1994

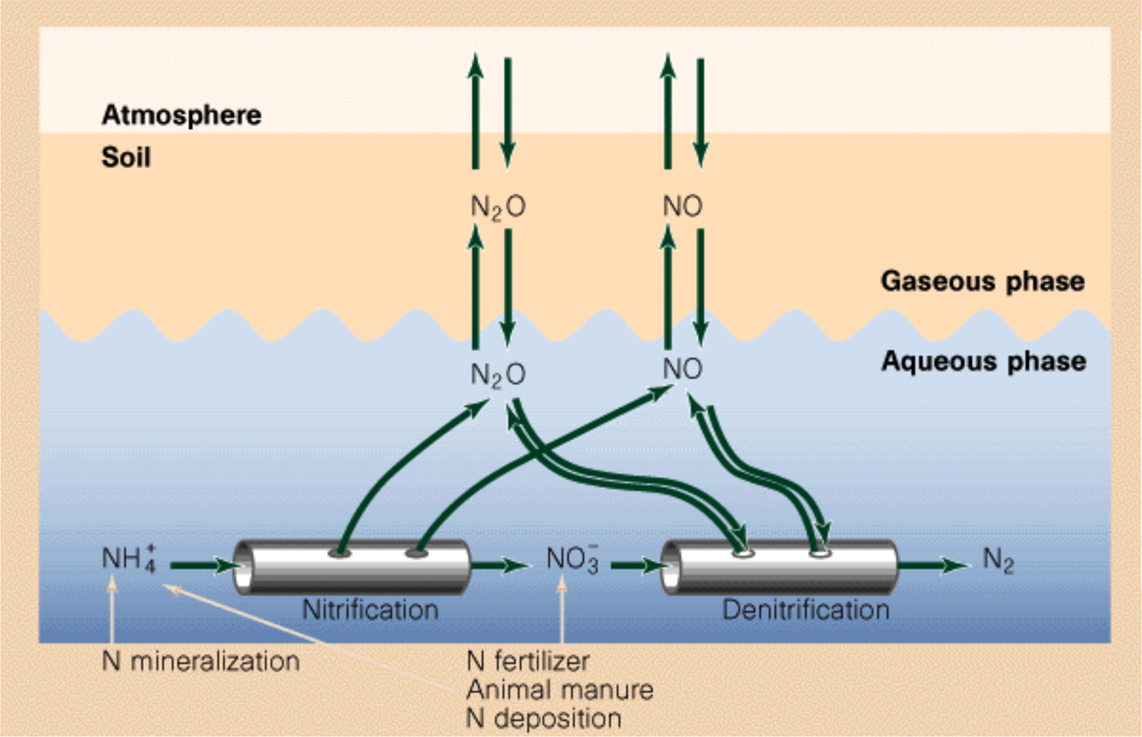
Nitrogen loss

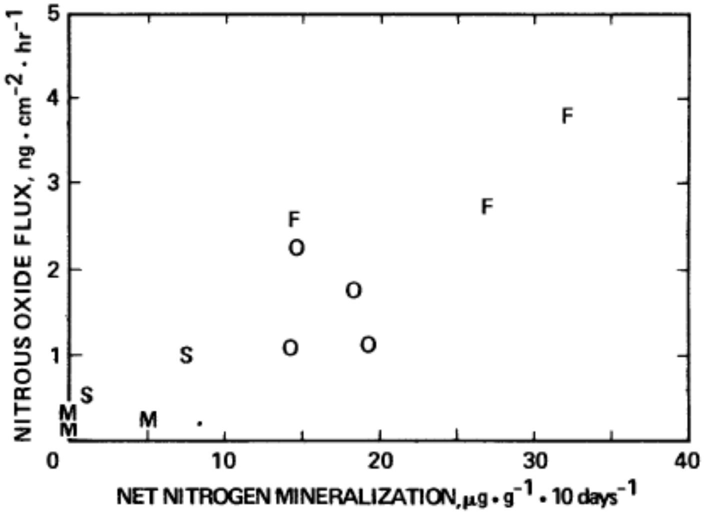
Nitrogen leaching represent a loss of inorganic N (nitrate) and organic N from terrestrial ecosystems.

Globally it can be larger than gaseous loss (Bai et al. 2012), accounting for about 65% of N loss from natural ecosystems.

For managed the systems, fraction of gaseous loss can be significantly larger than leaching, but loss of N_2 is difficult to measure, therefore closing a N budget is difficult for many ecosystems .

Nitrogen gaseous loss (hole in the pipe)





Matson and Vitousek 1990

Source: Bouwman 1998

Two approaches for N loss

1: A hole in the pipe approach

Total N loss ∝ gross N min.

NO:N2O:N2 = function (WFPS)

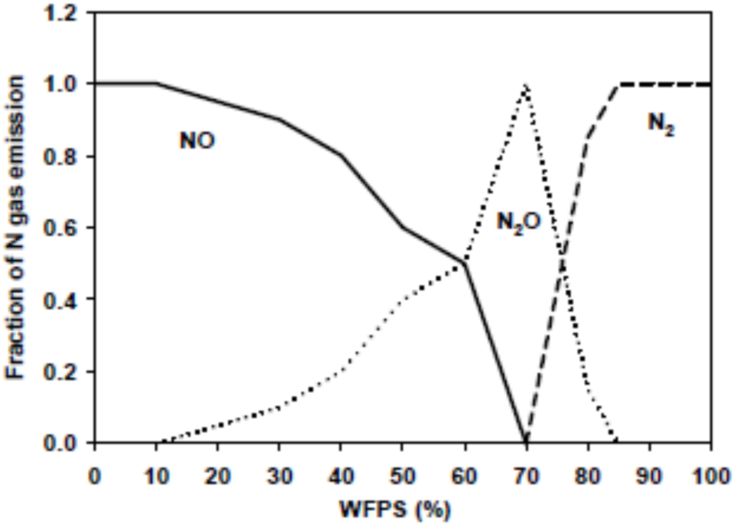
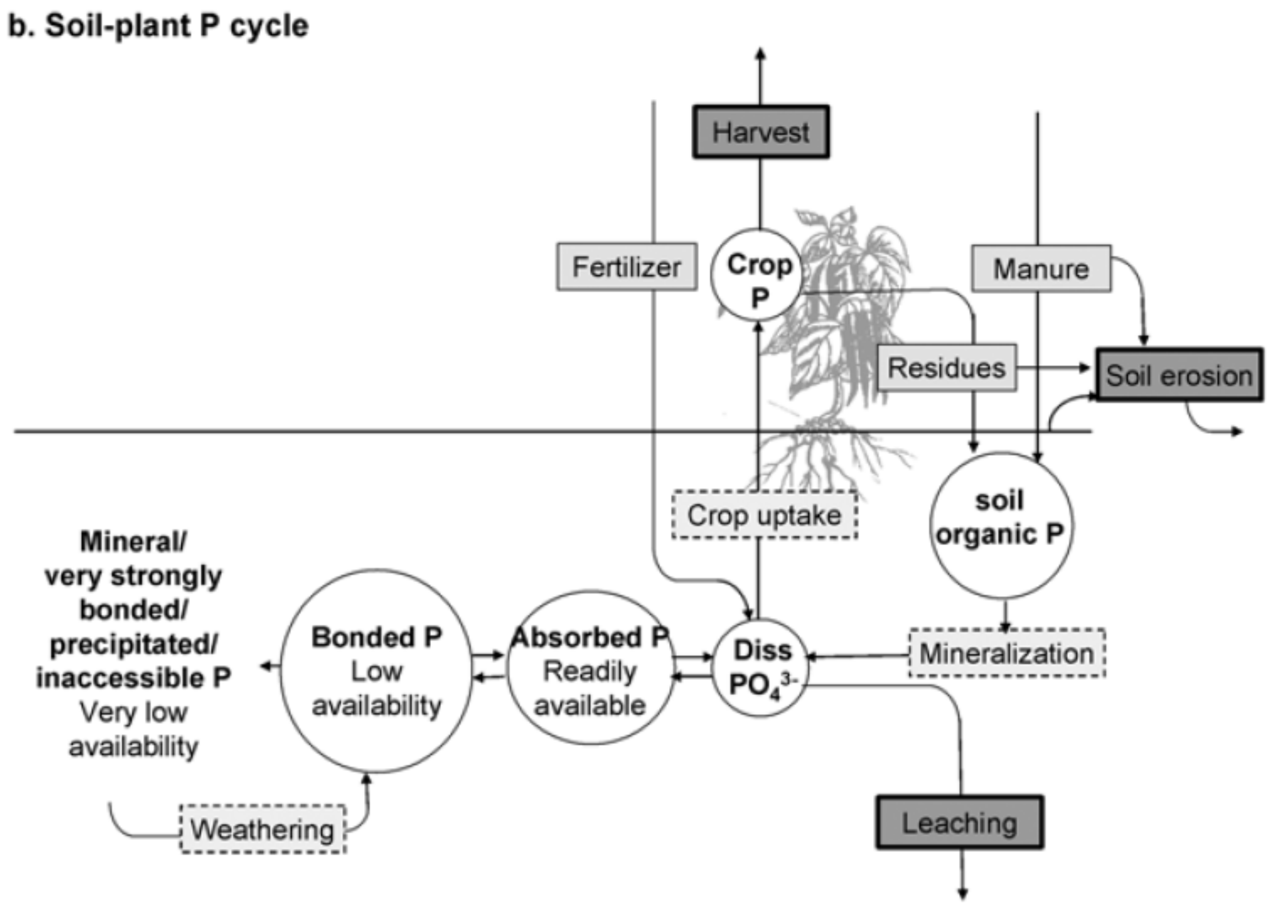


Fig. 3. Model of N gas production as a function of WFPS (water-filled pore space, %). The solid line represents NO; short dashed line represents N_2O fraction; and long dashed line represents N_2.

Davidson 1991, Potter et al. 1996

2: explicit representation of

- Anaerobic fraction
- nitrification
- denitrification
- diffusion of O_2, N_2O



Forms: organic, inorganic (H_2PO_4, HPO_4, PO_4)
Inputs: weathering
dust deposition
Anthropogenic P input
Outputs: Leaching, runoff, erosion, adsorption

Internal cycling:
assimilation (soil to plant)
resorption (plant)
litter fall (plant to litter)
Biological mineralization
Biochemical mineralization

Sources: Bouwman et al. 2009

Soil P availability

- Soil pH determines the most abundant form of inorganic P in soil

$$H_2PO_4^- \leftrightarrow H^+ + H_2PO_4^{2-} \leftrightarrow 2H^+ + PO_4^{3-}$$

4 10 14 [pH range]

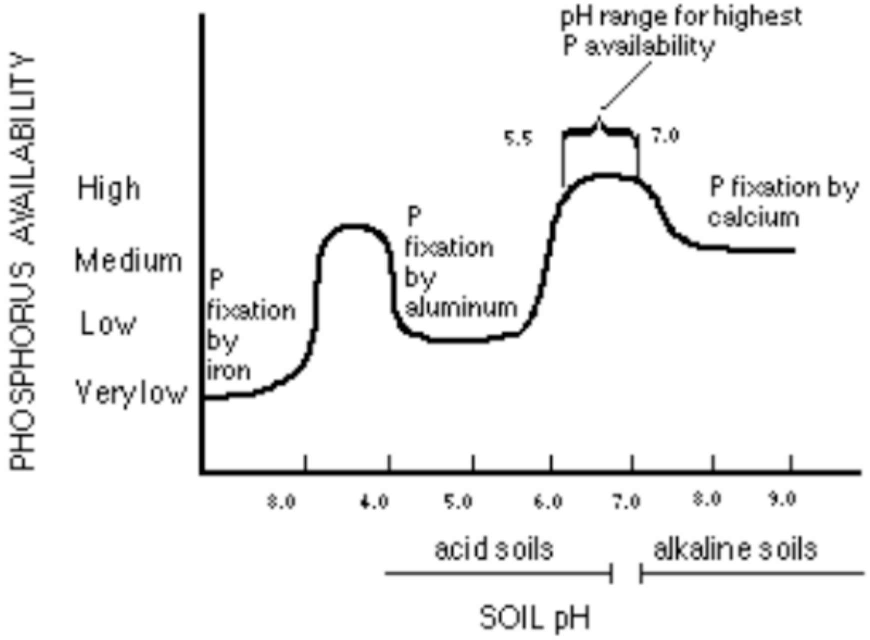
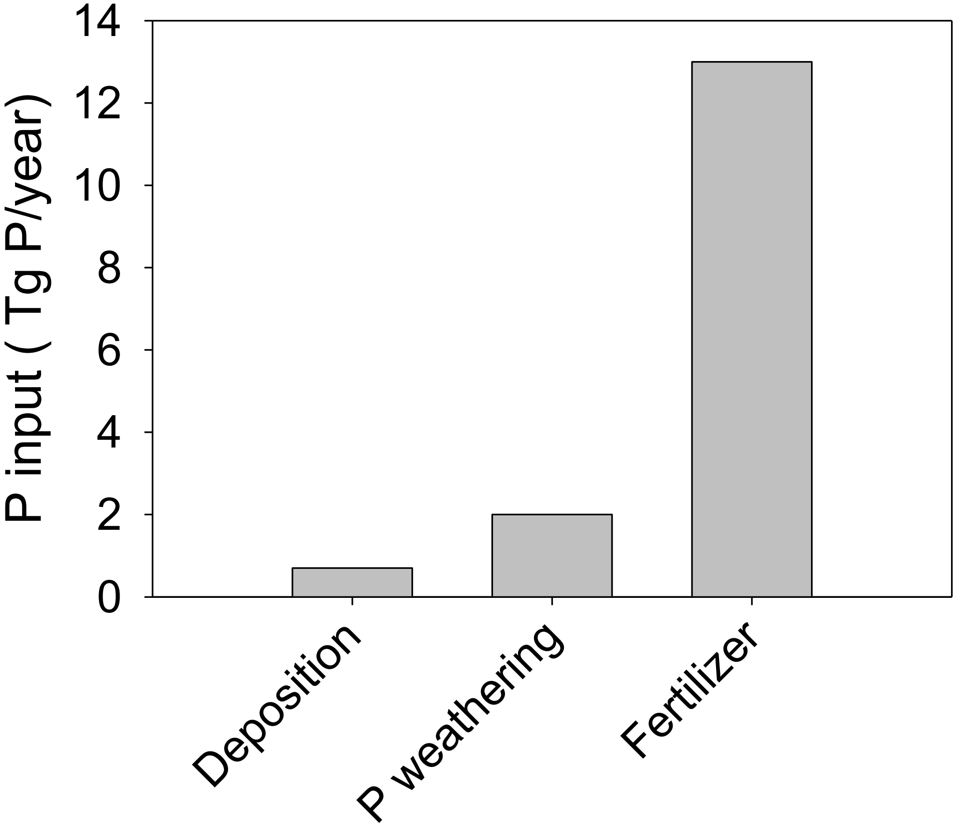


Figure 3. The availability of phosphorus is affected by soil pH.

Input

P weathering rate of different soils

	(g P m^{-2} $year^{-1}$)
Entisol	0.05
Aridisol	0.01
Ultisol	0.005
Oxisol	0.003



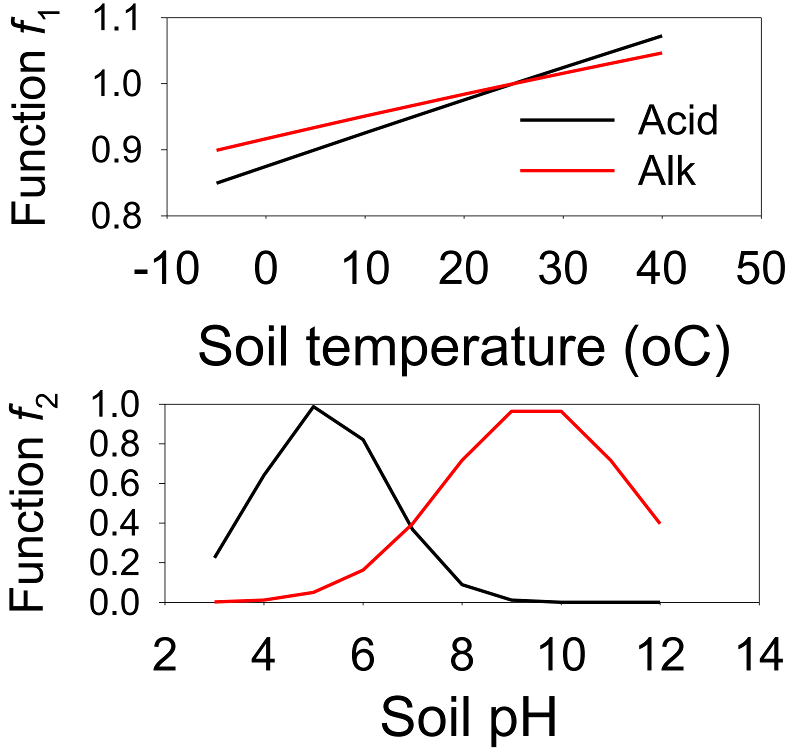
Biochemical mineralization

Biochemical mineralization is the processes of converting organic P to inorganic P by enzymatic reaction (phosphatase). Both plant roots and soil microbes can produce phosphatase (acid and alkaline phosphatase). Following Hui et al. (2013), the activity of phosphatase, V, can be modeled as

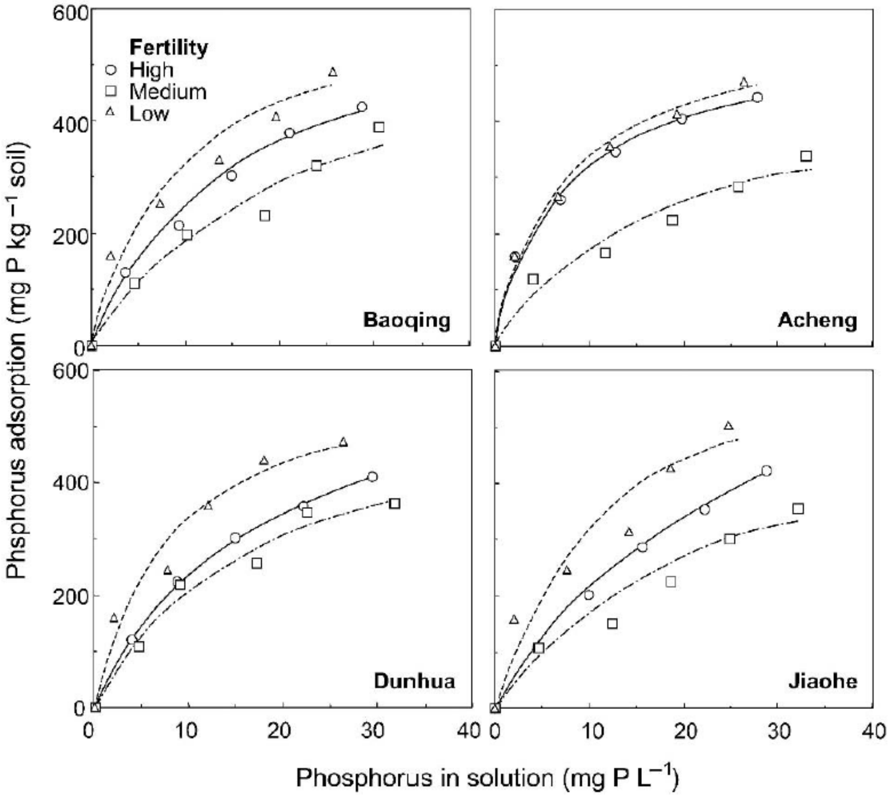
$$V = V_0 f_1(T) f_2(pH)$$

$$f_1(T) = exp\left(-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

$$f_2(pH) = exp\left(-\left(\frac{pH - pH_{opt}}{pH_{sen}}\right)^2\right)$$



P sorption in soil



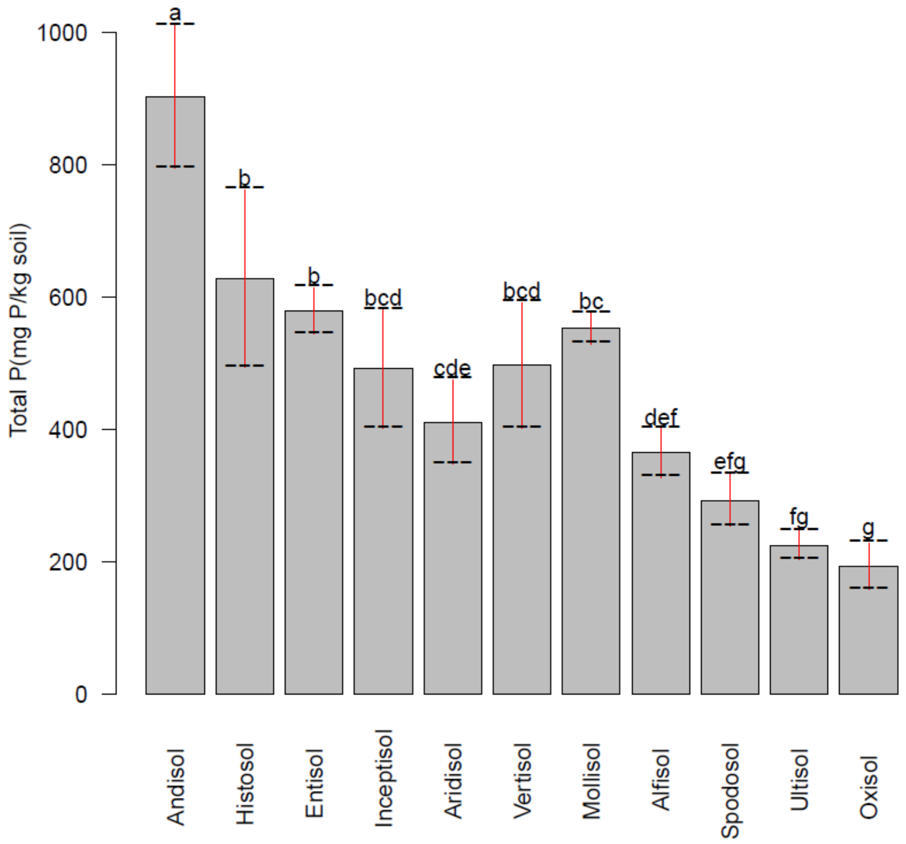
Han et al. 2005

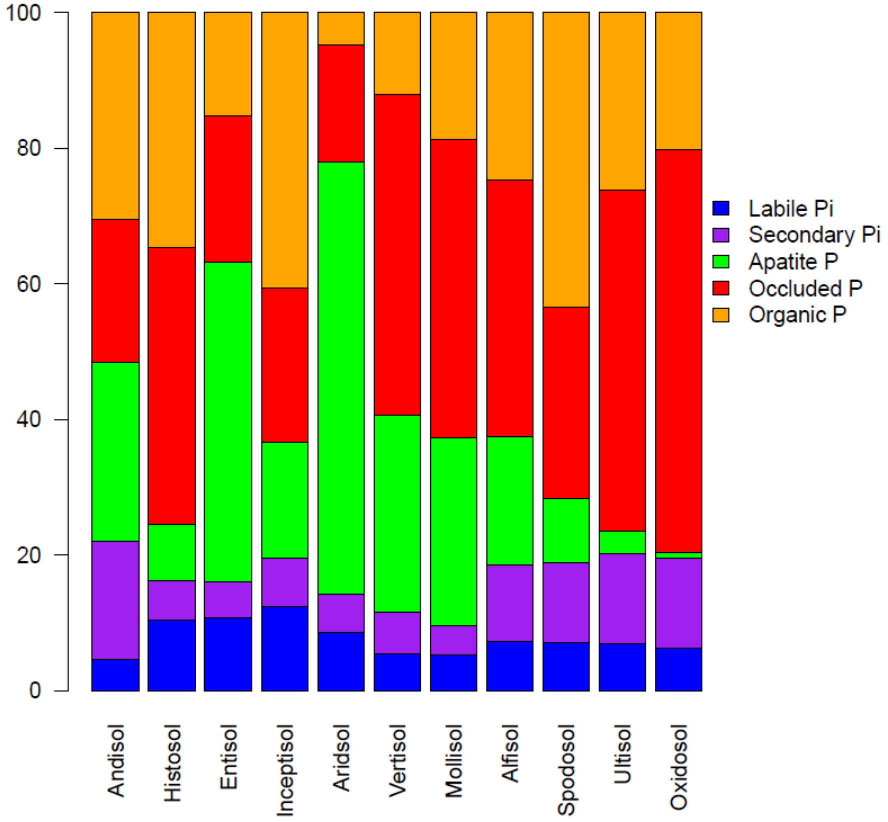
P sorption in soil can be modelled using the Langmuire equation:

$$\frac{P_{solution}}{P_{sorbed}} = \frac{1}{bS_{max}} + \frac{P_{solution}}{S_{max}}$$

Parameter b is a constant related to bonding energy, S_{max} is the Langmuir sorption maximum, both S_{max} and b vary with soil pH, content of Al, Fe, Clay and organic C content etc.

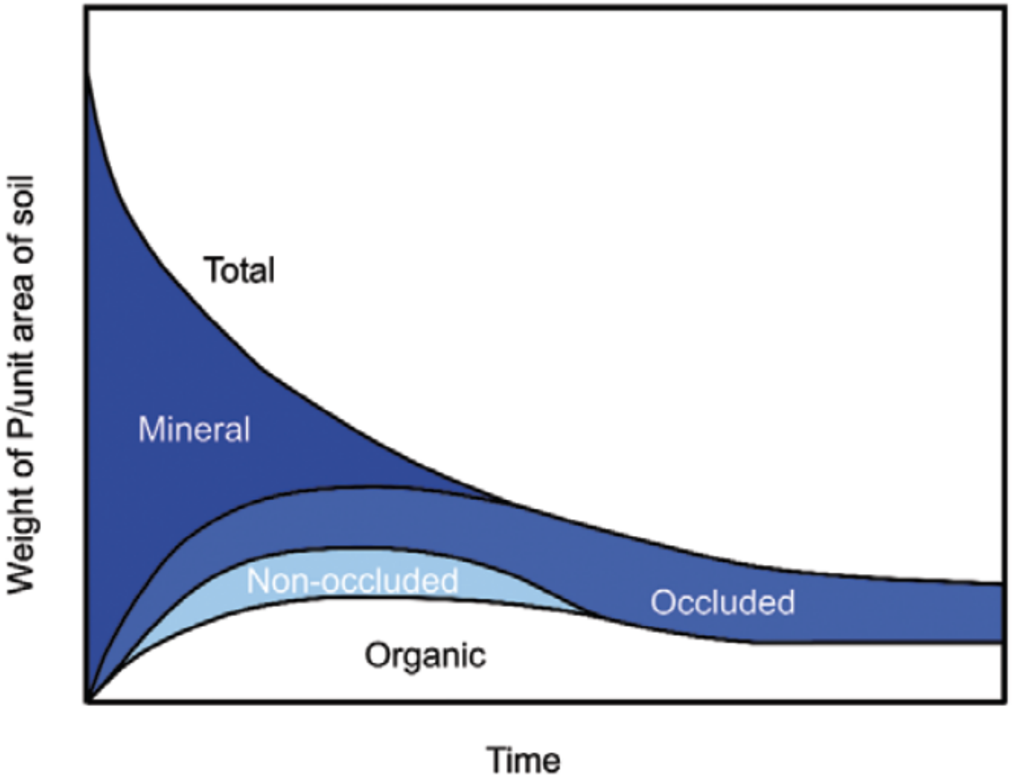
Fractionation of soil P





Source: Yang and Post 2011

Soil P dynamics at geological time scale (Walker and Syers' theory)



Source: Filippelli 2002

Key points:

all P land biosphere is derived from Rock weathering.

For young soil, most P is in mineral form, and P available for plant uptake is high, as soil ages, mineral P becomes adsorbed, and unavailable to plant.

Therefore productivity of plant ecosystem is P limited.

Total amount of soil P also decreases as soil ages, as soil P is lost via leaching or soil erosion.

Global N and P fluxes (Tg N or P/yr)

Input:

N deposition:	**70**
N fertilizer:	**90**
N fixation:	**140**

Output

N leaching:	**110**
N gas flux:	**190**

Internal cycling

N uptake:	**1080**
N mineralization	**1080**

Input:

P deposition:	**0.7**
P fertilizer:	**13**
P weathering:	**2**

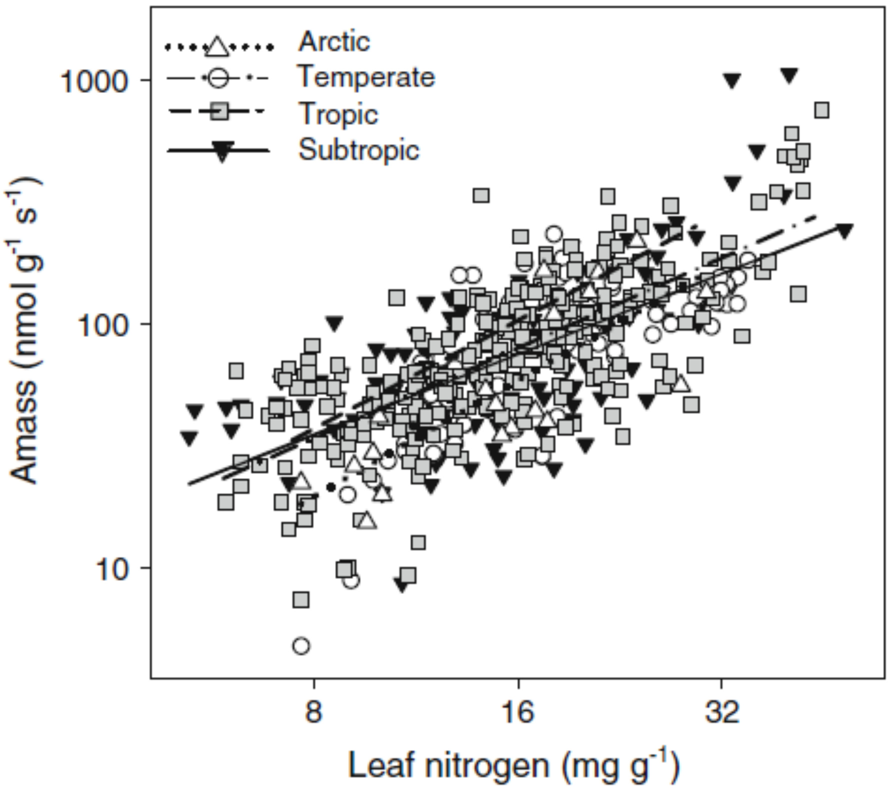
Output

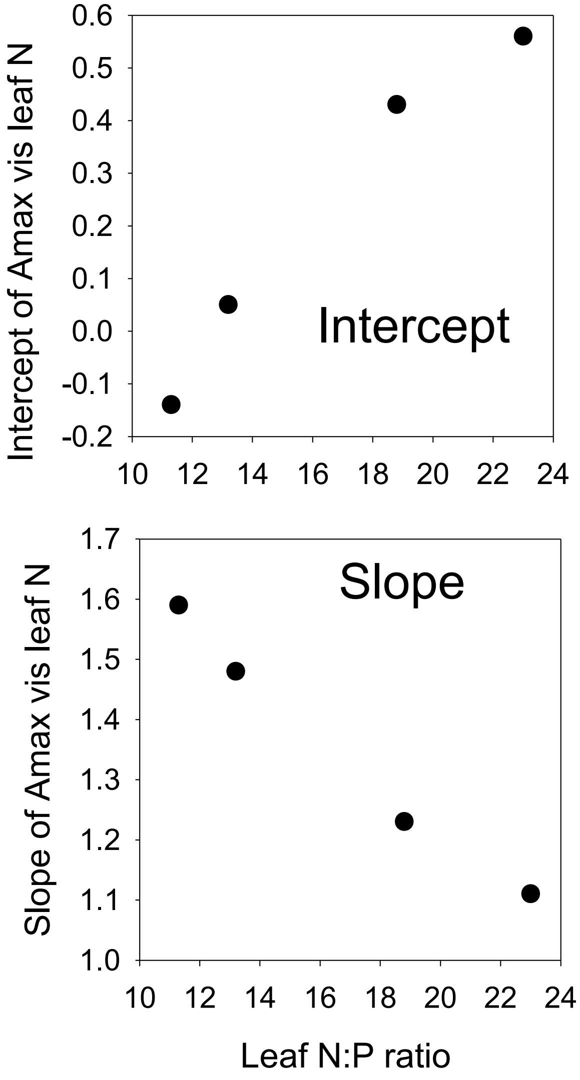
P leaching:	**13.7**
P fixation:	**2**

Internal cycling

P uptake	**60**
P mineralization	**60**

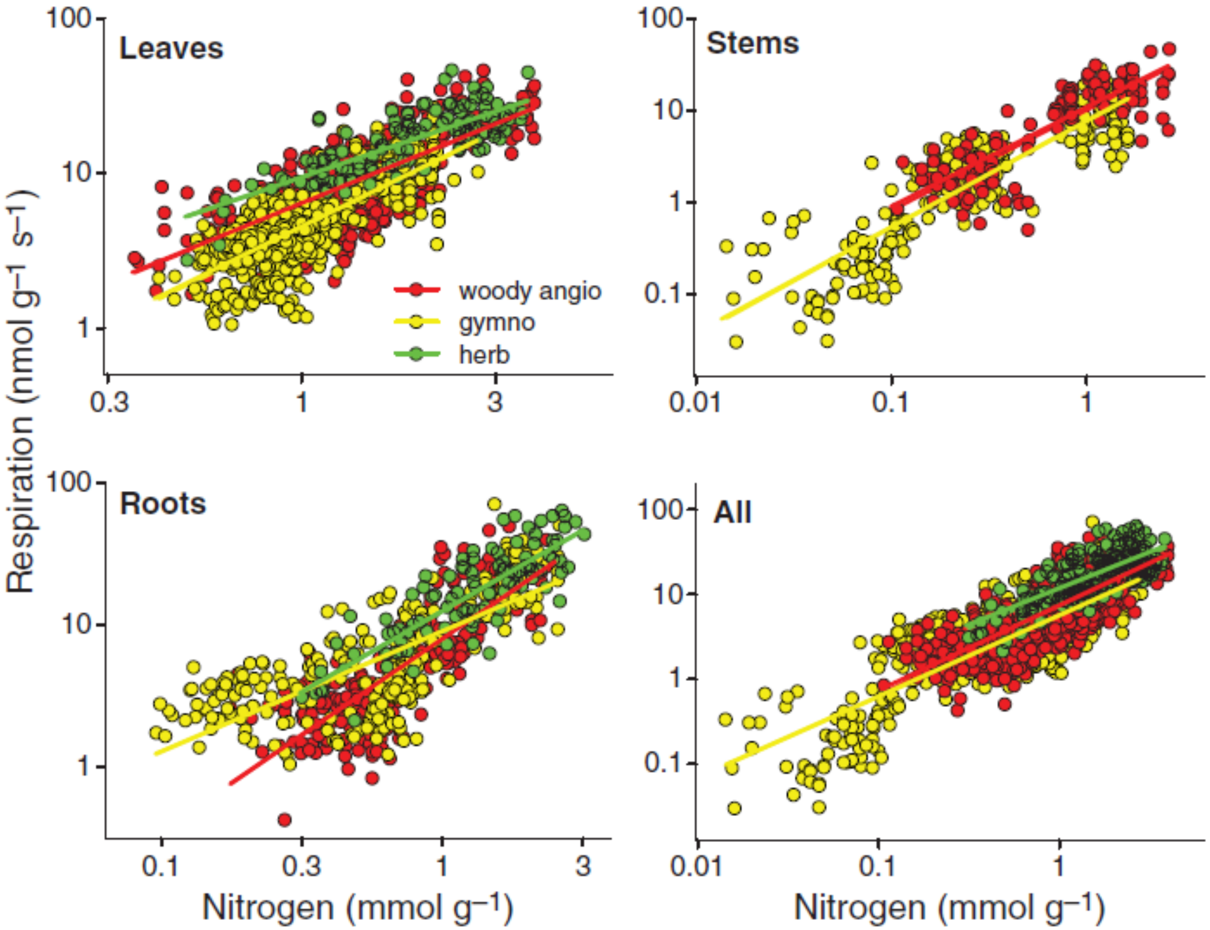
Effect of N and P on photosynthesis





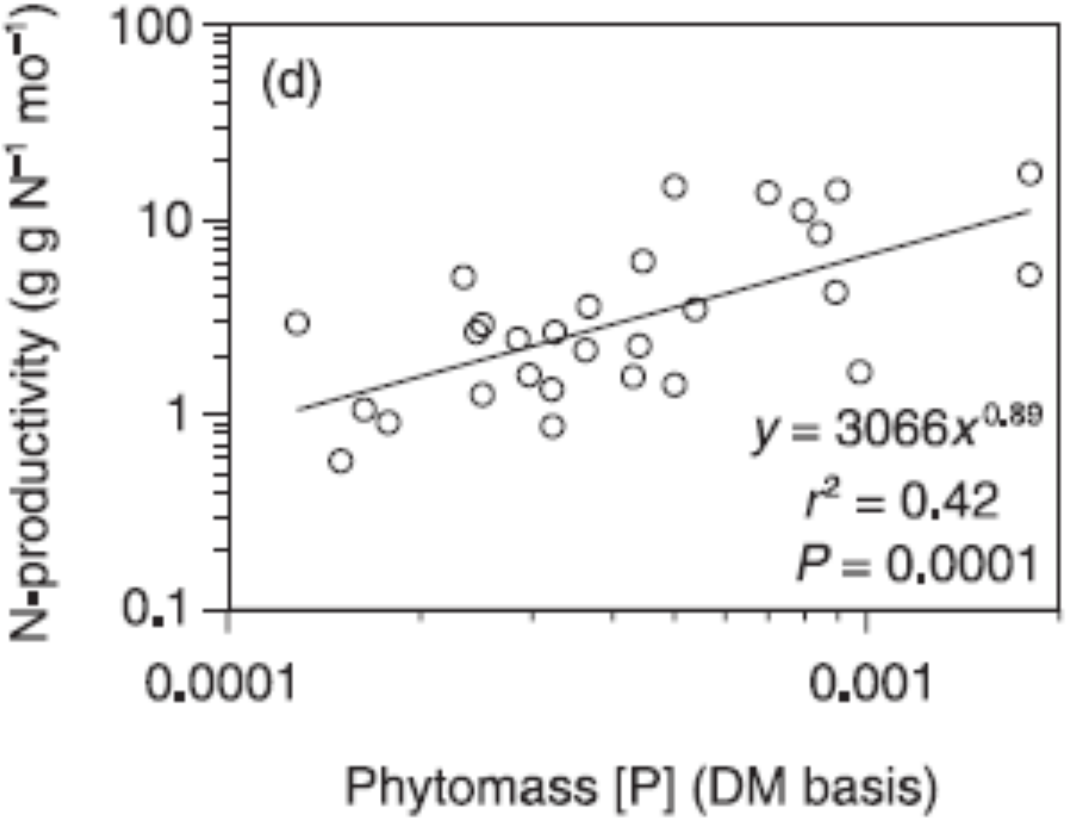
Source: Reich et al. 2009 for 314 species

Effect of nitrogen on carbon fluxes



Reich et al. 2008

Effect of phosphorous on carbon cycle

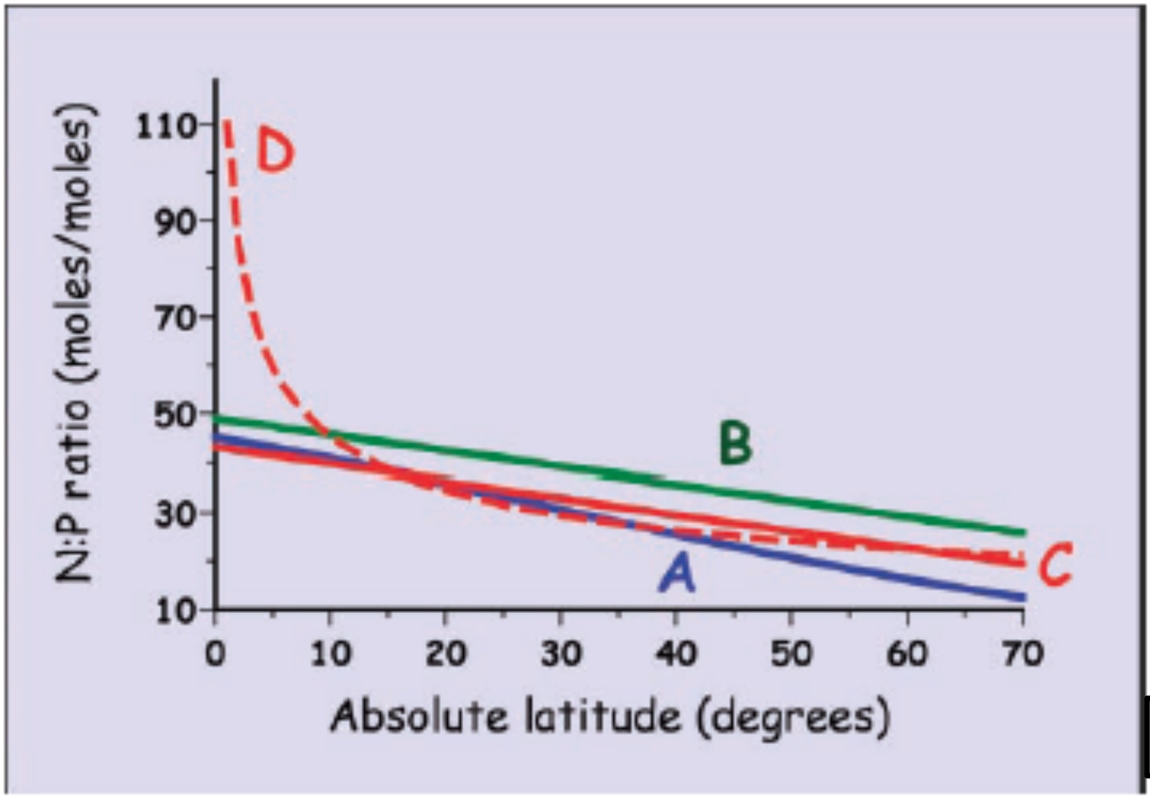


$$G = Y_g\left(A - R_m\right)$$

$$Y_g \propto \frac{N_b}{P_b}$$

Source: Kerkhoff et al. 2005

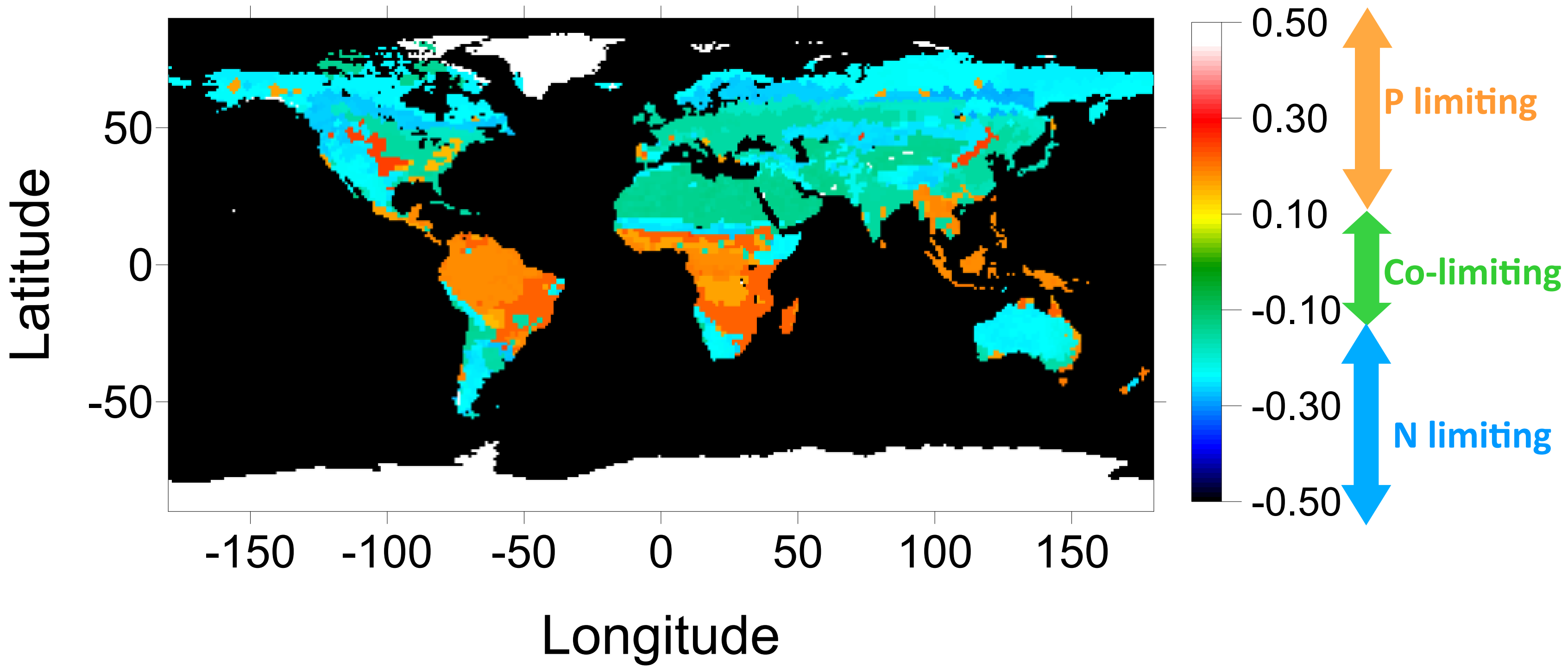
Global pattern of N vis P limitation



Source: Hedin 2004

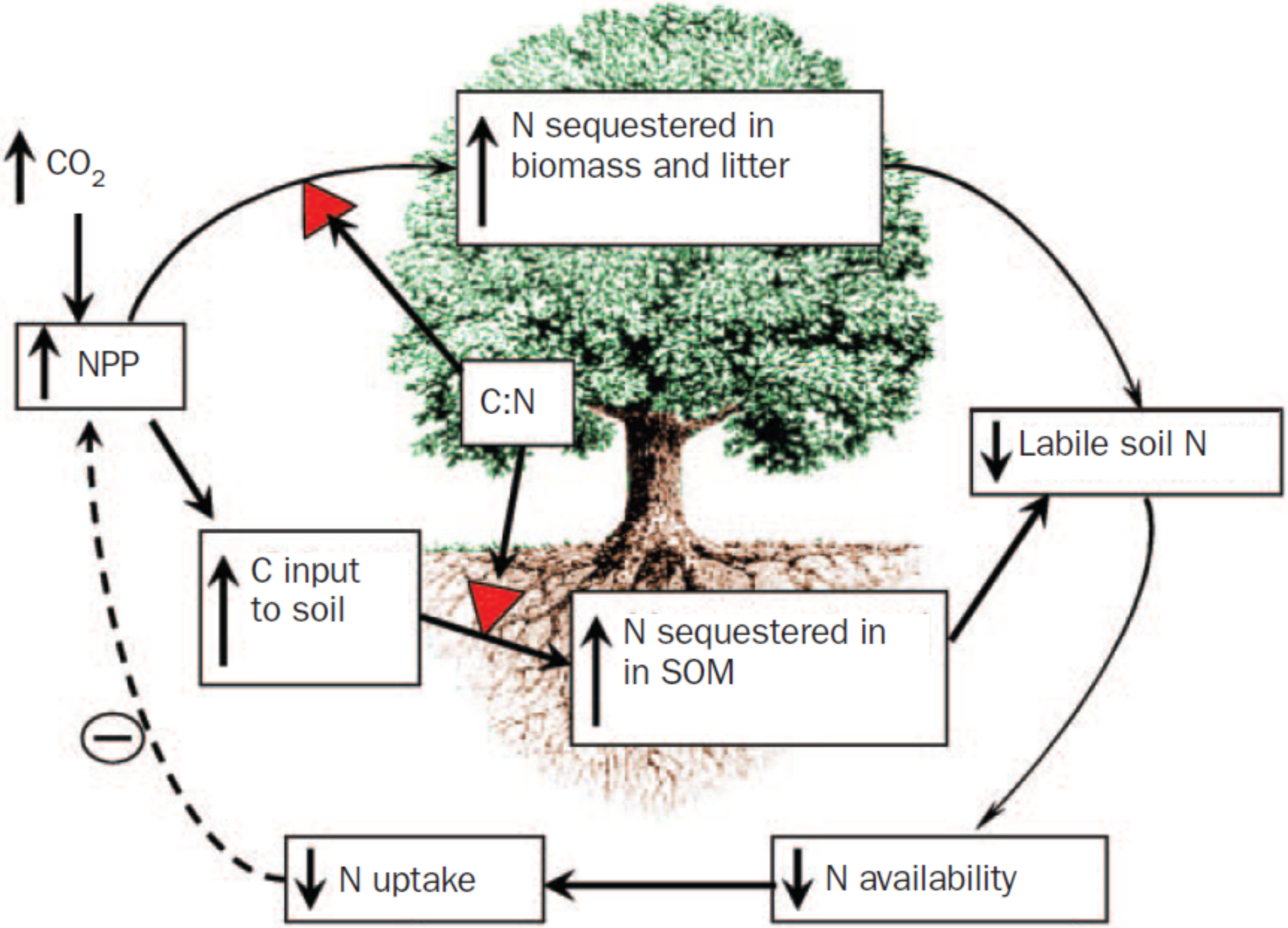
N:P <14, N limiting;
N:P >16, P limiting
(Koerselman and Meuleman (1996))

Global nutrient limitation



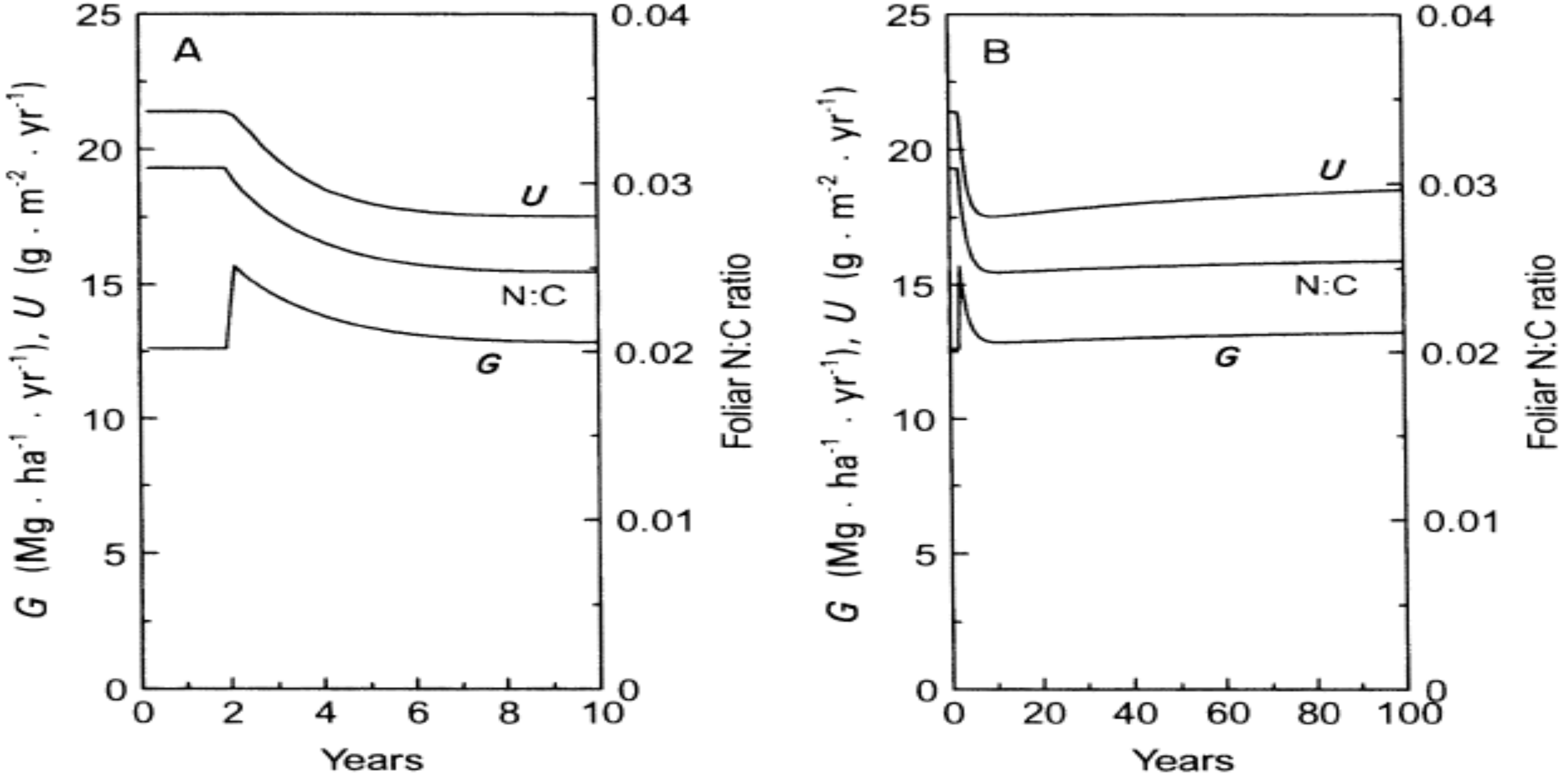
Wang, Law and Pak et al. 2010, Biogeosciences

Progressive nitrogen limitation



Luo et al. 2004,

Response of C flux to $2xCO_2$



Source: Cumins and McMurtrie 1993

Modelling N and P cycles on land

Compartmental modeling approach:

Compartmental modeling: divide the pools by function (Plant, litter, soil) and residence time (fast, slow);

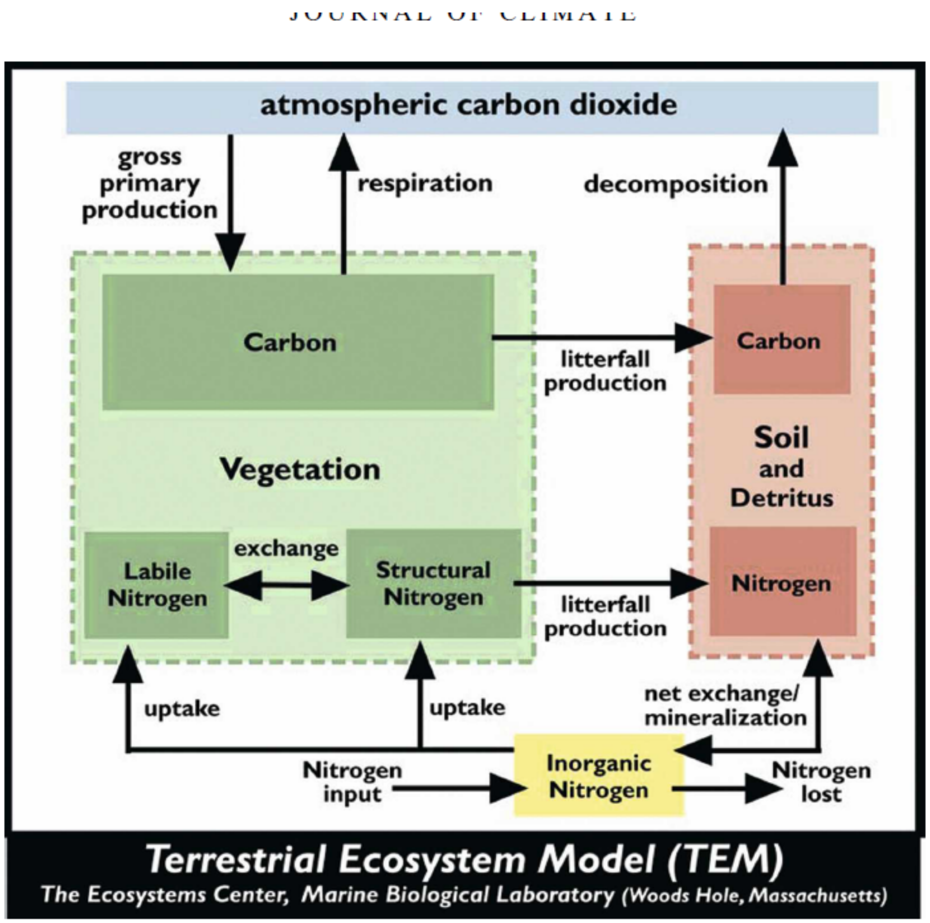
Plant: leaf, wood, root (coarse root, fine root)

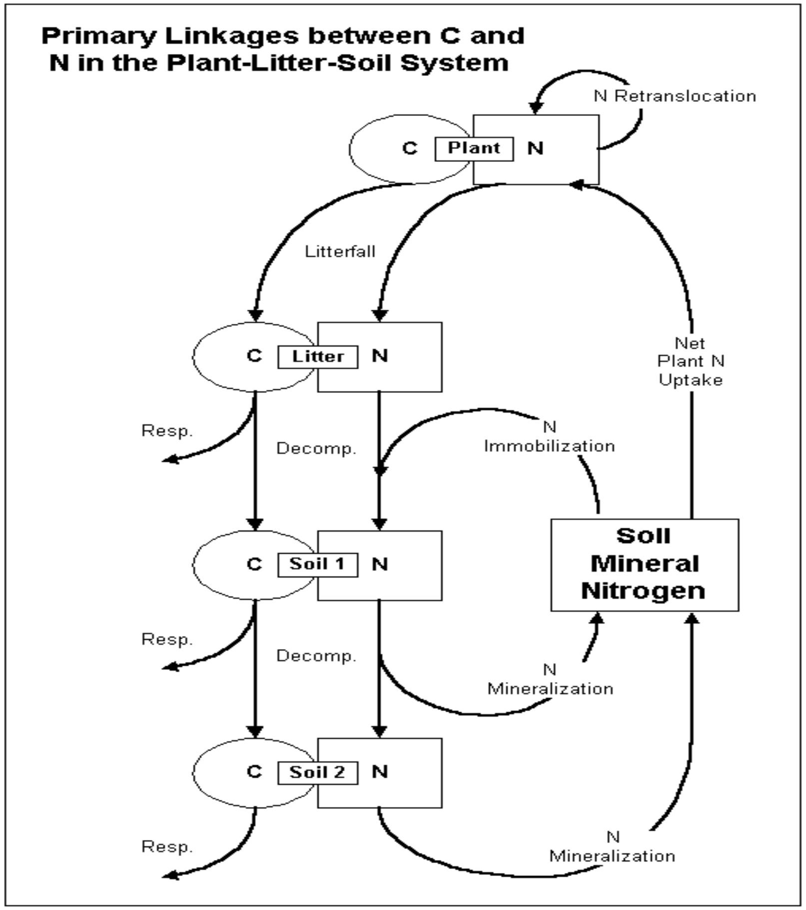
Litter: metabolic, structure litter, coarse woody debris

Soil: organic and inorganic

Pool dynamics is modeled using first-order, or Michaelis-Menten kinetics

How nutrient-carbon interactions are represented in global land models?





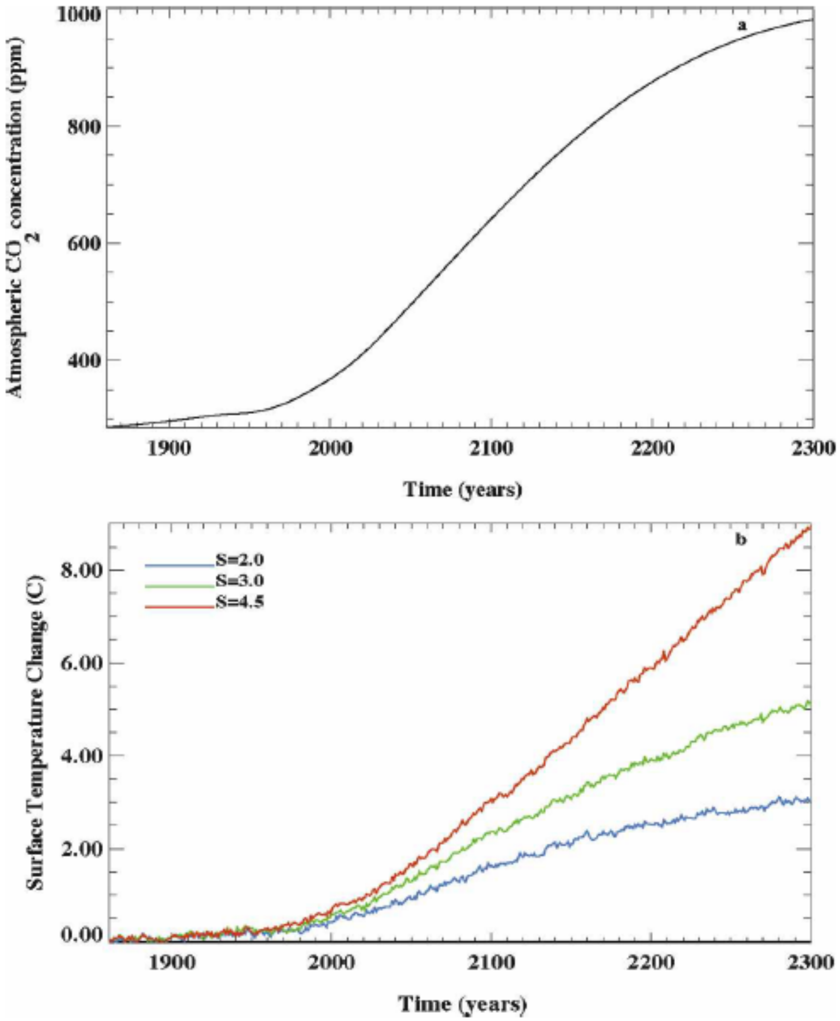
Source: Sokolov et al. 2008

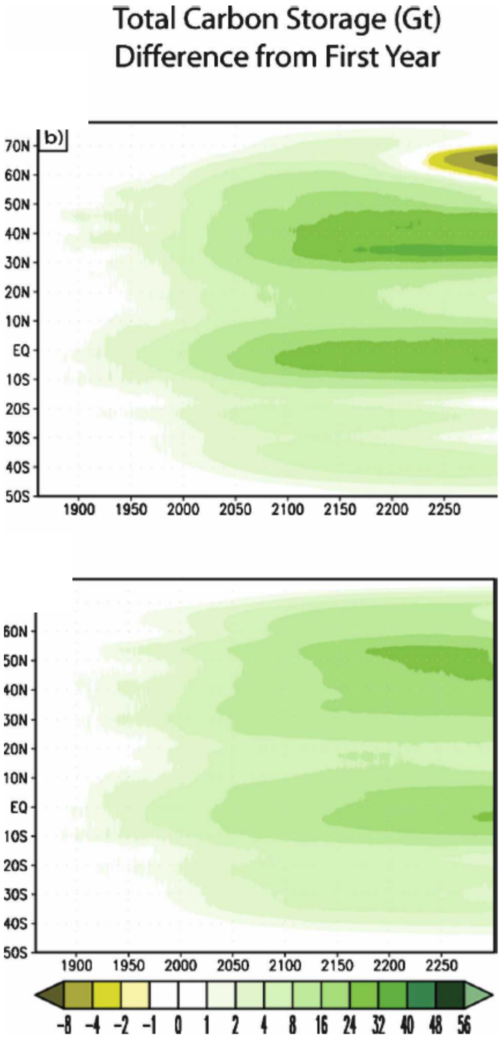
Source: http://www.ntsg.umt.edu/project/biome-bgc

Comparing the two models

	IGSM (TEM)	CCSM (CN)
Biophysics	CLM2.0	CLM4.0
Time step	daily	hourly
Nitrogen feedback on GPP and Rm	Empirical model	Vcmax =f(leaf n) Rm= f2(tissue N)
Stomatal conductance	Not modelled	Ball-Berry model
Plant uptake	Michaelis-menton	A function of demand
C and N pools	2 C pools 3 N pools	>30 C pools >30 N pools
N fixation and N pools	prescribed	modelled

Effects of nitrogen limitation (IGSM)



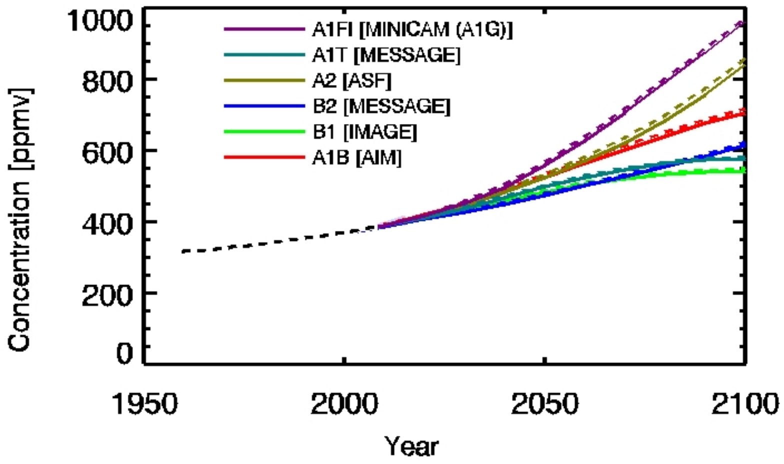


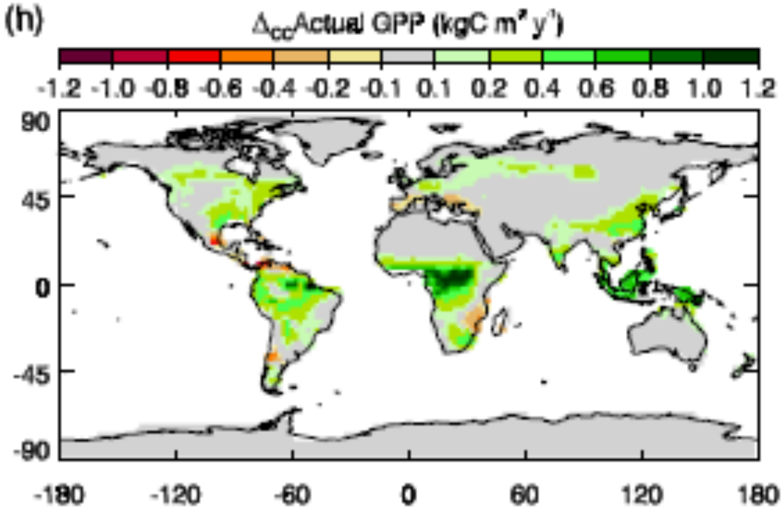
C-TEM

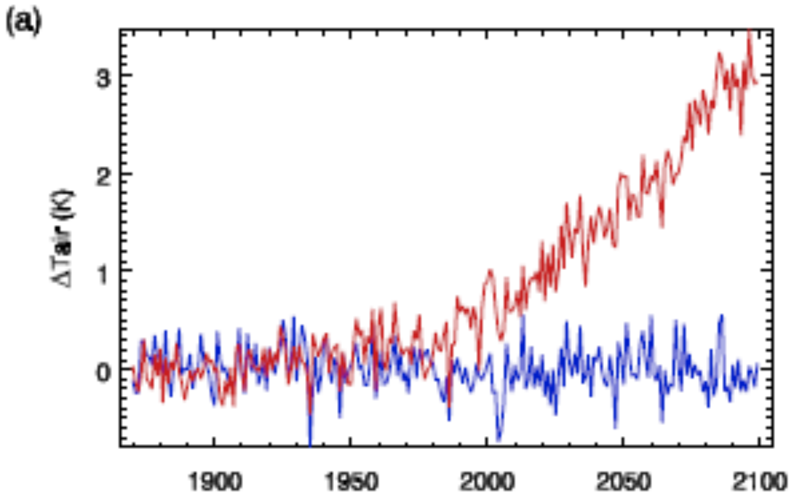
CN-TEM

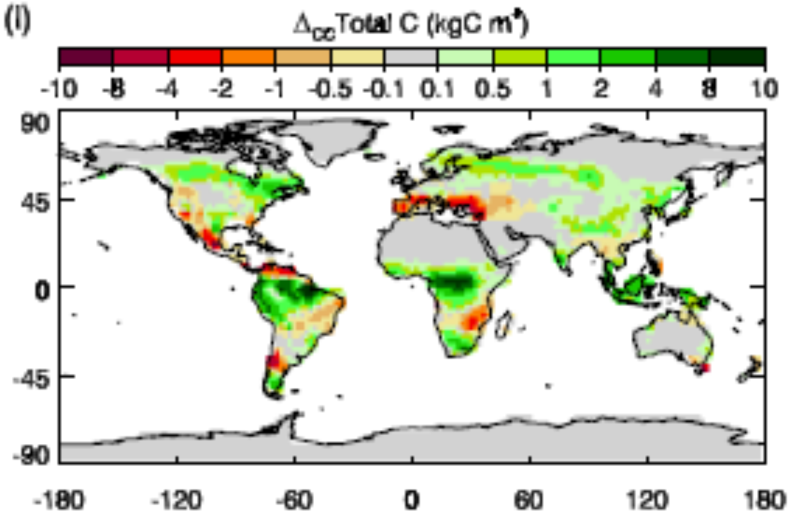
Source: Sokolov et al. 2008

Effect of nitrogen limitation (CCSM3)



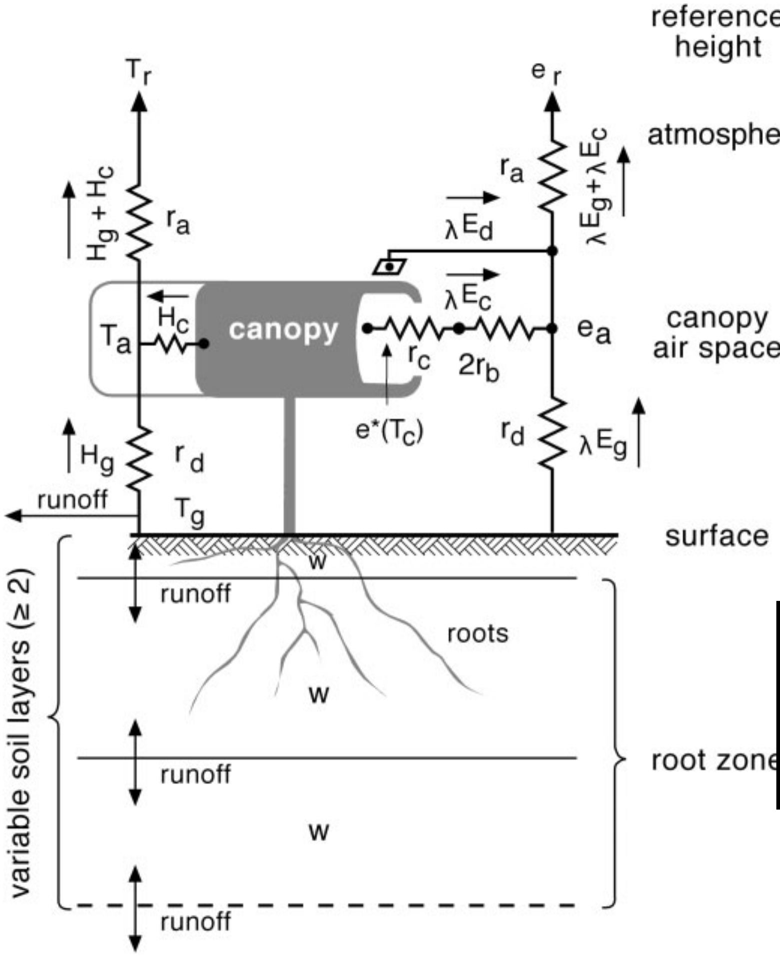


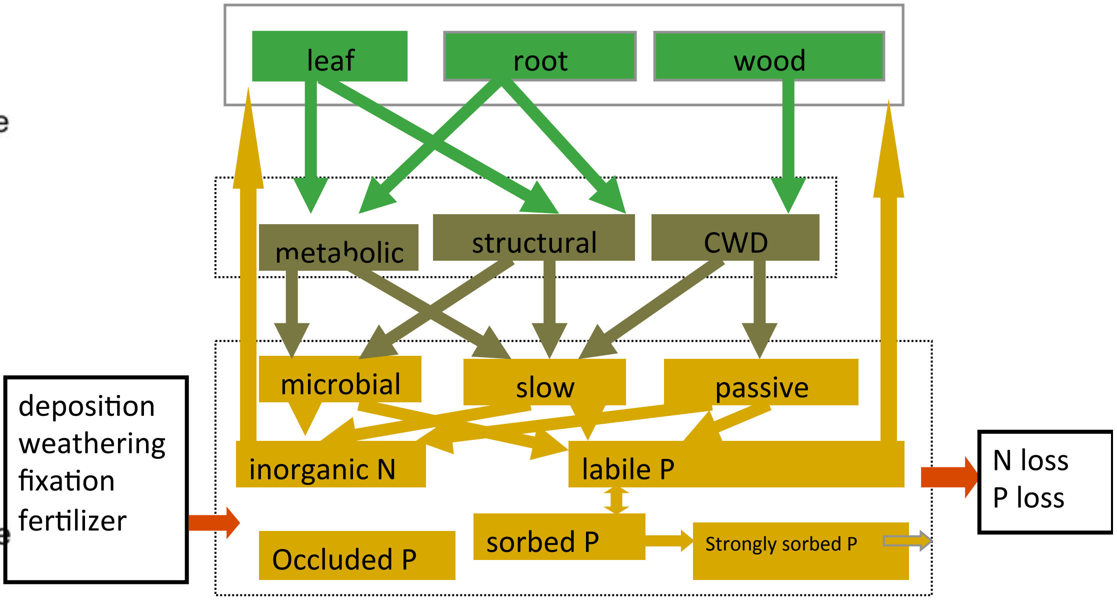




Source: Thornton et al. 2009

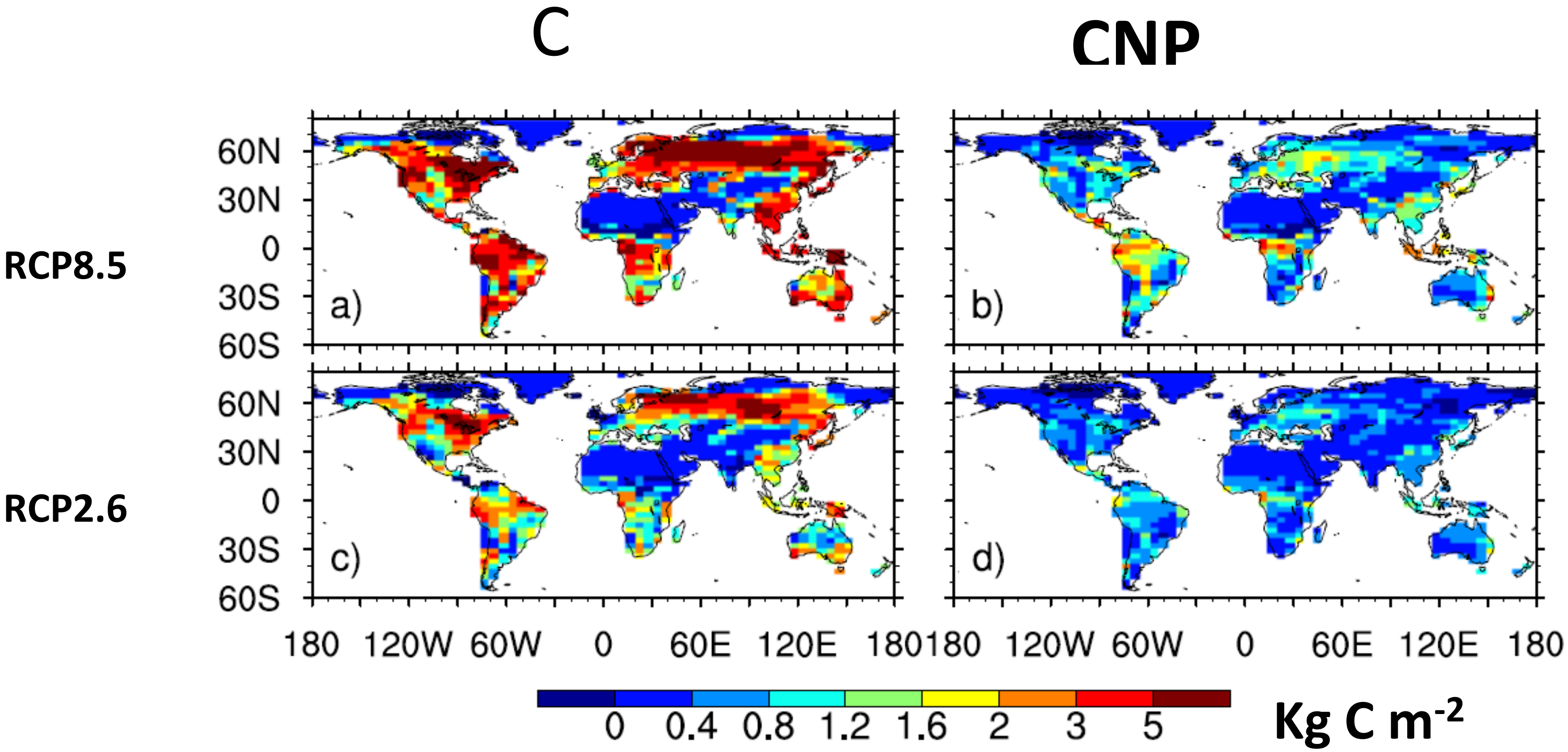
CABLE: its components





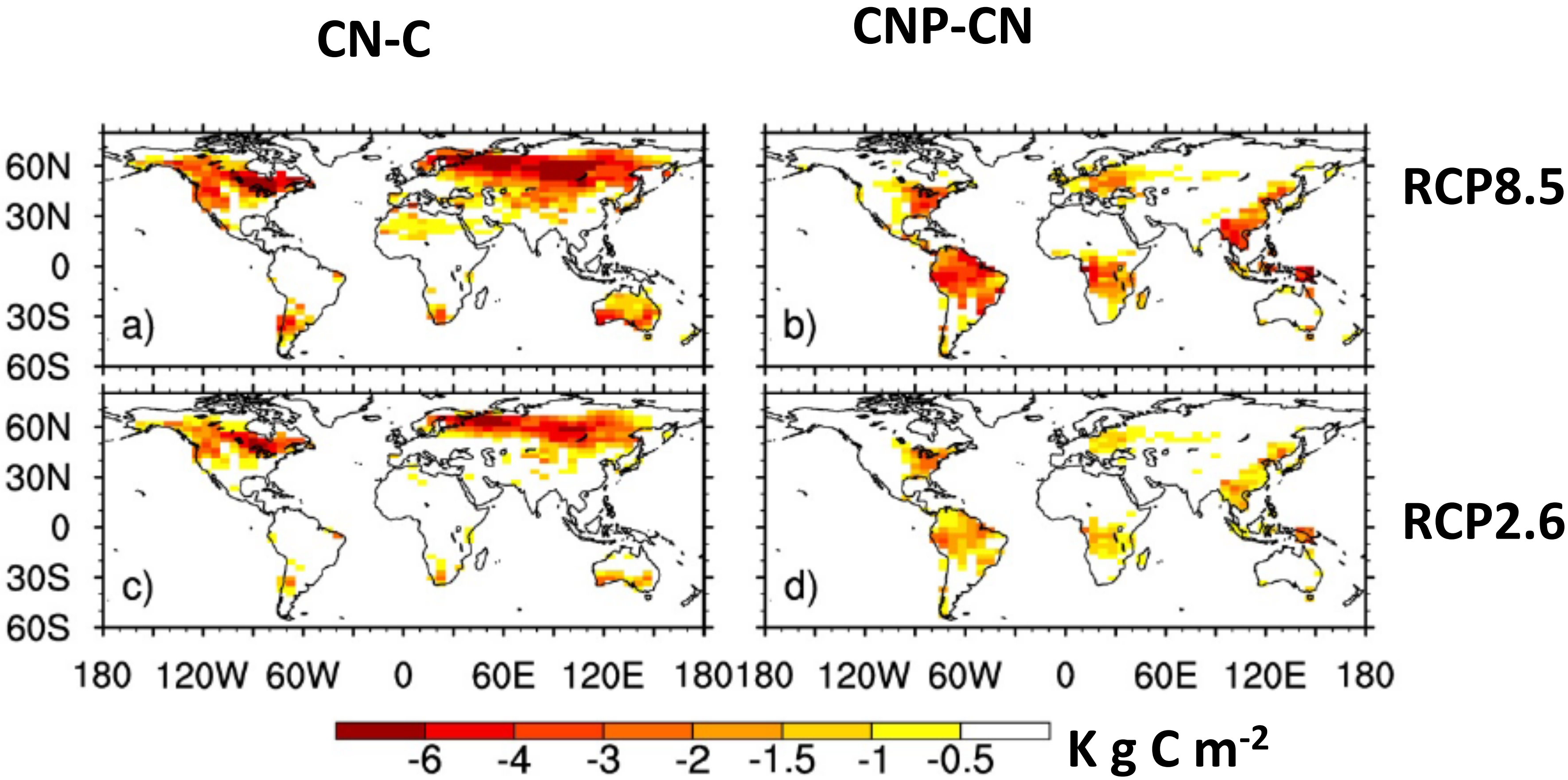
Biophysics + Biogeochemistry = CABLE

C accumulation from 1850 to 2100



Zhang et al. submitted

Effects of both N and P



Source: Zhang et al. submitted

Sensitivities of land carbon

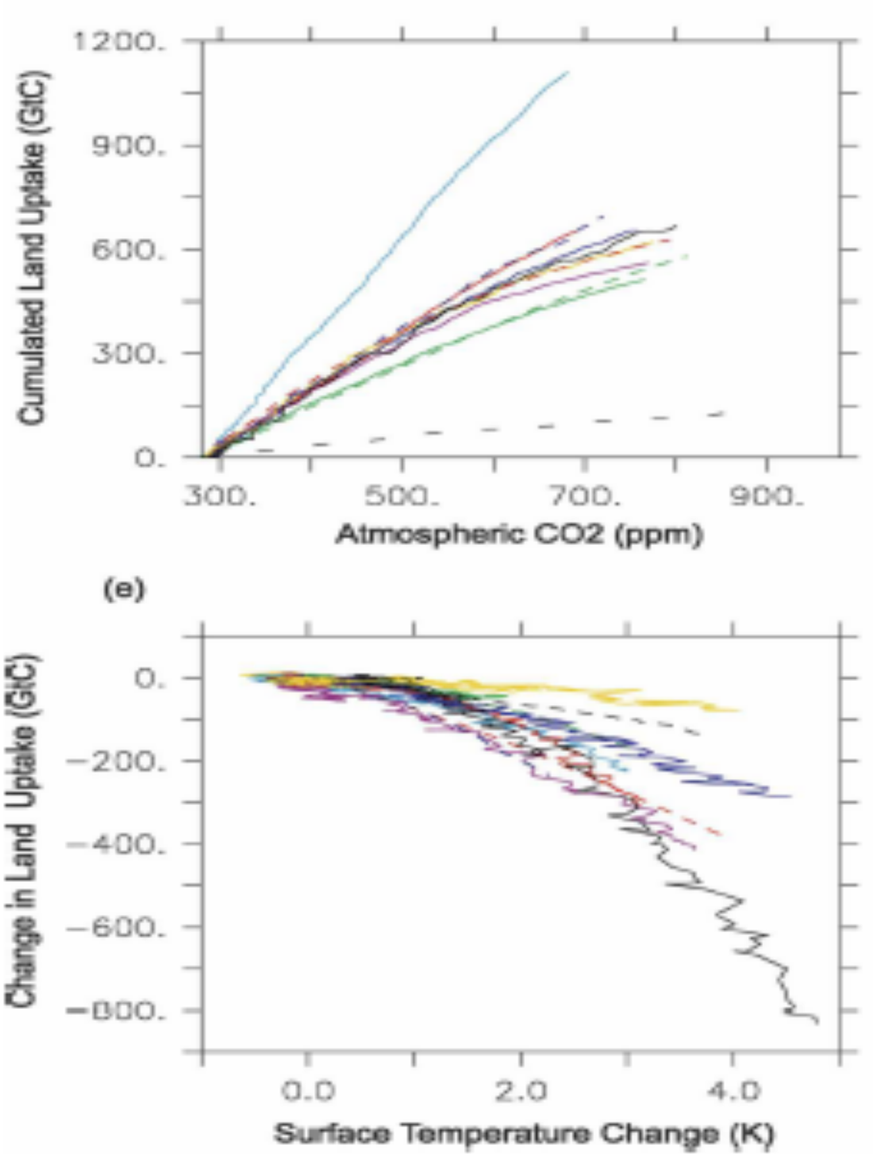
Change in total carbon pool, (ΔC_L) in response to increasing atmospheric CO_2 (ΔCO_2) and climate change (ΔT) can be approximated as

$$\Delta C_L = \beta_L \, \Delta CO_2 + \gamma_L \, \Delta T$$

β_L is the CO_2 sensitivities of land carbon in Gt C/ppm (>0)
γ_L is the climate sensitivity of land carbon in Gt C/K (<0).

Values of β_L and γ_L are estimated from the differences of simulated carbon pool size between control, uncoupled (only changing CO2 is seen by land biosphere) and coupled (both climate and CO2 are seen by land biosphere) simulations.

The T and CO_2 sensitivities of global land carbon uptake

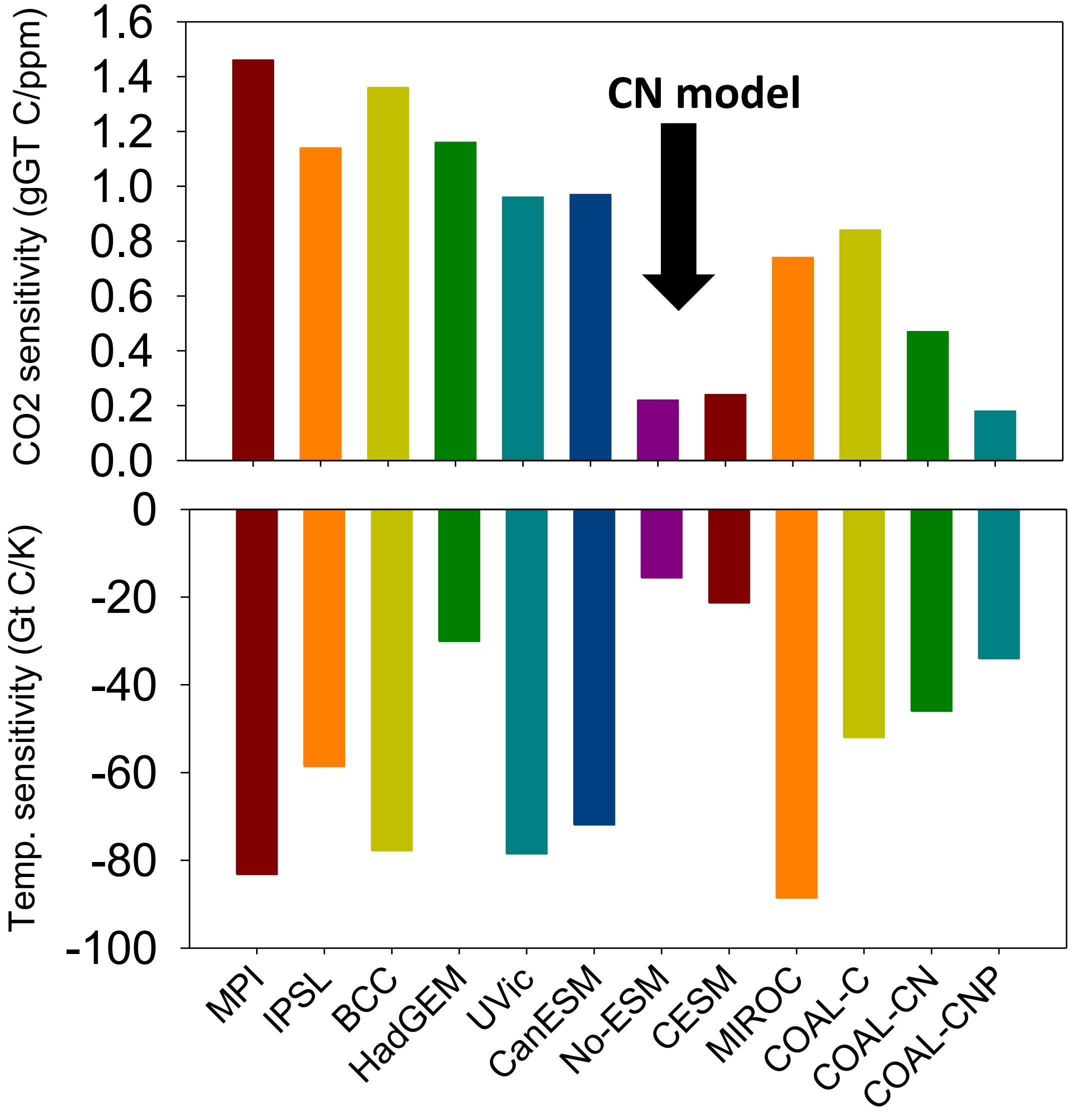


$$\Delta C_l = \alpha \Delta T + \beta \Delta c$$

$$\alpha < 0.0$$

$$\beta > 0.0$$

IPCC AR5 models +COAL



Summary

Human activities have significantly altered the nutrient cycles globally;
Nutrient limitation can significantly affect all carbon fluxes in terrestrial ecosystem;
N limitation dominates at mid- and high latitudes while P limitation dominates at low latitudes and southern hemisphere;
Globally, sensitivity of photosynthetic carbon uptake to increasing CO_2, so-called CO_2 fertilization effect, by 2100 can be reduced by 50% by nitrogen limitation, and another 40% by phosphorous limitation. These estimates have very large uncertainties.

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