Soils and nutrient cycling in tropical forests

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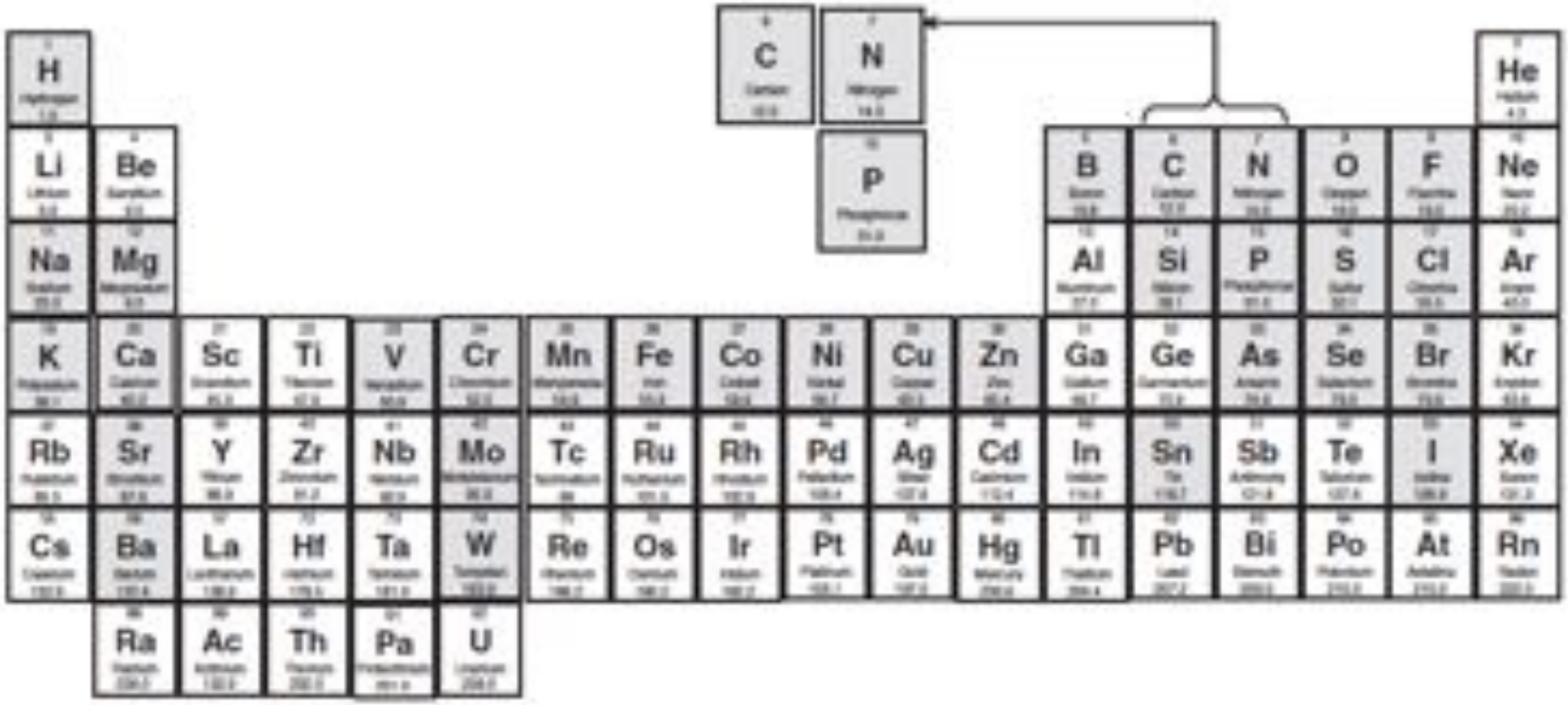
Outline

- Nutrient plant demands
- The biogeochemical heterogeneity of the tropical biome
- Humans and the cycling of nutrients

Essential elements for life



Essential Nutrients of Plants

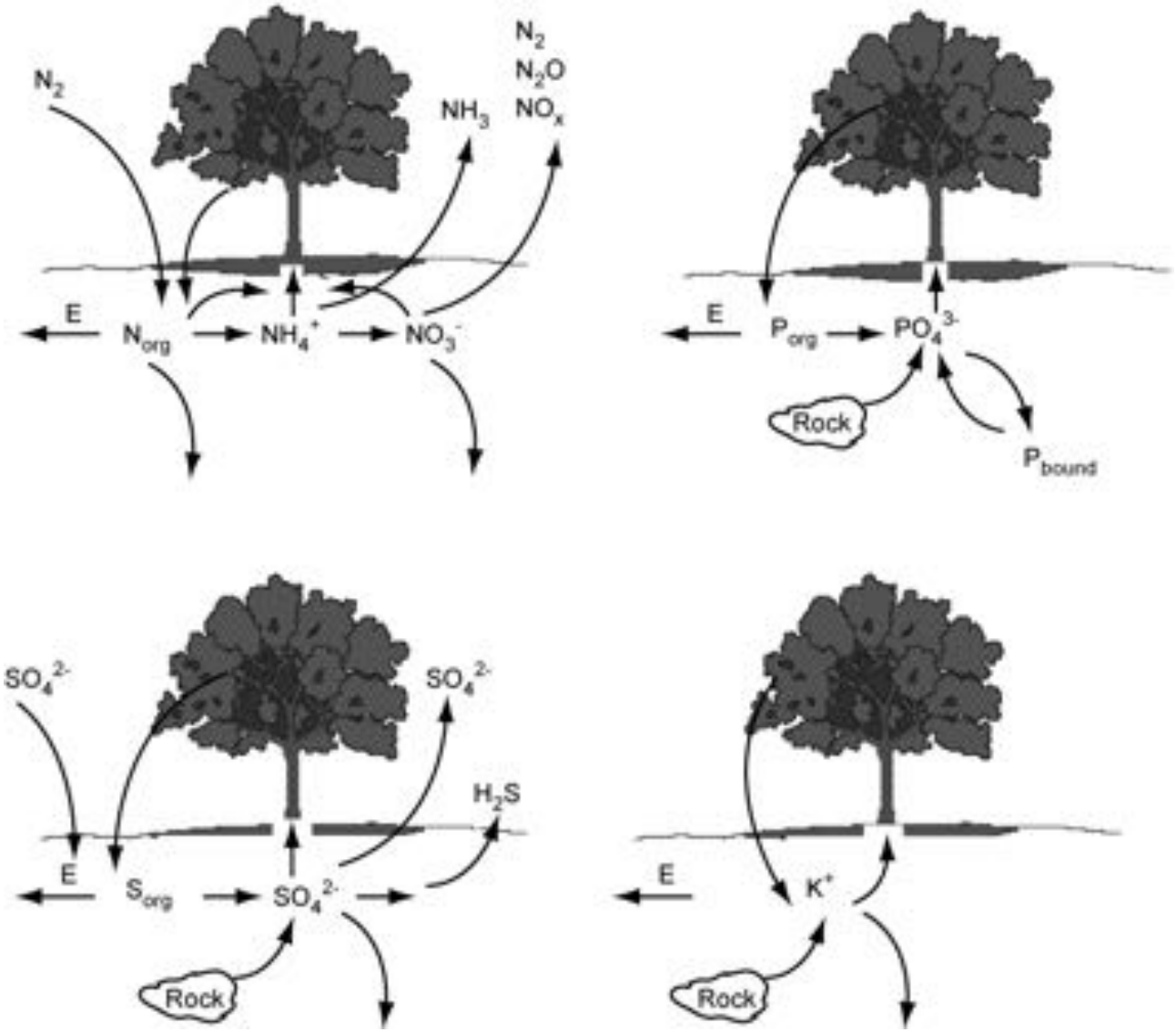
Element	Chemical symbol	Atomic weight	Ionic forms Absorbed by plants	Approximate dry concentration
Macronutrients				
Nitrogen	N	14.01	NO_3^-, NH_4^+	4.0 %
Phosphorus	P	30.98	PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$	0.5 %
Potassium	K	39.10	K^+	4.0 %
Magnesium	Mg	24.32	Mg^{2+}	0.5 %
Sulfur	S	32.07	SO_4^{2-}	0.5 %
Calcium	Ca	40.08	Ca^{2+}	1.0 %
Micronutrients				
Iron	Fe	55.85	Fe^{2+}, Fe^{3+}	200 ppm
Manganese	Mn	54.94	Mn^{2+}	200 ppm
Zinc	Zn	65.38	Zn^{2+}	30 ppm
Copper	Cu	63.54	Cu_2^+	10 ppm
Boron	B	10.82	BO_3^{2-}, $B_4O_7^{2-}$	60 ppm
Molybdenum	Mo	95.95	MoO_4^{2-}	2 ppm
Chlorine	Cl	35.46	Cl^-	3000 ppm
Essential				
Carbon	C	12.01	CO_2	40 %
Hydrogen	H	1.01	H_2O	6 %
Oxygen	O	16.00	O_2, H_2O	40 %

Plant tissues also contain other elements (Na, Se, Co, Si, Rb, Sr, F, I) which are not needed for the normal growth and development.

Primary functions of elements

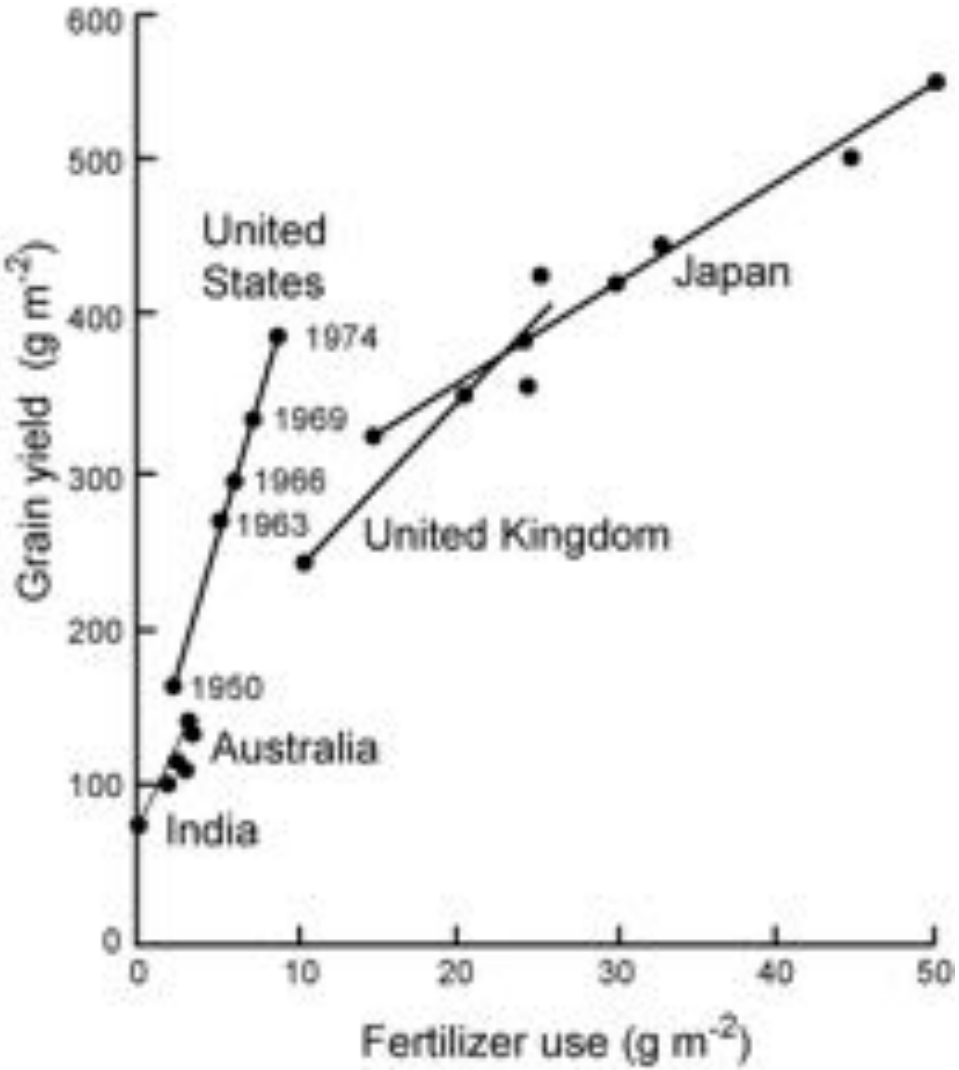
Function	Elements	Chemical form	Examples
Structural	H, O, C, N, P, S, Si, B, F, Ca	Organic compounds	Biological molecules, cell walls, tissue, skeletons, etc.
Electrochemical	H, Na, K, Cl, HPO_4^{-2}	Free ions	Message transmission, cellular signaling, energy metabolisms
Catalytic (acid base)	Zn, Ni, Fe, Mn	Complexed with enzymes	Digestion, hydrolisis, PO_4 removal in acid media
Catalytic (redox)	Fe, Cu, Mn, Mo, Se	Complexed with enzymes	Reactions with O_2, N fixation, reduction of nucleotides

Sterner & Elser, 2002.



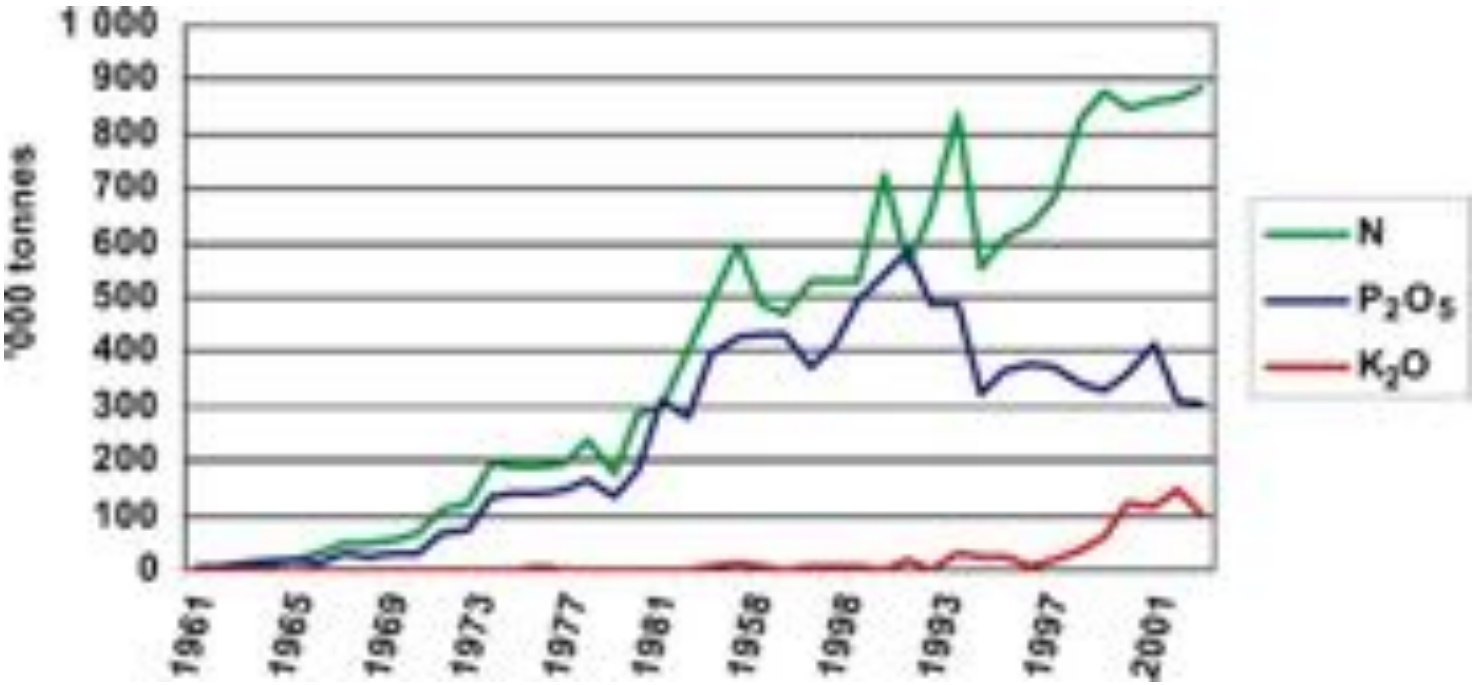
Chapin et al., 2011

Nutrient supply constraints the productivity of terrestrial ecosystems



Chapin et al. 2002.

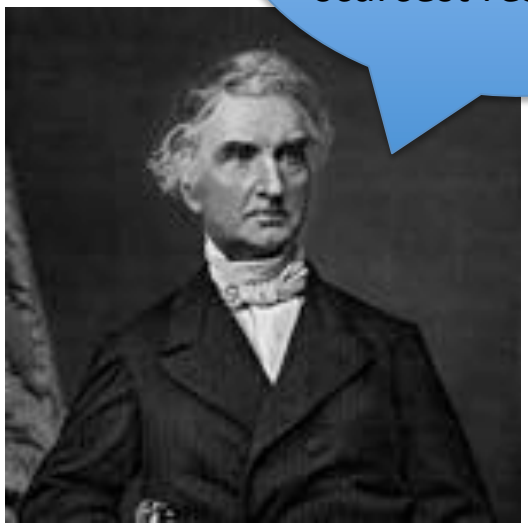
N, P, and K are the most important nutrients that contribute to plant growth in agro-ecosystems



Source: FAO 2005

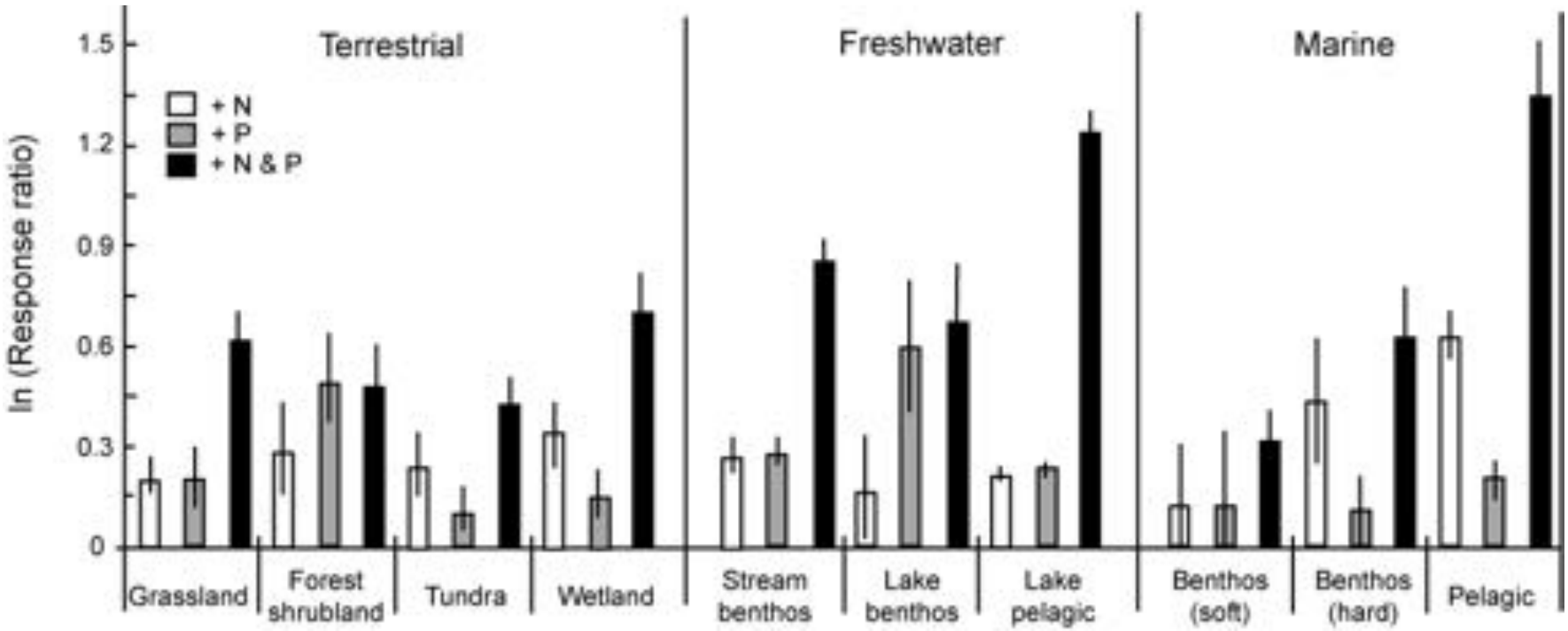
Justus von Liebig's **Law of the Minimum**

"Plant growth is controlled not by the total amount of resources, but by the scarcest resource"

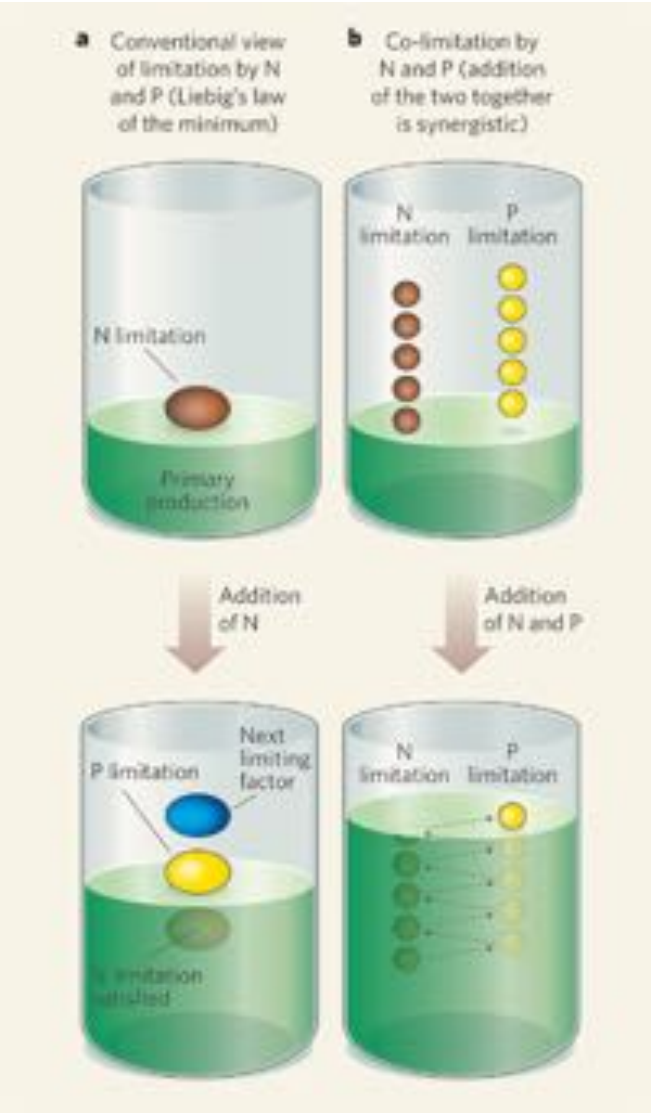


$$y = \min\{f_N(N), f_P(P), f_K(K), \ldots, f_L(L)\}$$

Nutrient supply constraints the productivity of ecosystems



The supply of, and demand for, N and P are usually in close balance



Davidson & Howarth 2007.

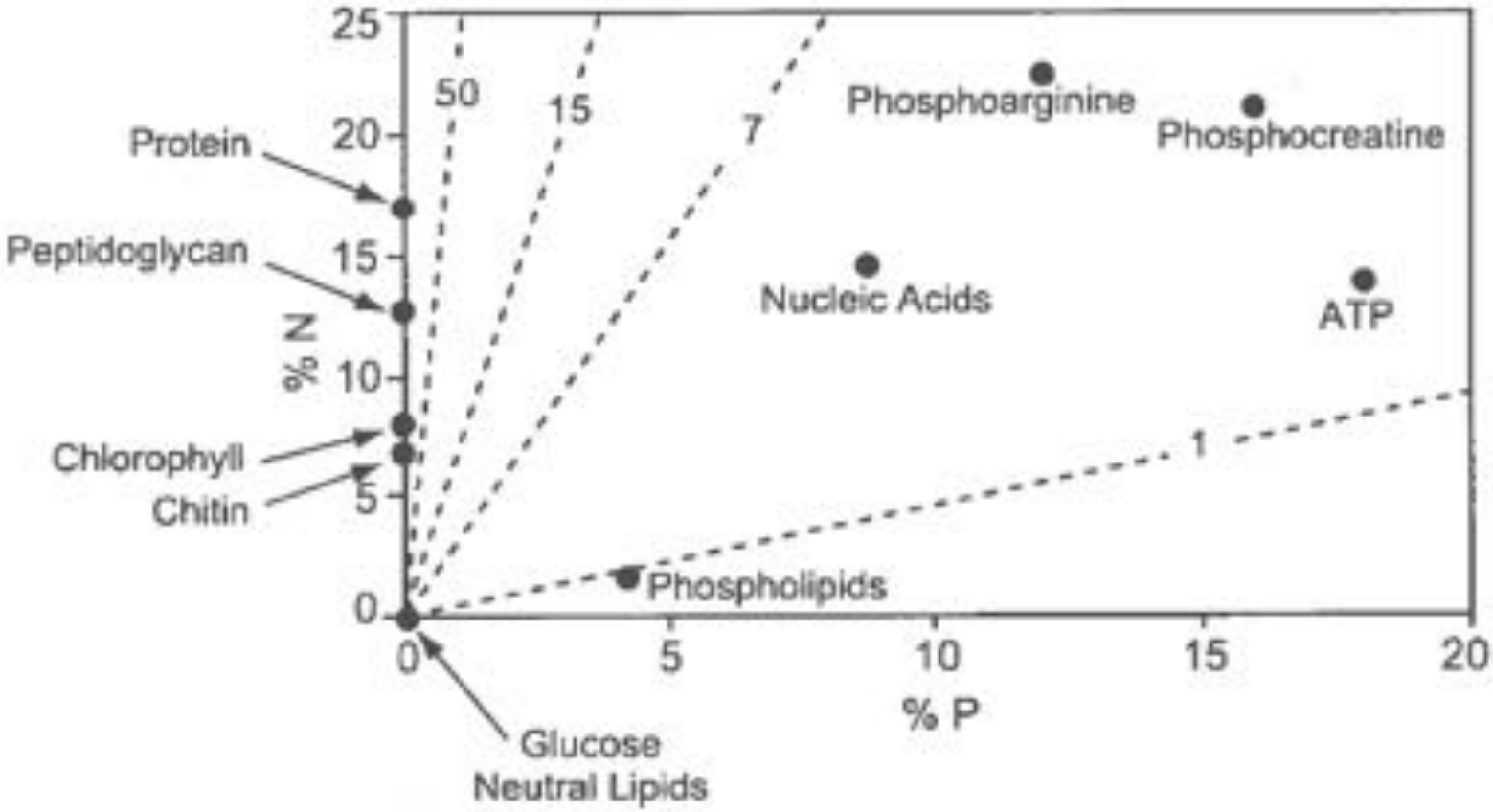
N and P are the most important nutrients for biological activity

TABLE 2.2
The dominant classes of ubiquitous biological materials that contain C, N, or P. Parentheses indicate that the element indicated is found only in certain forms of the biological material considered

Biological Material	*Examples*	*Functions*	*Comments*
Protein: C, N, (P)	Collagen, RUBISCO	Structure, regulation, communication, metabolism	Average N content of the 20 amino acids in proteins is 17%
Nucleic acids: C, N, P	DNA, mRNA, tRNA, rRNA	Storage, transmission, and expression of genetic information	DNA content is conservative; RNA:DNA is typically greater than 5:1 by mass; rRNA dominates total RNA
Lipids: C, (N), (P)	Phospholipids, neutral lipids	Cell membranes, energy storage	Carbon-rich molecules; phospholipids are relatively minor components of cells (<5% of total mass)
Energetic nucleotides: C, N, P	ATP, phosphocreatine	High-energy carrier or storage molecules	ATP is only approximately 0.05% of invertebrate body mass
Carbohydrates: C, (N)	Glucose, starch, glycogen, cellulose, lignin, chitin, peptidoglycan	Energy storage, structure	Generally lacking in N and P (peptidoglycan and chitin are exceptions but still have relatively low % N)
Pigments: C, N	Chlorophyll	Light absorption	Chlorophyll is 6.5% N
Inorganic materials: C, P	polyphosphate, hydroxyapatite, $CaCO_3$	Nutrient and energy storage, mechanical support and protection	In some situations, polyphosphate can be a major storage pool in bacteria, algae, fungi, and some higher plants, but not in metazoans

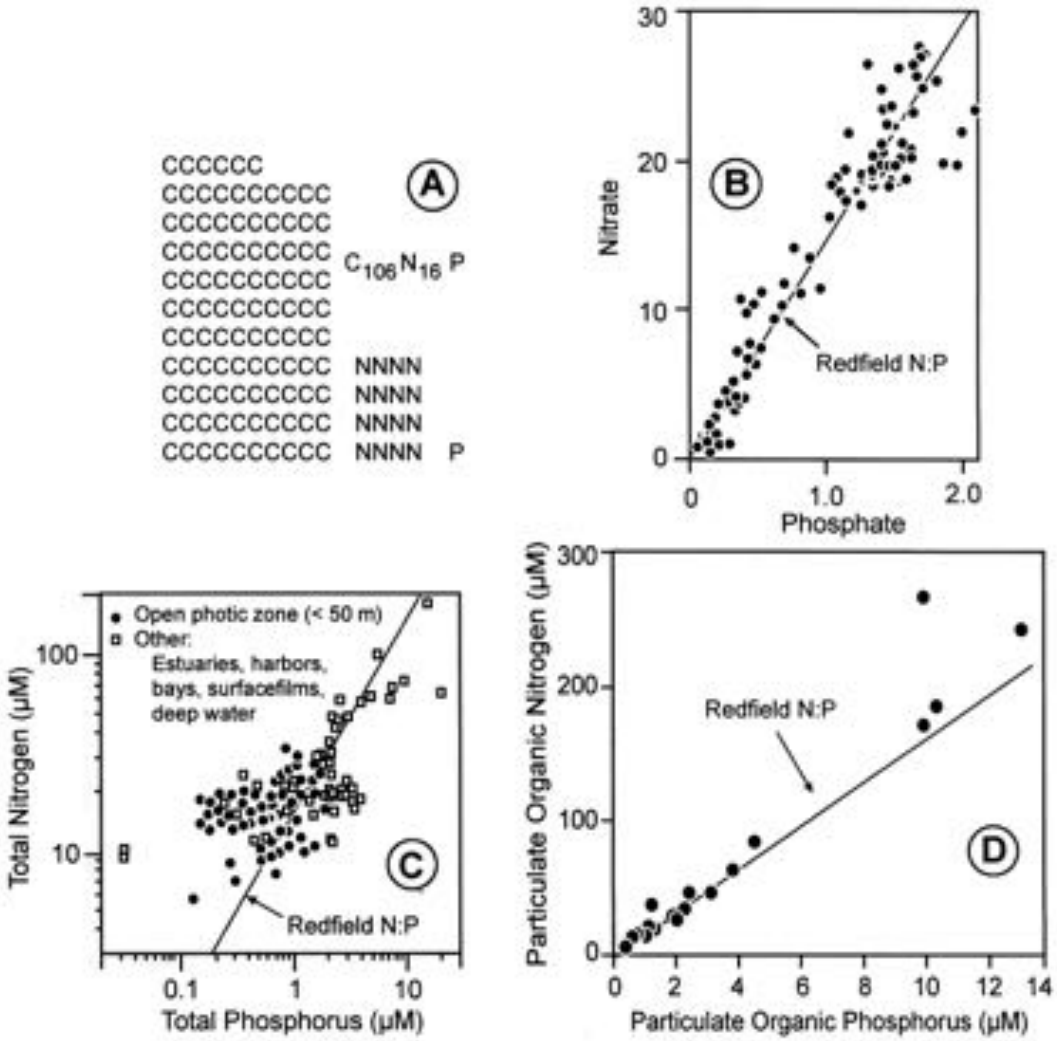
Sterner & Elser 2002

Different biological molecules have fixed stoichiometric proportions

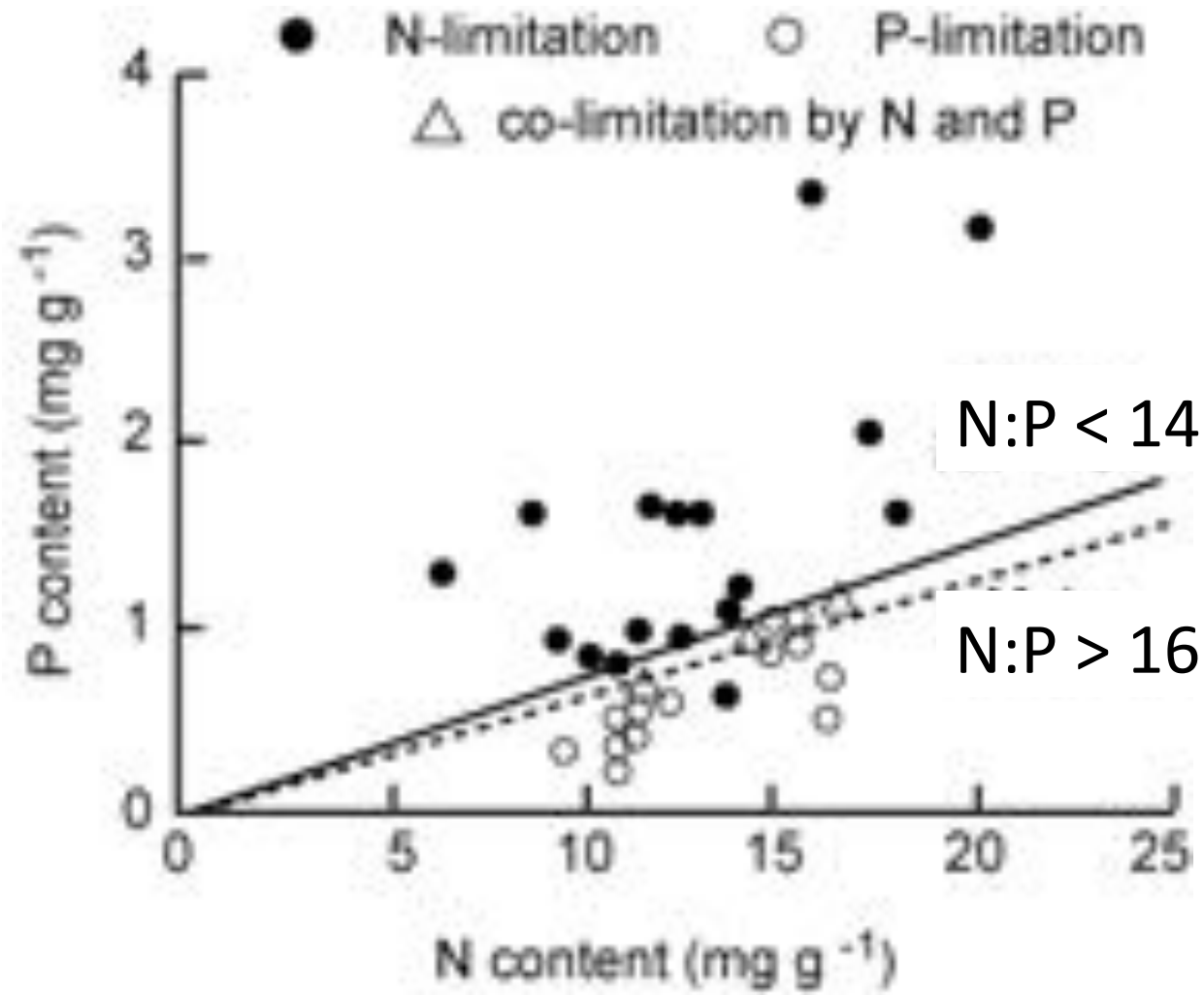


Sterner & Elser 2002

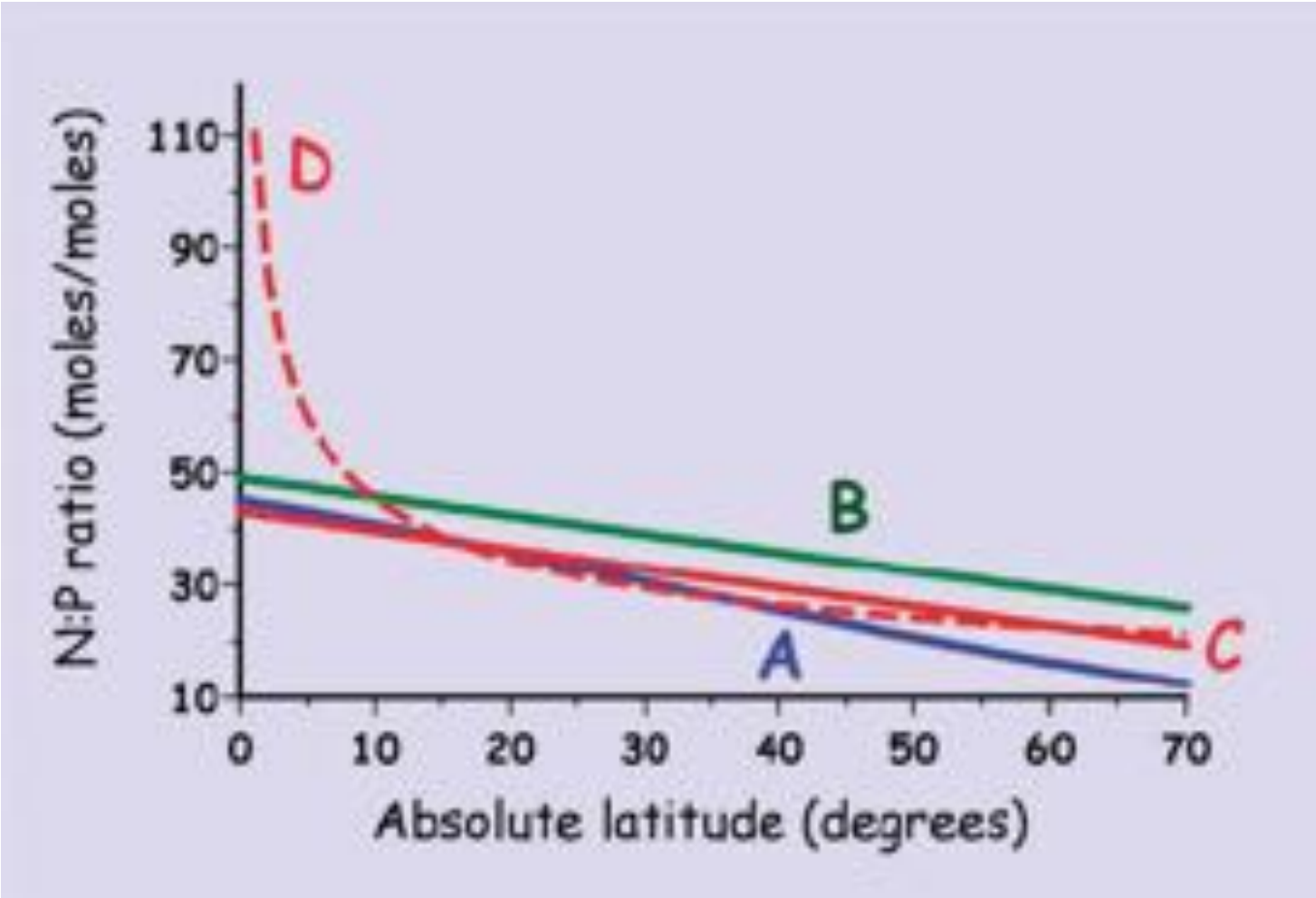
C, N, and P can be found in constant proportions in the oceans



N:P ratios might be indicators of nutrient limitation in terrestrial ecosystems

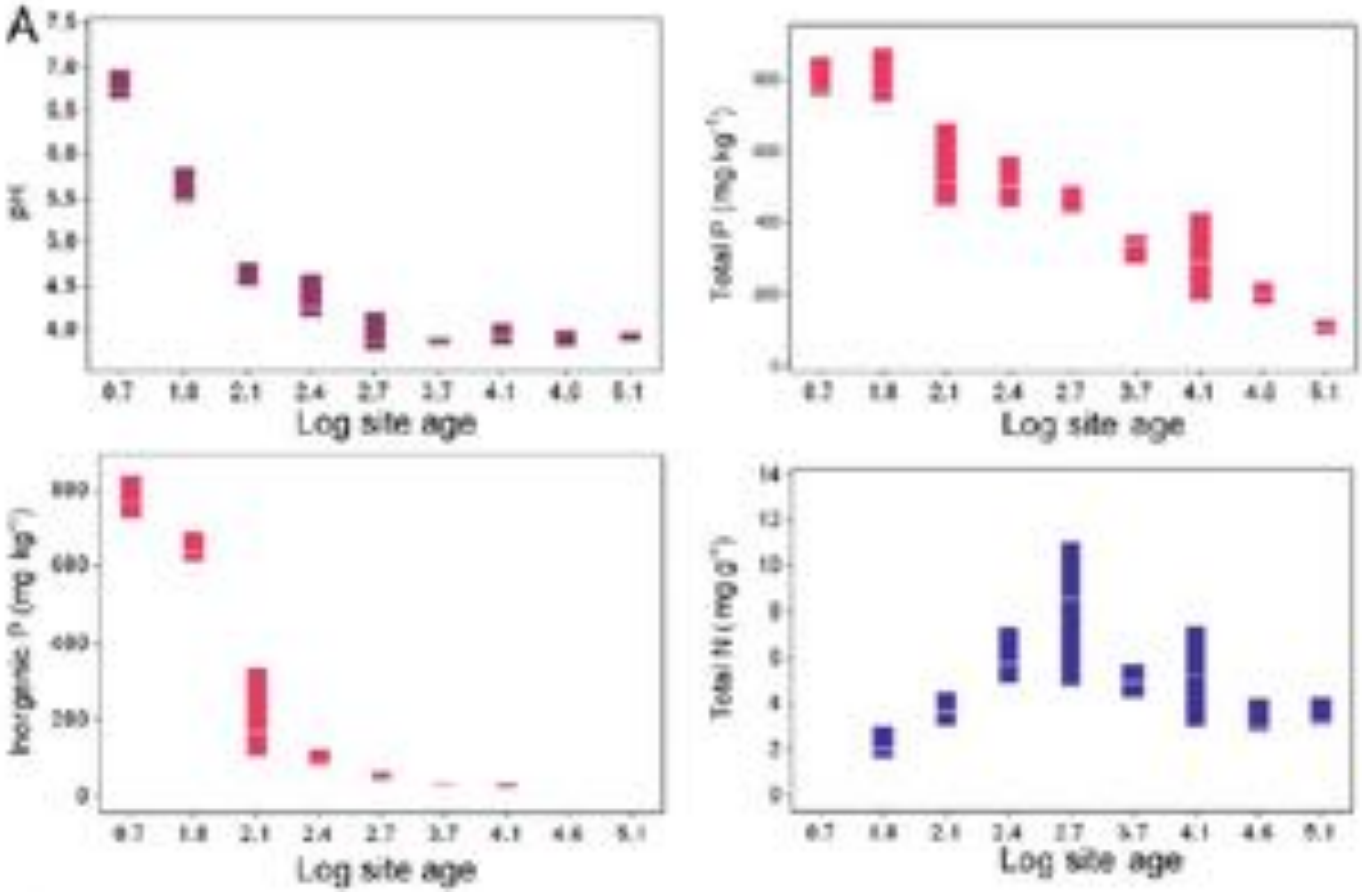


N:P ratios appear to indicate P limitation in tropical ecosystems



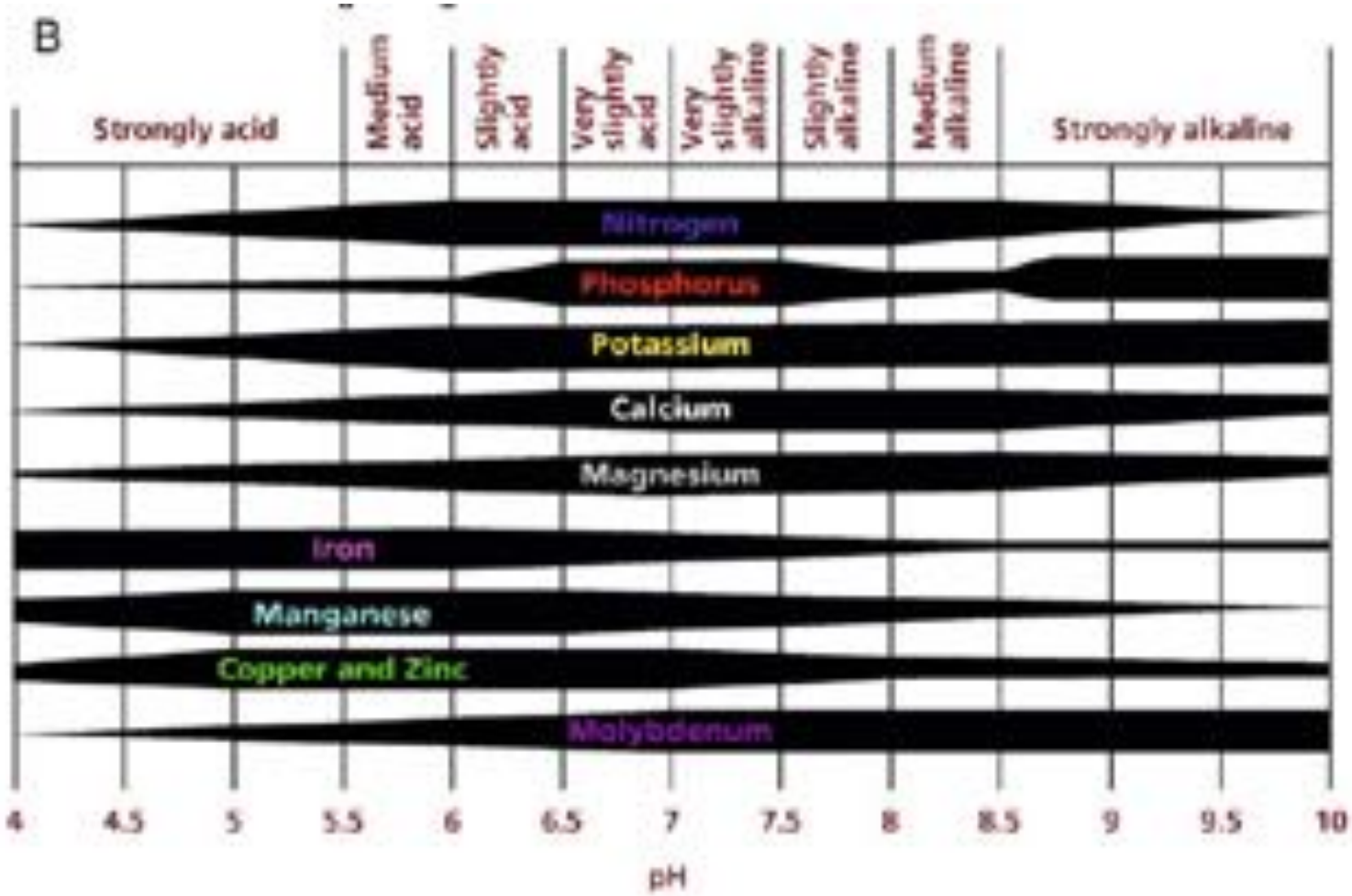
Hedin 2004

Soil nutrients change with soil development

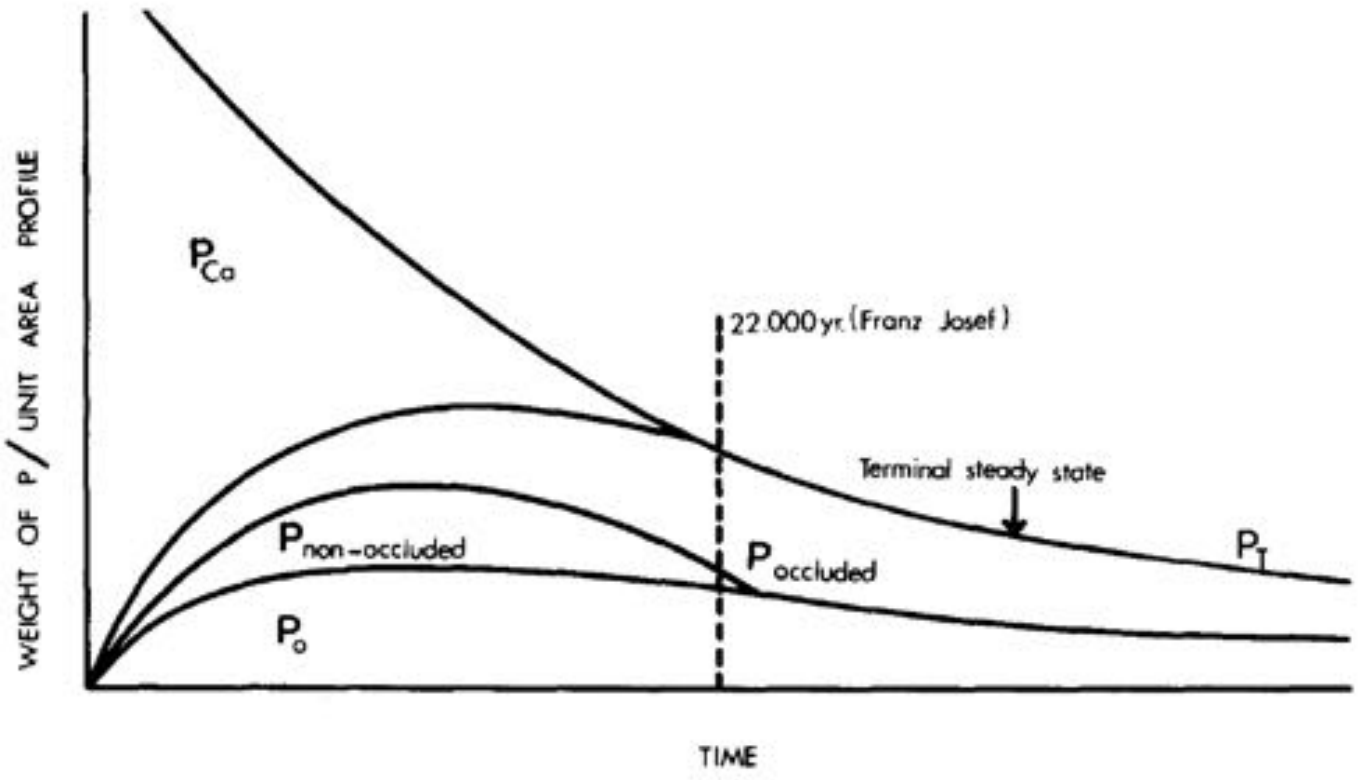


Lambers et al. 2008

Soil pH and nutrient concentrations



Phosphorus in soils decreases with time



Walker & Syers 1976

Test of the Walker & Syers' model in a long-term chronosequence in Hawaii

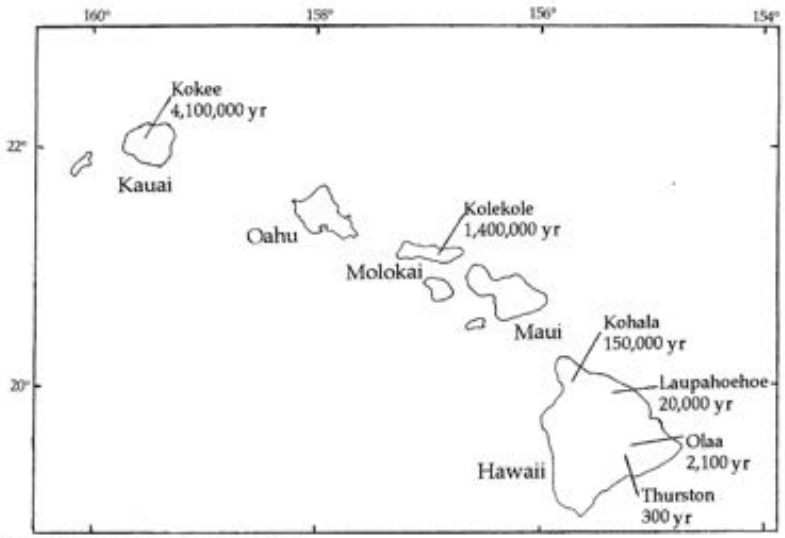
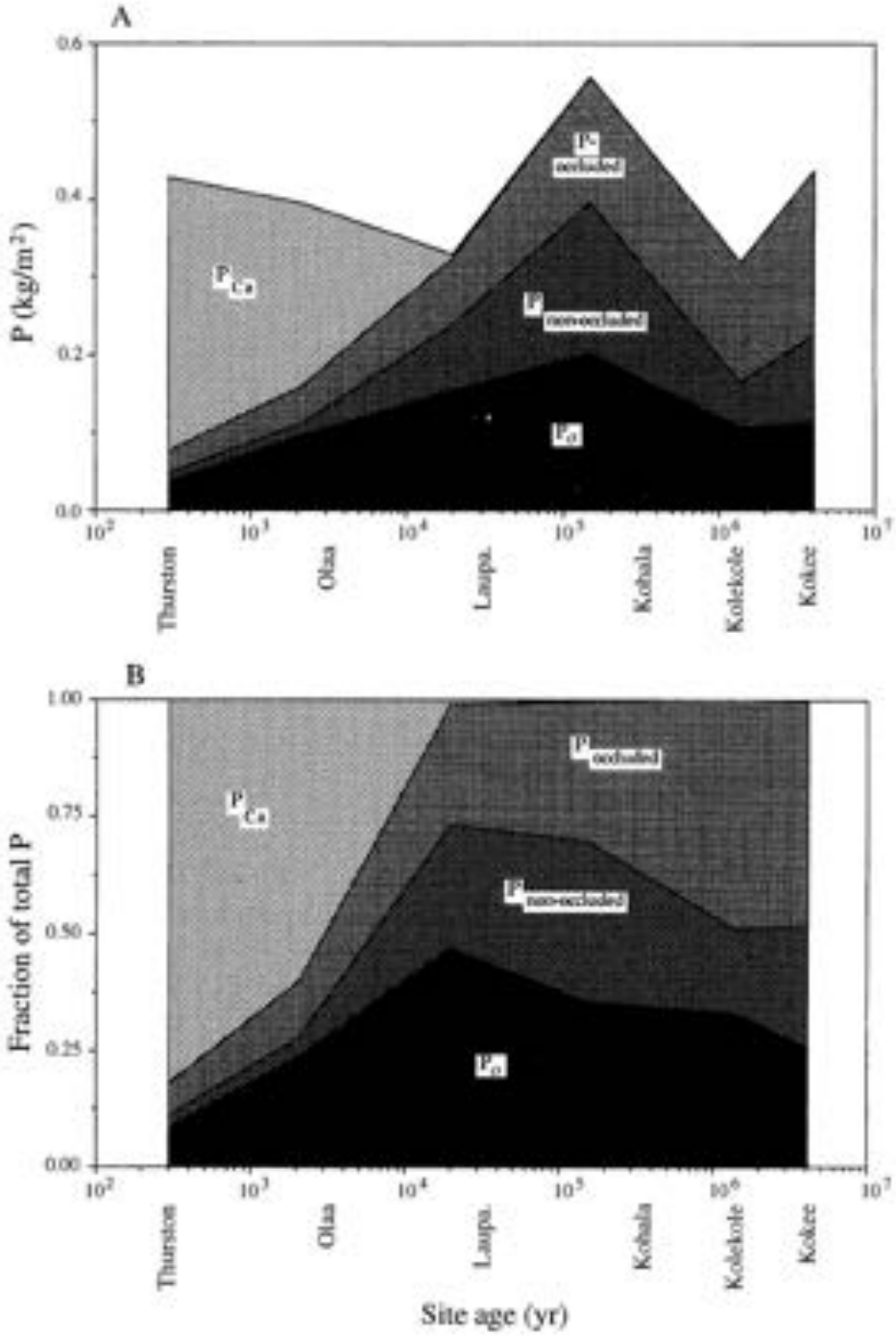


TABLE 1. Hawaiian chronosequence: site descriptions.

Site	Parent material age (10^3 yr)	Elevation (m)	Approx. mean annual temp. (°C)	Approx. mean annual precip. (mm)	Soil classification	Location
Thurston	0.3	1176	16	2500	Hydric Dystrandept	Hawaii Volcanoes National Park
Olaa	2.1	1200	16	2500	Typic Hydrandept	Hawaii Volcanoes National Park
Laupahoehoe	20	1170	16	2500	Typic Hydrandept	Laupahoehoe Forest Reserve
Kohala	150	1122	16	2500	Typic Placandept	Kohala Forest Reserve
Kolekole	1,400	1210	16	2500	Petroferric Acrohumox	Nature Conservancy Kamakou Preserve
Kokee	4,100	1134	16	2500	Plinthic Acrudox	Napali-Kona Forest Reserve

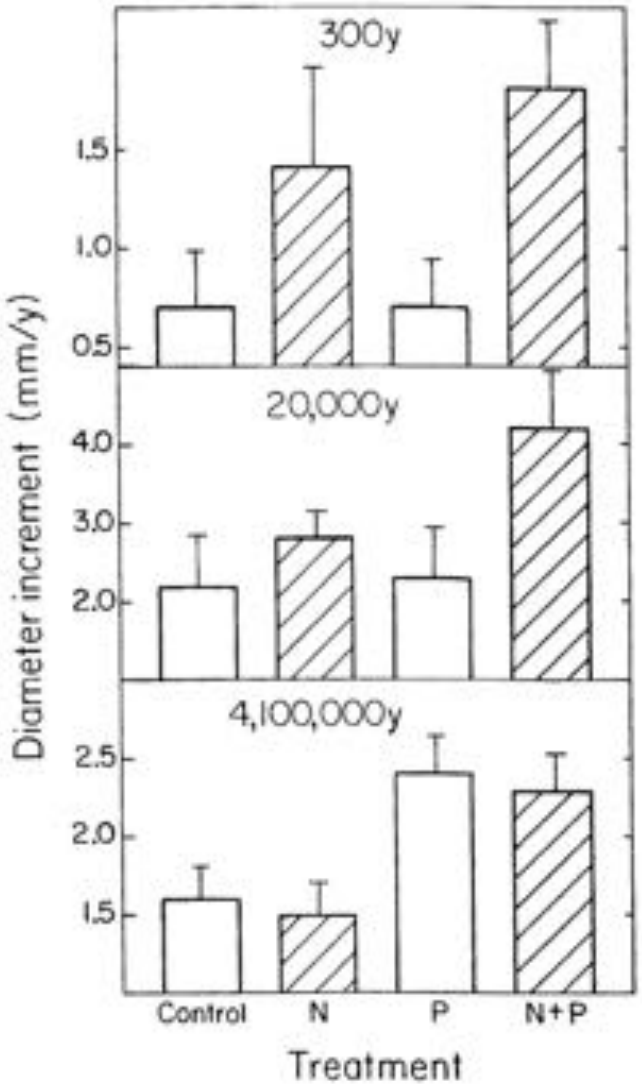
Crews et al. 1995

Test of the Walker & Syers' model in a long-term chronosequence in Hawaii



Crews et al. 1995

Changes in nutrient limitation with soil development

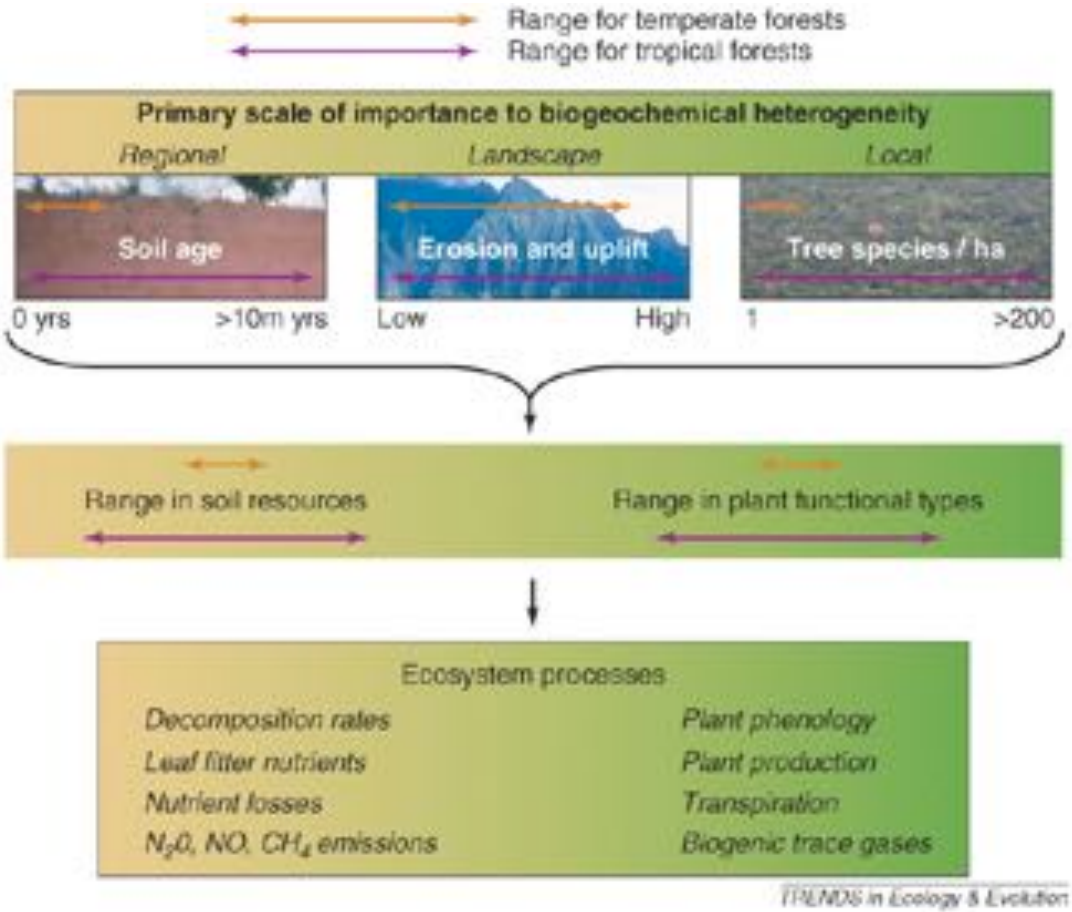


Vitousek & Farrington 1997

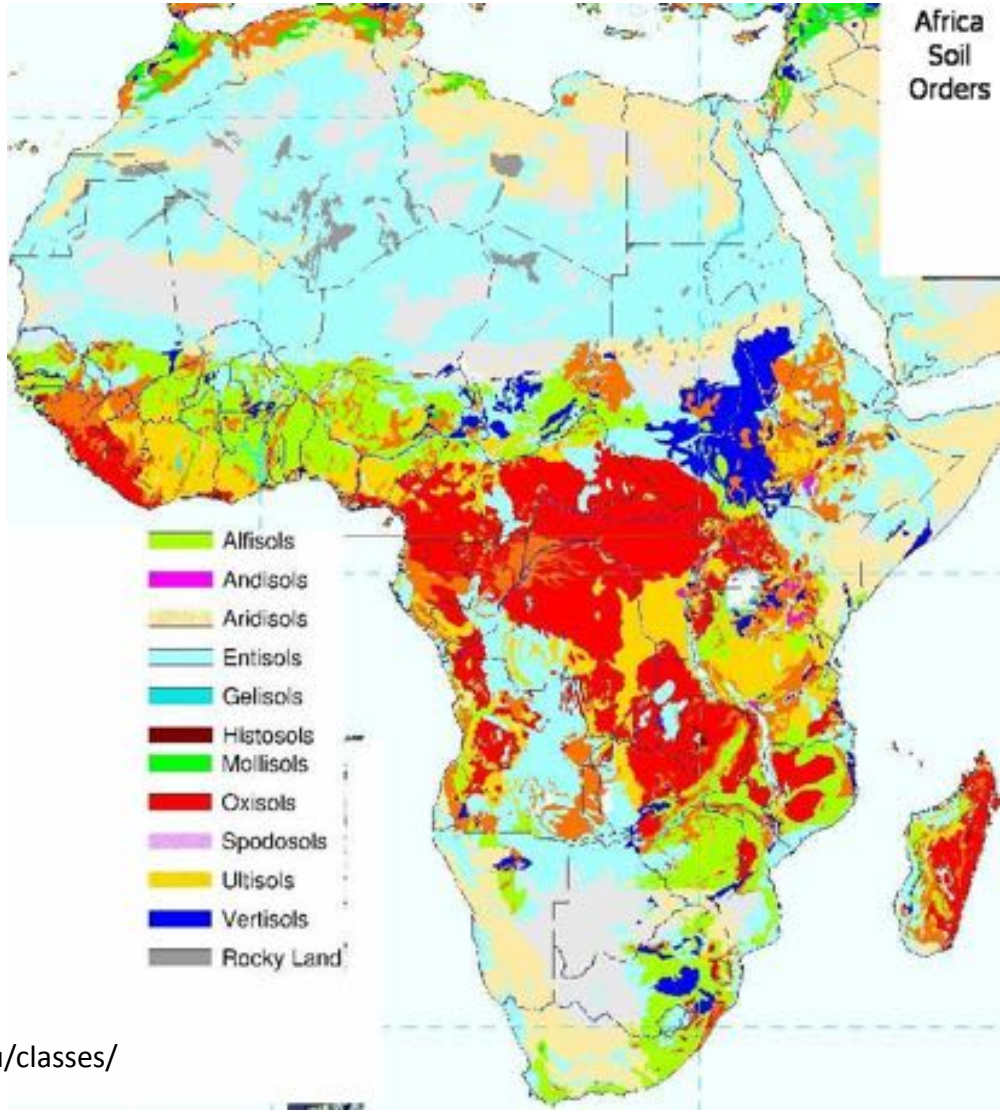
Take home messages

- Nitrogen and phosphorus are the main nutrients that control plant growth
- N and P limits plant production in a synergistic fashion. Additions of N must be balanced by more P and vice versa.
- P limitation is related to soil development. As a consequence tropical forests are believe to be P limited.

The biogeochemical heterogeneity of the tropical biome



Soils of Africa



Source: http://www.swac.umn.edu/classes/soil4505/doc/unit10af.htm

USDA soil orders and soil development

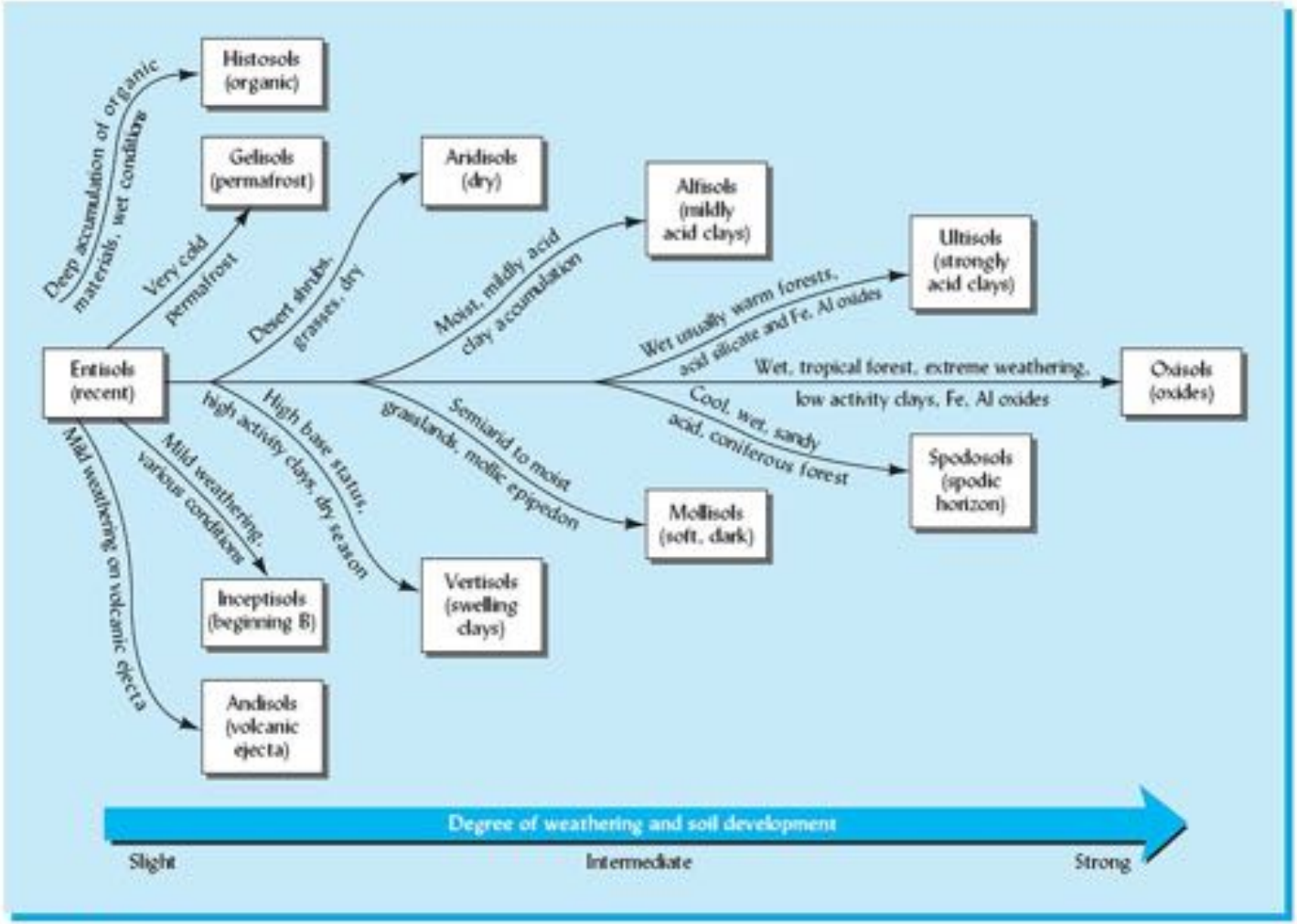
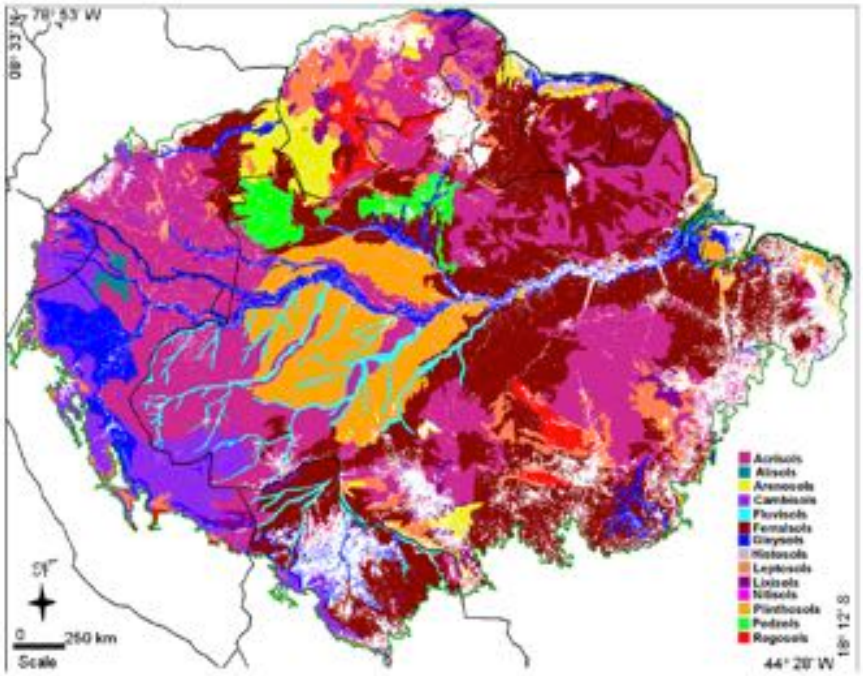
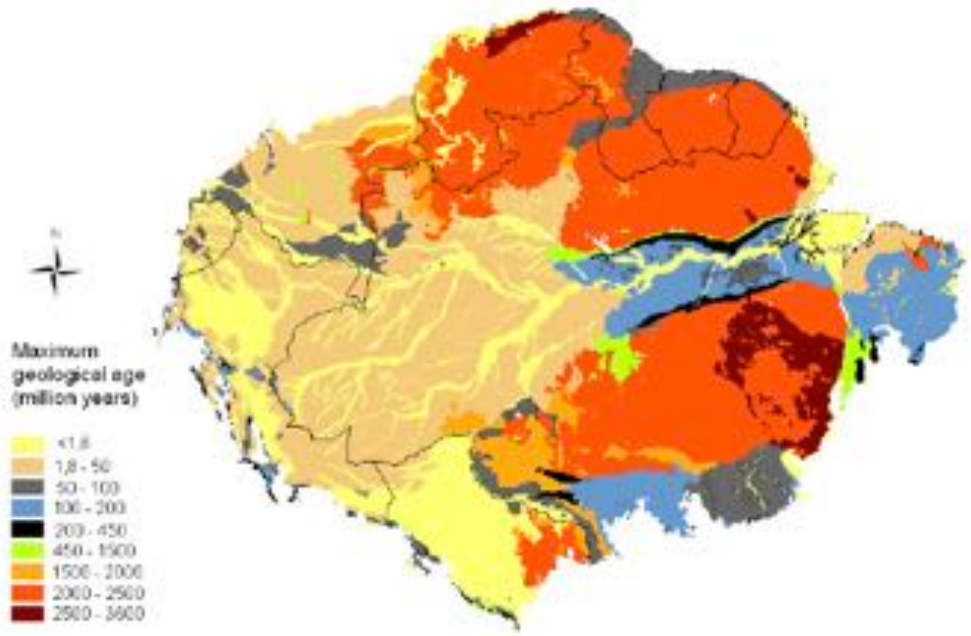


FIGURE 3.8 Diagram showing general degree of weathering and soil development in the different soil orders classified in *Soil Taxonomy*. Also shown are the general climatic and vegetative conditions under which soils in each order are formed.

Soils of the Amazon basin





Quesada et al. 2011

Soil development in the Amazon

Fig. 20. Simplified scheme for soil development in Amazonia.

Oxisols (USDA) or Ferralsols (WRB)

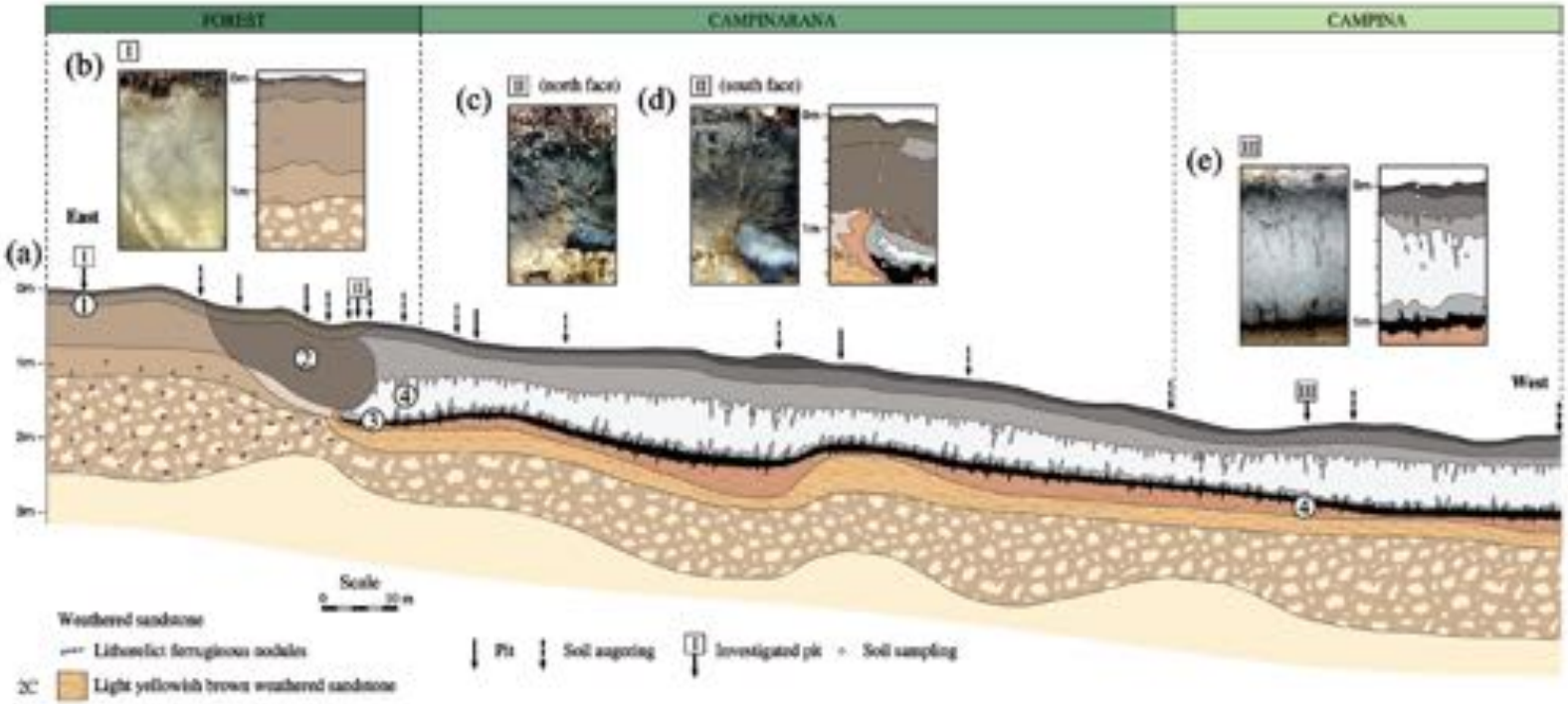
- Highly weathered
- High clay content but of low activity (1:1-type)
- Deep soils > 20m
- Good drainage
- Low natural fertility
- High concentrations of Fe and Al oxides
- Moderately acid

Ultisols (overlaps with Plinthosols)

- Highly weathered
- Clay weathering and translocation
- Acid B horizon with < 35% CEC
- No calcareous material
- < 10% weatherable minerals in topsoil

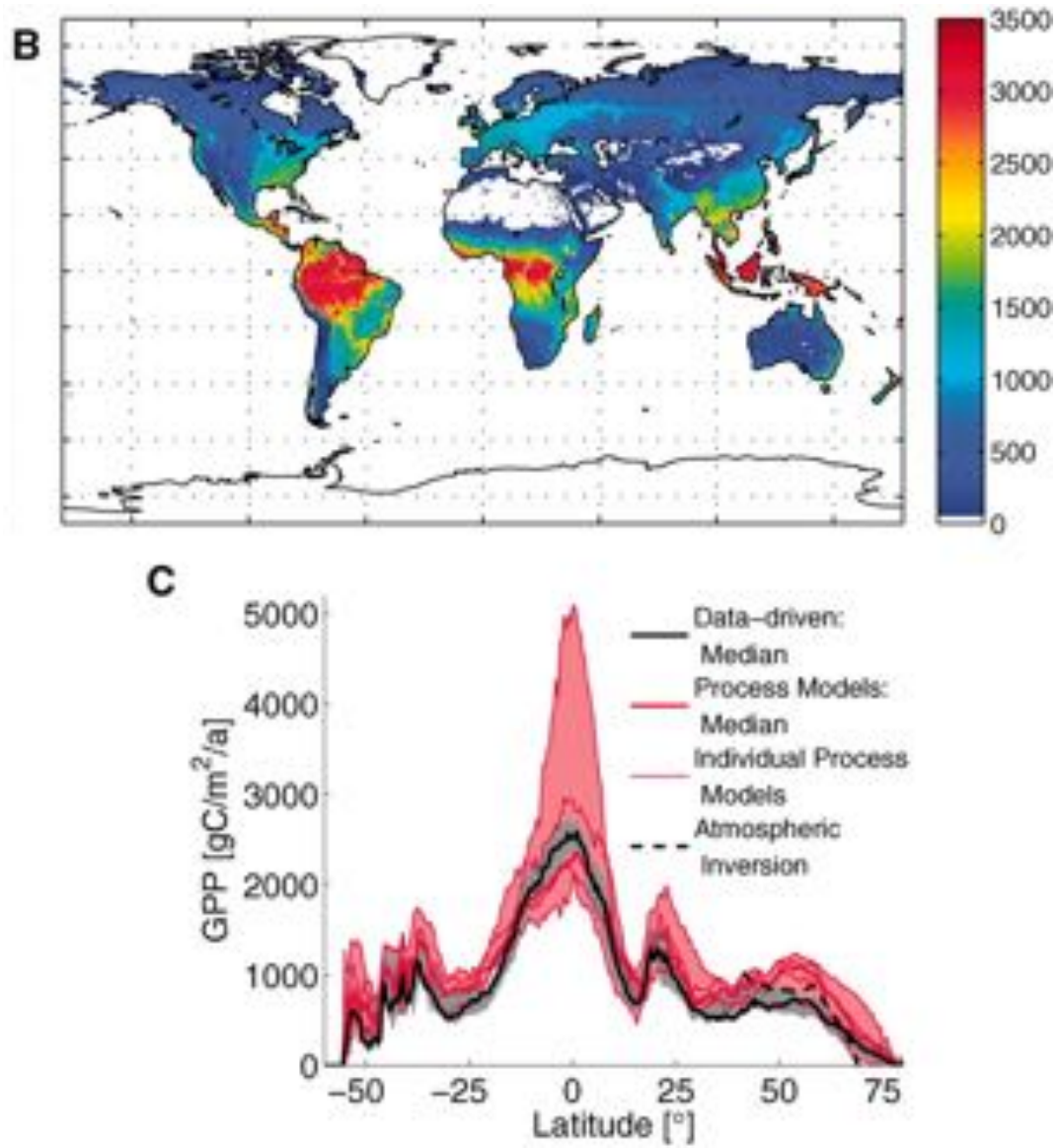
Spodosolos (Podzols)

- Intensive acid leaching
- Subsurface horizon with illuviation of organic matter
- White-sand horizon of eluviation
- Some of the most nutrient poor forest in the tropics



do Nascimento et al. (2004)

But tropical forests are supposed to be the most productive ecosystems on Earth!



Beer et al. 2010

Tropical forest paradox

„The tropical rainforest thus has a relatively rich nutrient economy perched on a nutrient-poor substrate“

Whittaker 1975

Primary productivity is controlled by the availability and the efficiency of resources

$$NPP = \min\{L \cdot LUE, N \cdot NUE, W \cdot WUE\}$$

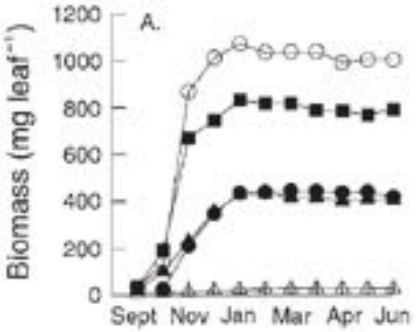
$$L = Light$$
$$N = Nutrients$$
$$W = Water$$

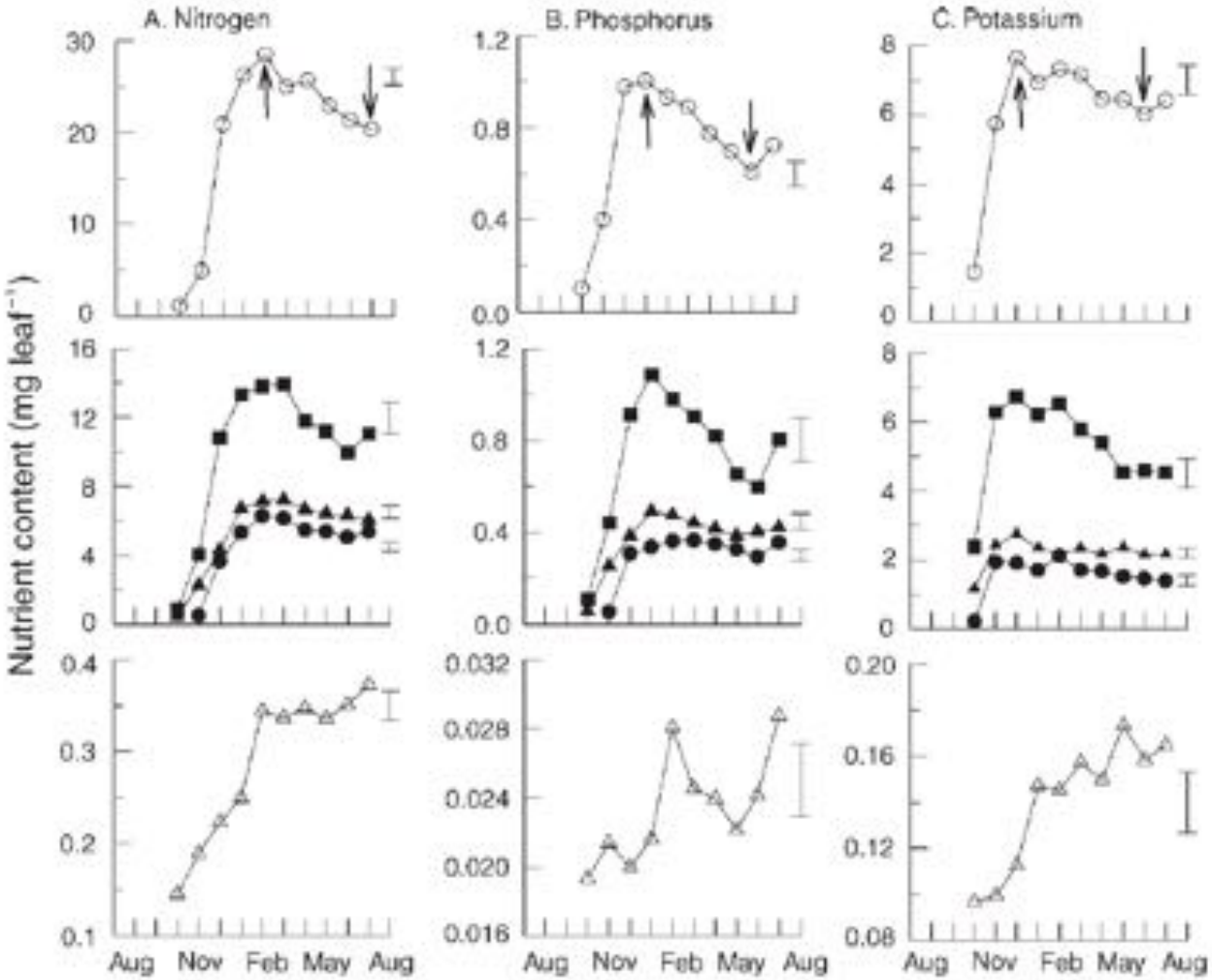
Agren & Andersson 2012

Strategies to increase NUE in tropical forests

- Retranslocation
- N-fixation and symbiotic associations
- Root mats

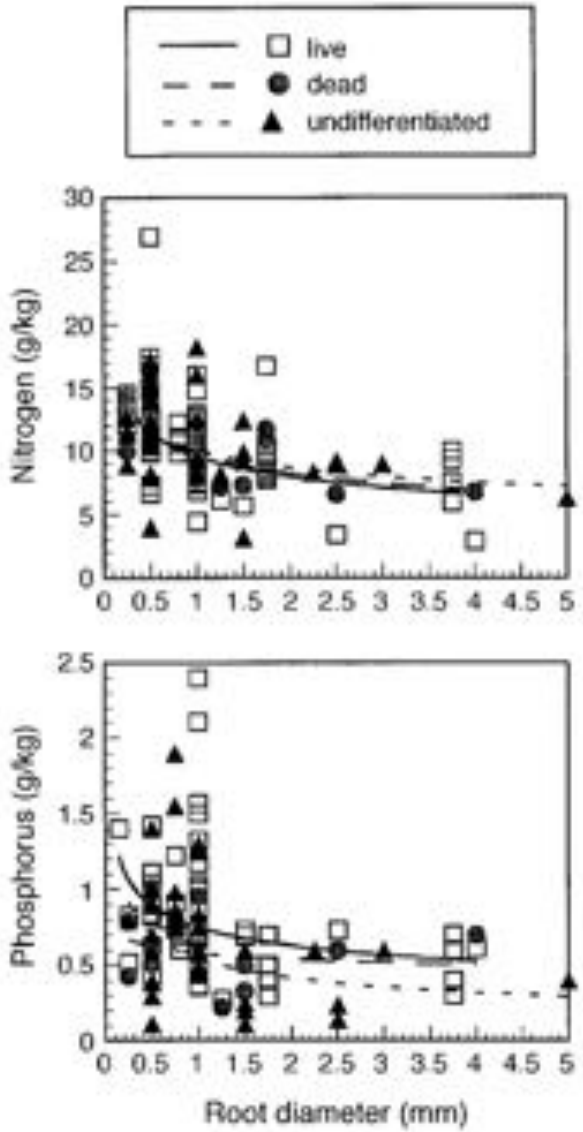
Limiting nutrients are retranslocated before leaf abscission





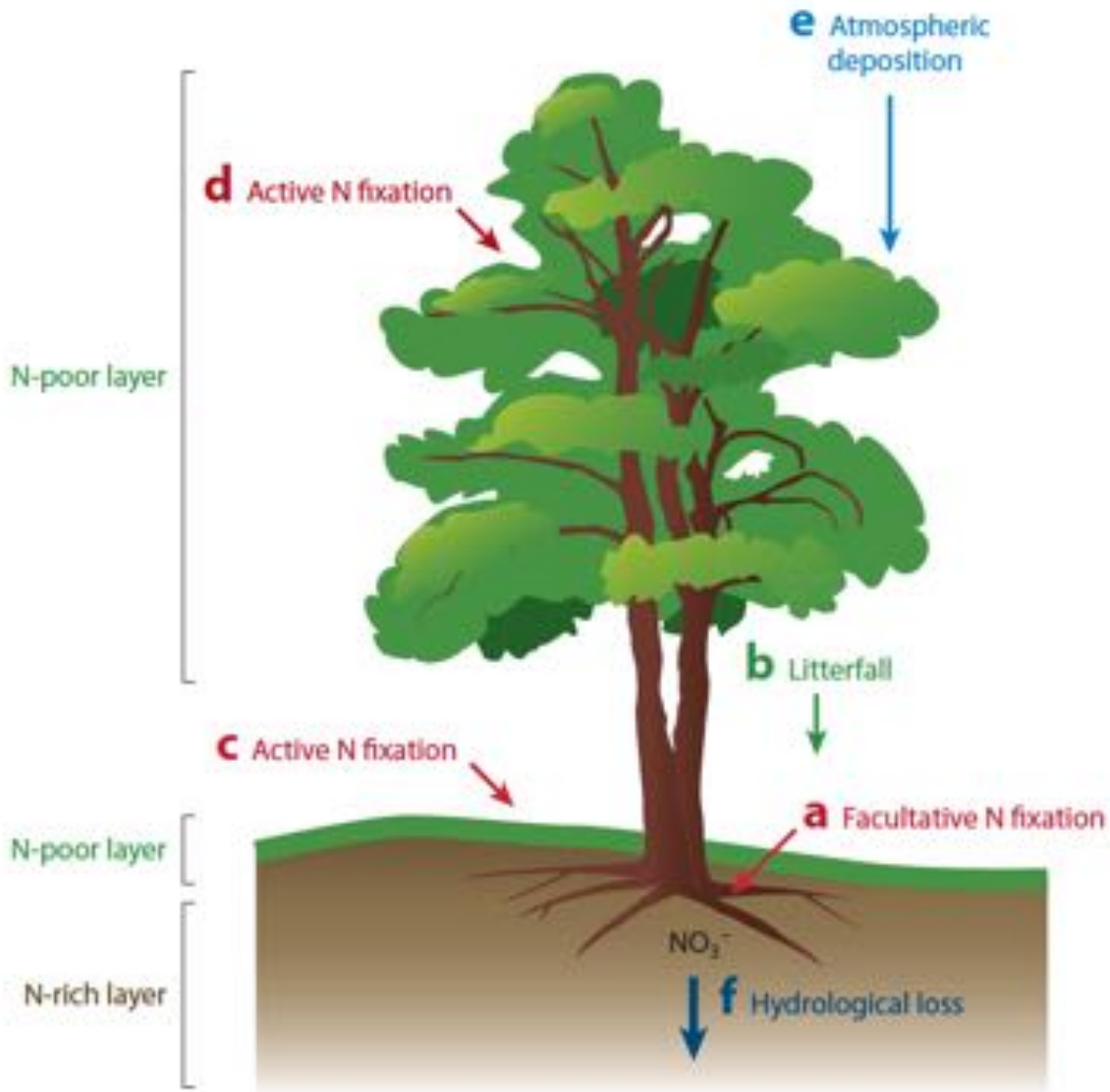
Fife et al. 2003

Roots do not appear to retranslocate nutrients



Gordon & Jackson 2000

N fixation in tropical forests



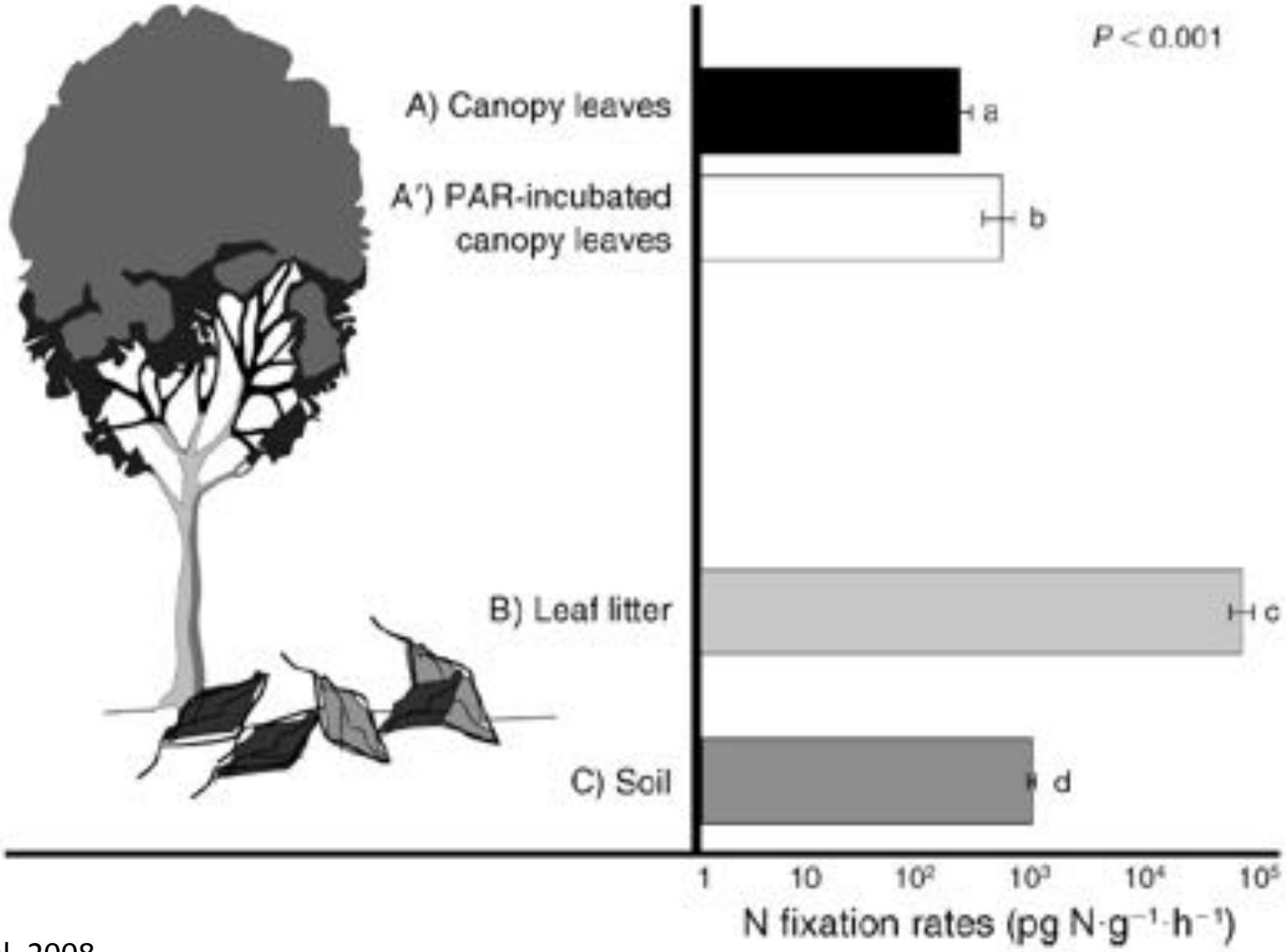
Hedin et al. 2009

N-fixing organisms

Table 9.1 Organisms and associations involved in di-nitrogen fixation

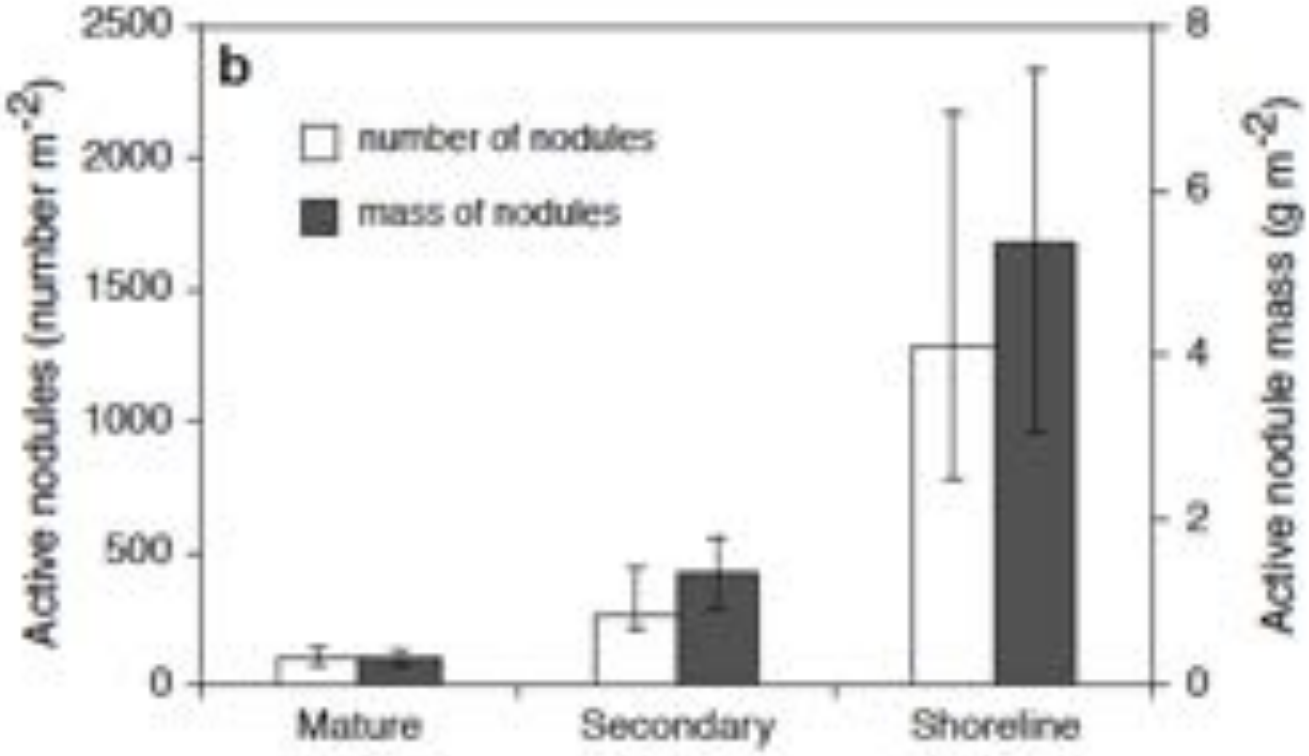
Type of association*	Key characteristics	Representative genera
Heterotrophic N fixers		Bacteria
Associative		
Nodulated (symbiotic)	Legume	*Rhizobium*
	Nonlegume woody plants	*Frankia*
Non-nodulated	Rhizosphere	*Azotobacter, Bacillus*
	Phyllosphere	*Klebsiella*
Free-living	Aerobic	*Azotobacter, Rhizobium*
	Facultative aerobic	*Bacillus*
	Anaerobic	*Clostridium*
Phototrophic N fixers		Cyanobacteria
Associative	Lichens	*Nostoc, Calothrix*
	Liverworts (*Marchantia*)	*Nostoc*
	Mosses	*Holosiphon*
	Gymnosperms (*Cycas*)	*Nostoc*
	Water fern (*Azolla*)	*Nostoc*
Free-living	Cyanobacteria	*Nostoc, Anabaena*
	Purple non-sulfur bacteria	*Rhodospirillum*
	Sulfur bacteria	*Chromatium*

Free-living N fixers in a tropical forest



Reed et al. 2008

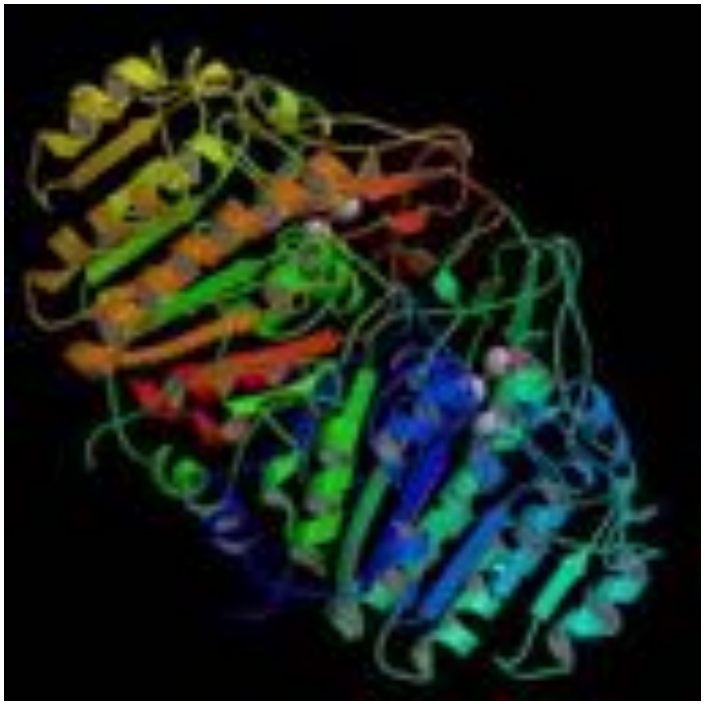
Legumes are important N-fixers, but not always, not everywhere

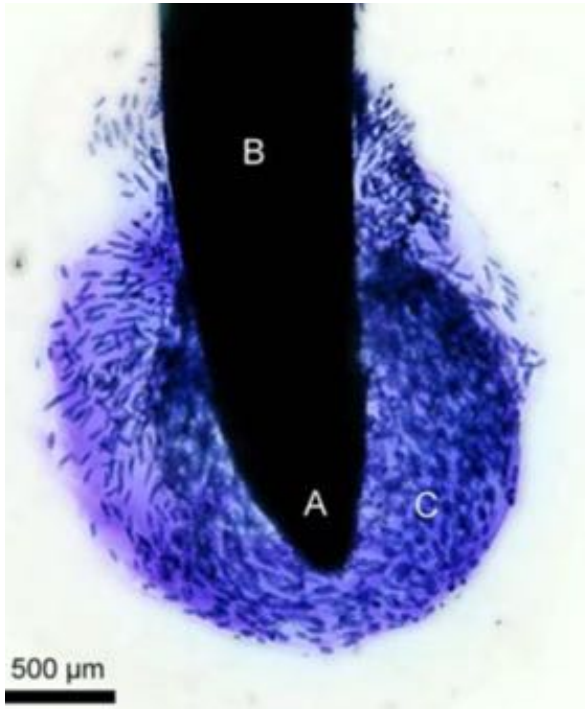


Barron et al. 2010

Roots release organic substances (chelates and phosphatases) to mineralize P

$$R{-}OPO_3^{2-} + H_2O \longrightarrow R{-}OH + H^+ + PO_4^{3-}$$





Root-mats

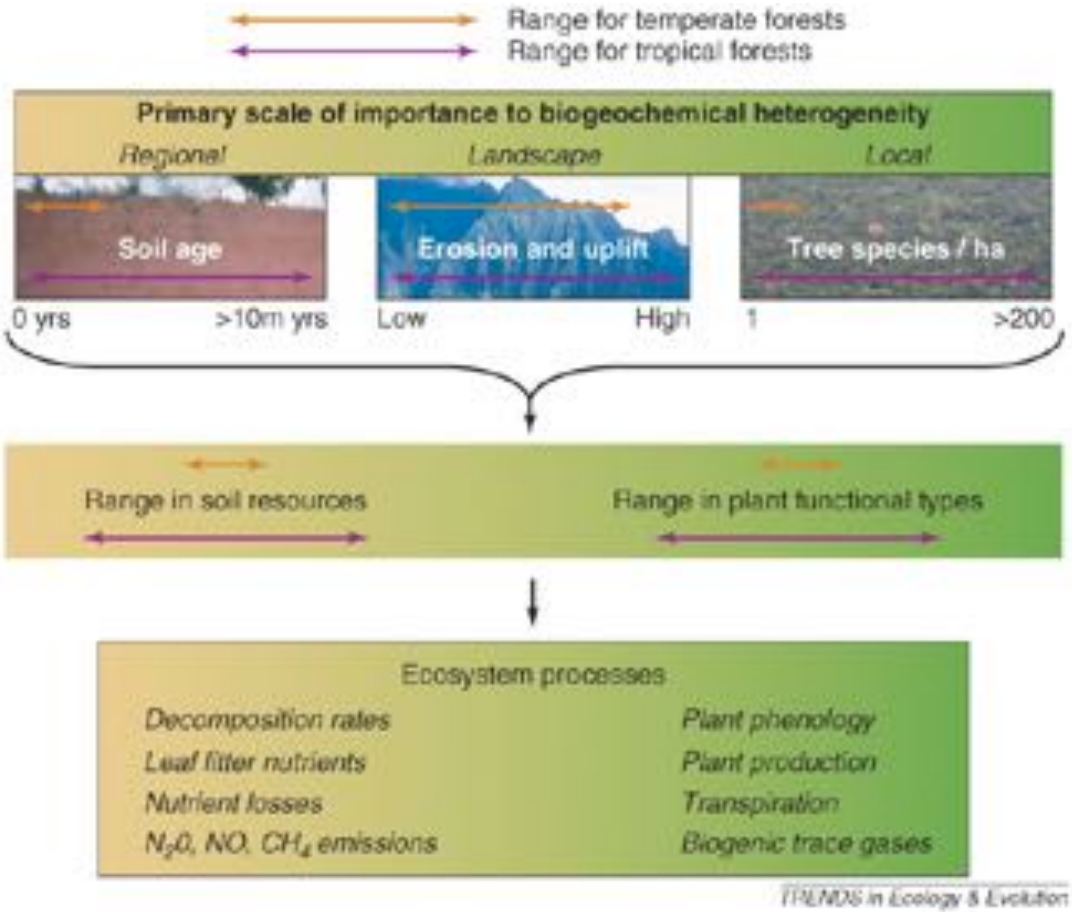
Jordan & Escalante 1980

Strategies to increase NUE in tropical forests

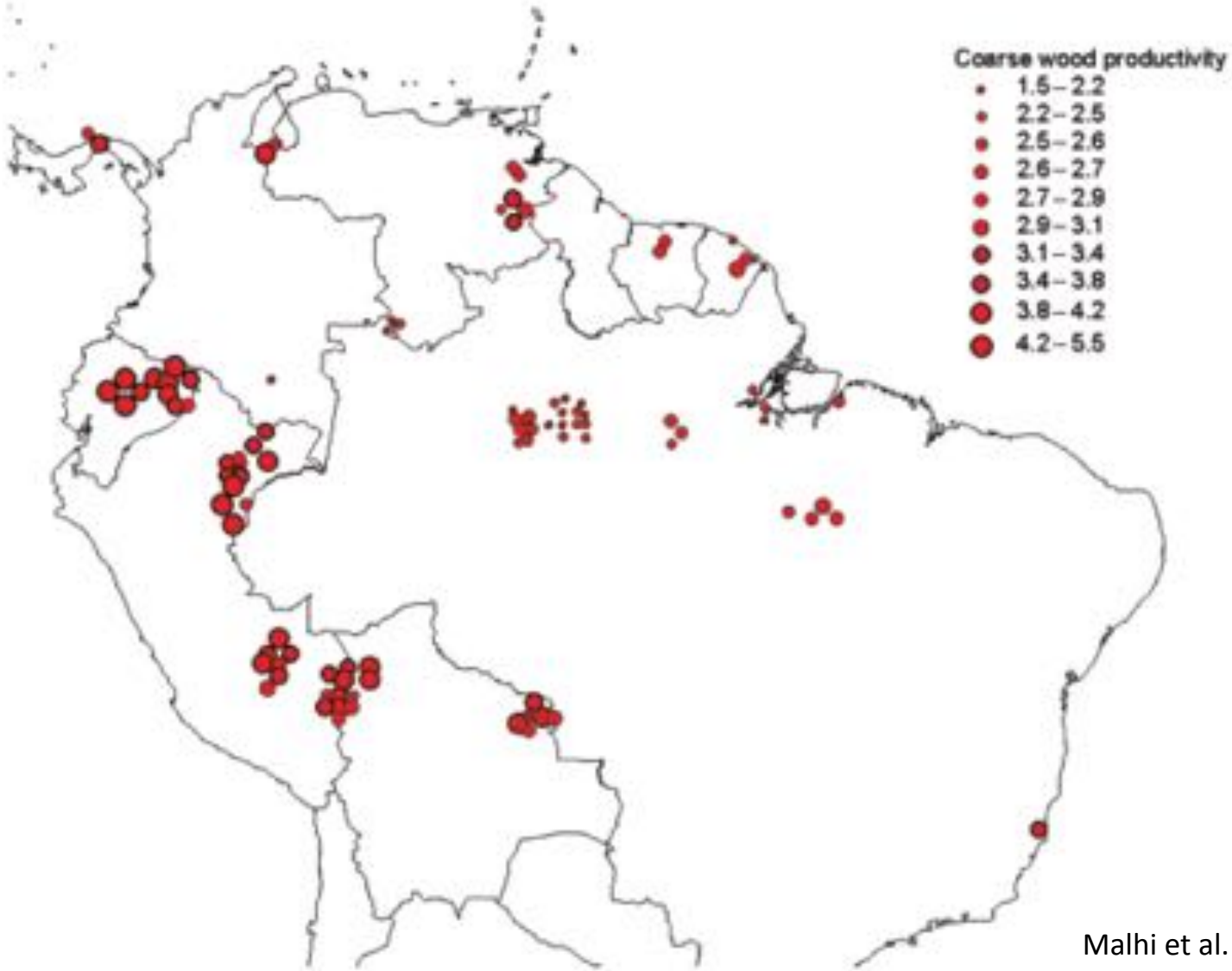
- Retranslocation
- N-fixation and symbiotic associations
- Root mats

- Long-lived tissue (leaves)
- Defense compounds against herbivory
- Adjust shoot to root ratios

The biogeochemical heterogeneity of the tropical biome

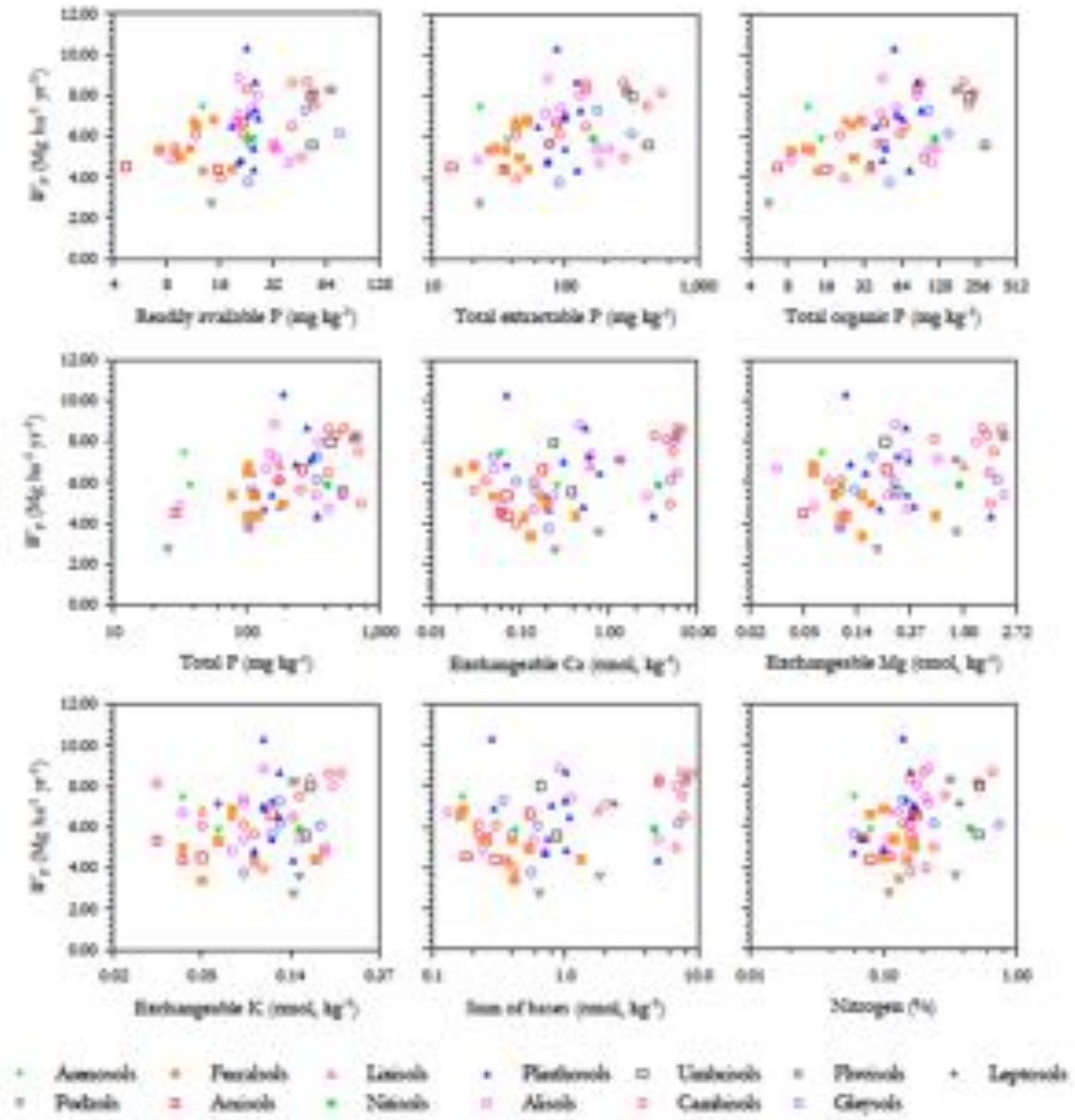


Wood productivity seems related to soil age in the Amazon basin

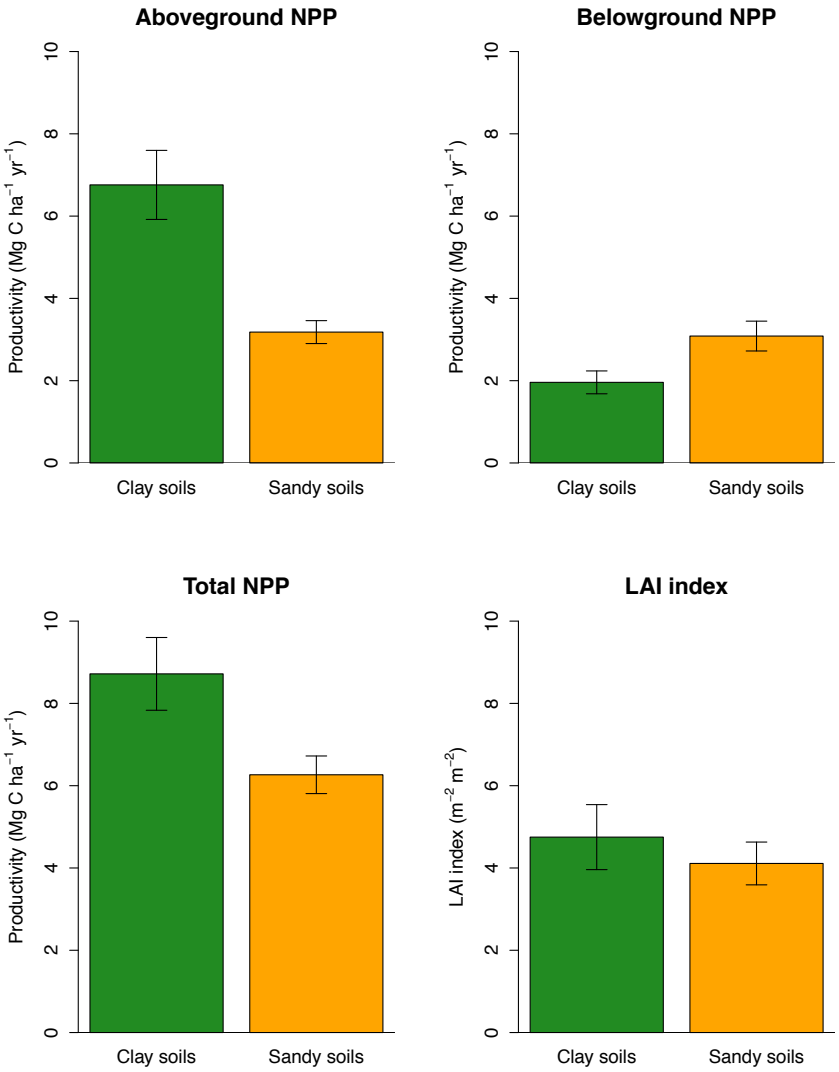


Malhi et al. 2004

Soil P may explain differences in aboveground wood production



But aboveground NPP may not tell us the whole story



Jimenez et al. 2014

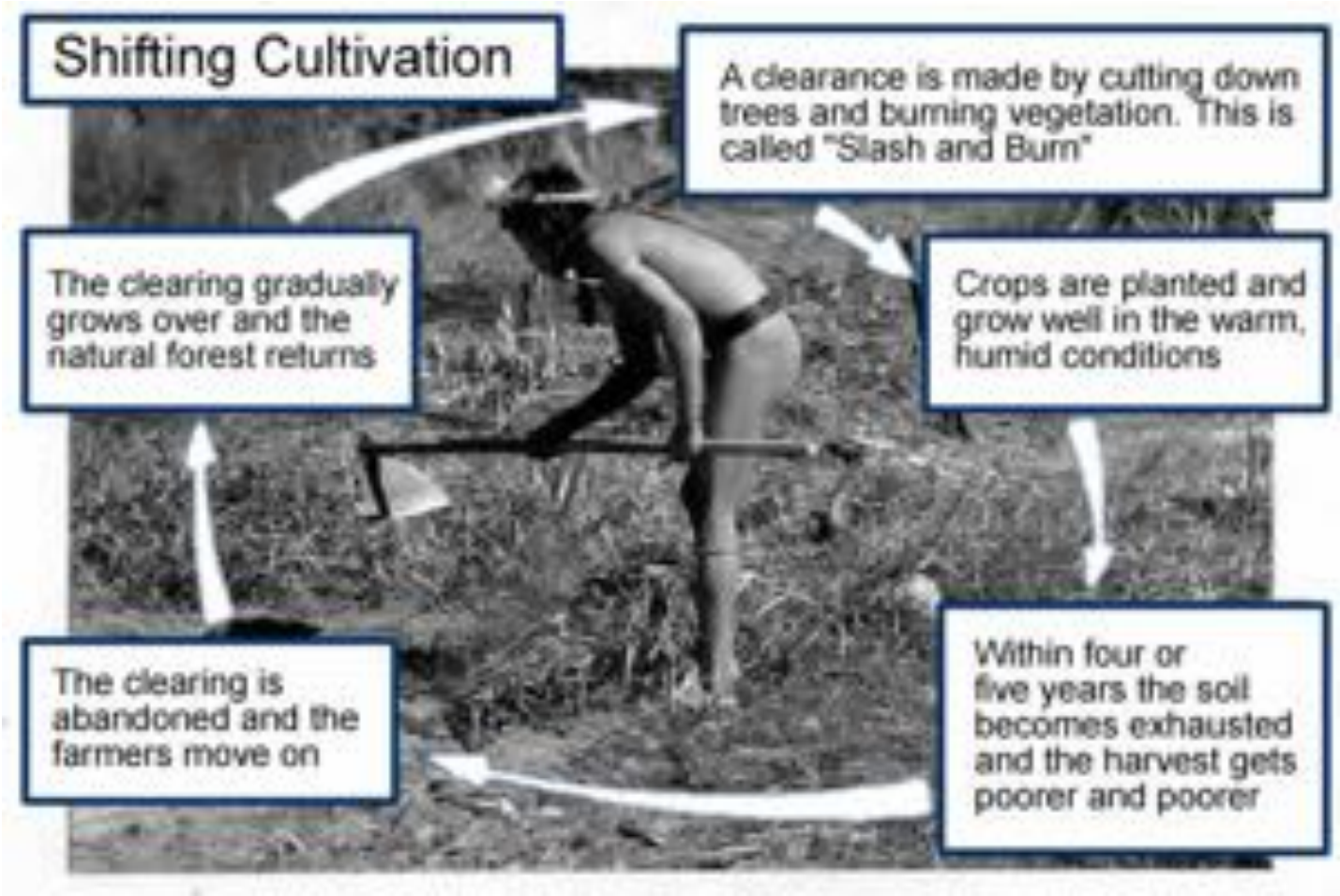
Take-home message

- The tropical biome is highly diverse in its biogeochemistry, but most regions have highly weathered soils
- Highly weathered soils suggest P limitation in these forests, however they are still highly productive
- This paradox can be resolved in terms of the efficiency of nutrient use

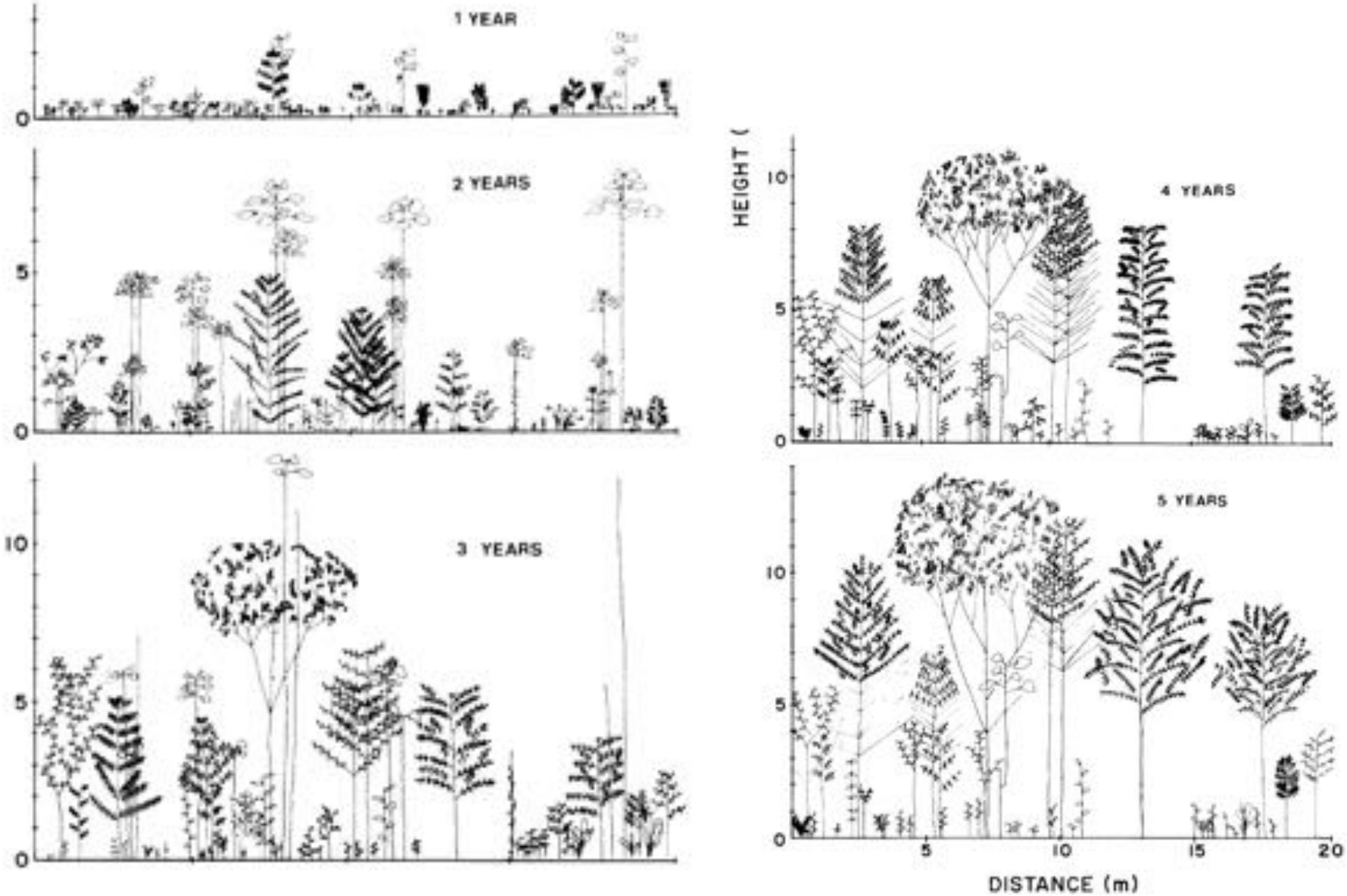
Humans and the cycling of nutrients

Shifting cultivation

Shifting cultivation



Ecosystem recovery after slash-and-burn



Uhl & Jordan 1984

Ecosystem recovery after slash-and-burn

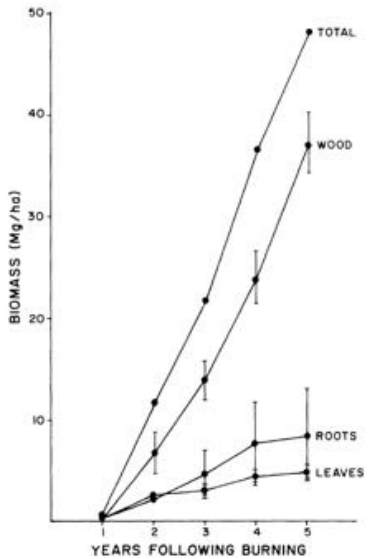
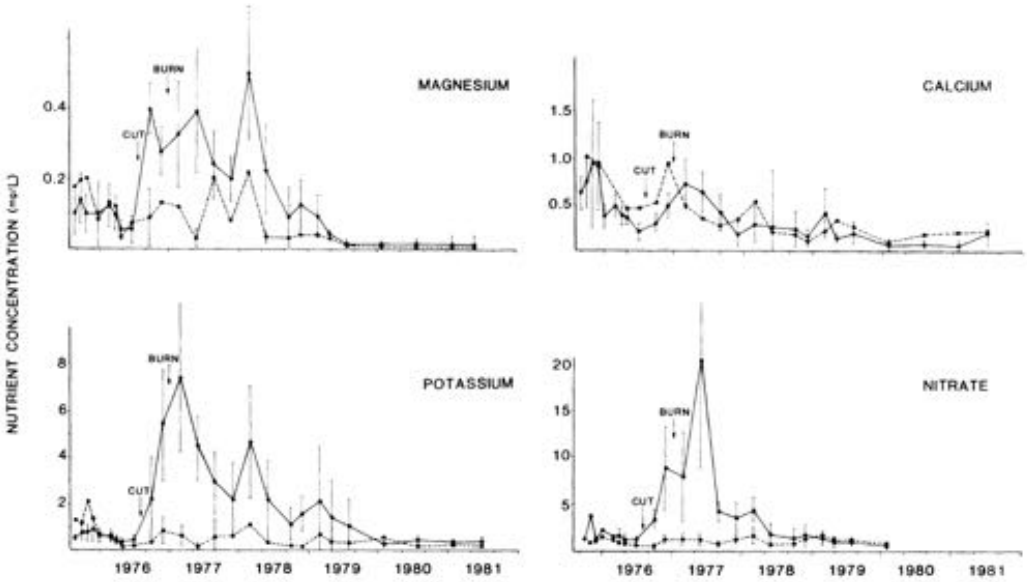


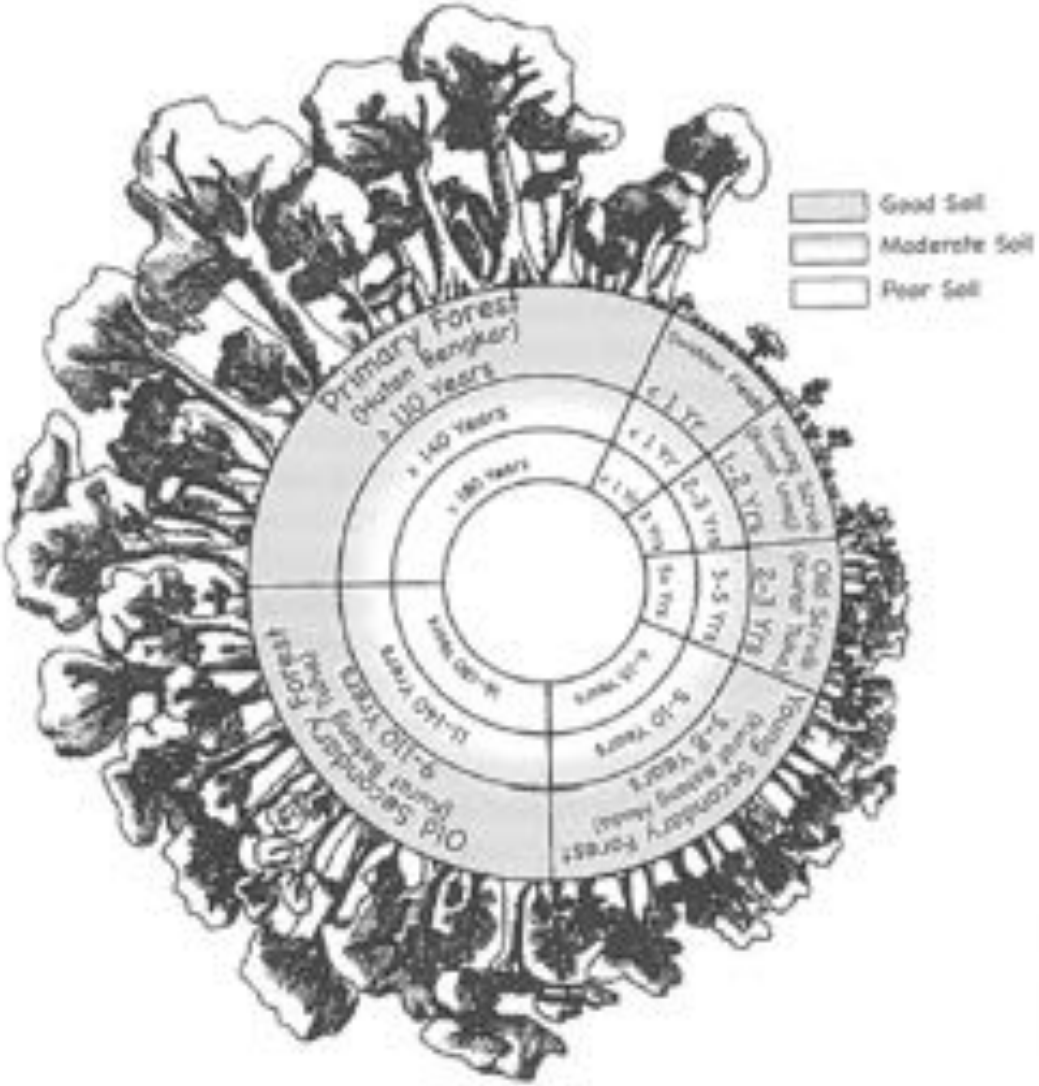
TABLE 6. Plant dry mass and nutrient standing stocks in ecosystem organic matter compartments on a mature forest stand near San Carlos de Río Negro, Venezuela, and on that same plot (i.e., the intensive study site) 5 yr after forest cutting and burning.

	Plant dry mass	N	P	K	Ca	Mg
	Kilograms per hectare					
Pre-burn forest*:						
Leaves	8,647	160	5.1	37.7	11.5	6.1
Stems†	252,318	785	26.0	207.2	194.1	49.3
Roots	48,525	540	17.1	43.1	45.4	11.6
Fine litter	7,650	109	2.1	8.3	3.4	1.9
Dead wood	21,200	128	1.1	3.4	6.6	2.5
Total	338,340	1,722	51.4	299.7	261.0	71.4
5-yr-old regrowth forest:						
Leaves	4,920	103	4.9	21.4	25.2	8.4
Stems†	35,170	65	3.5	58.0	70.7	18.3
Roots	8,350	61	2.7	33.7	23.8	3.2
Fine litter	5,180	69	1.6	6.0	30.8	13.9
Dead wood‡	68,762	443	4.2	12.8	25.4	9.8
Total	122,382	741	16.9	131.9	175.9	53.6
	Percentage					
Regrowth forest total live plus dead biomass ÷ pre-burn forest total mass	36	43	33	44	67	75
Regrowth forest live biomass ÷ pre-burn forest live biomass	16	15	23	39	48	45



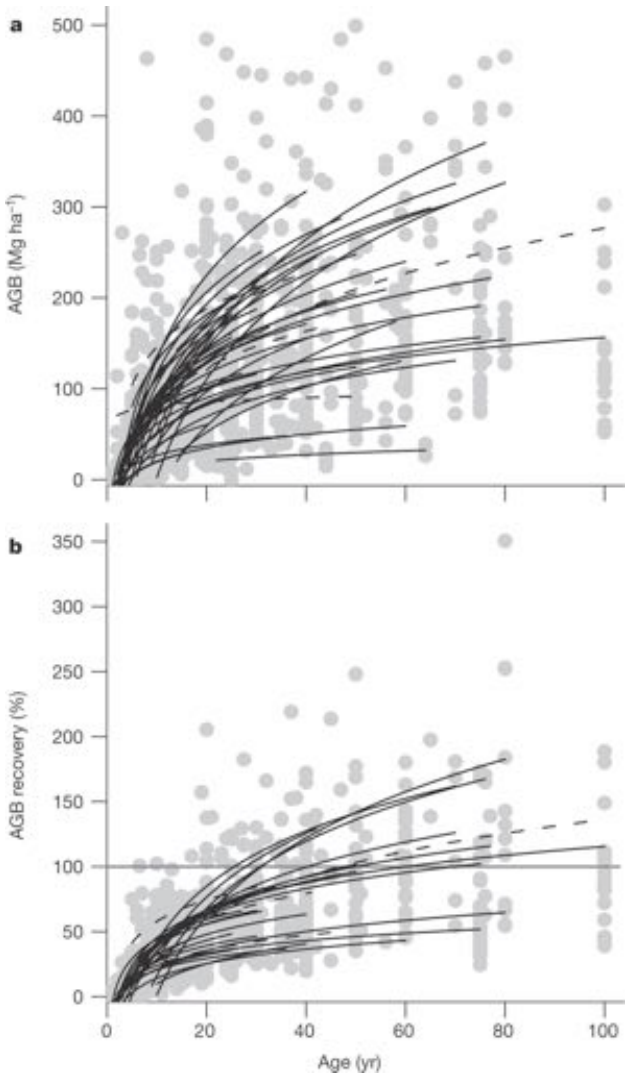
Uhl & Jordan 1984

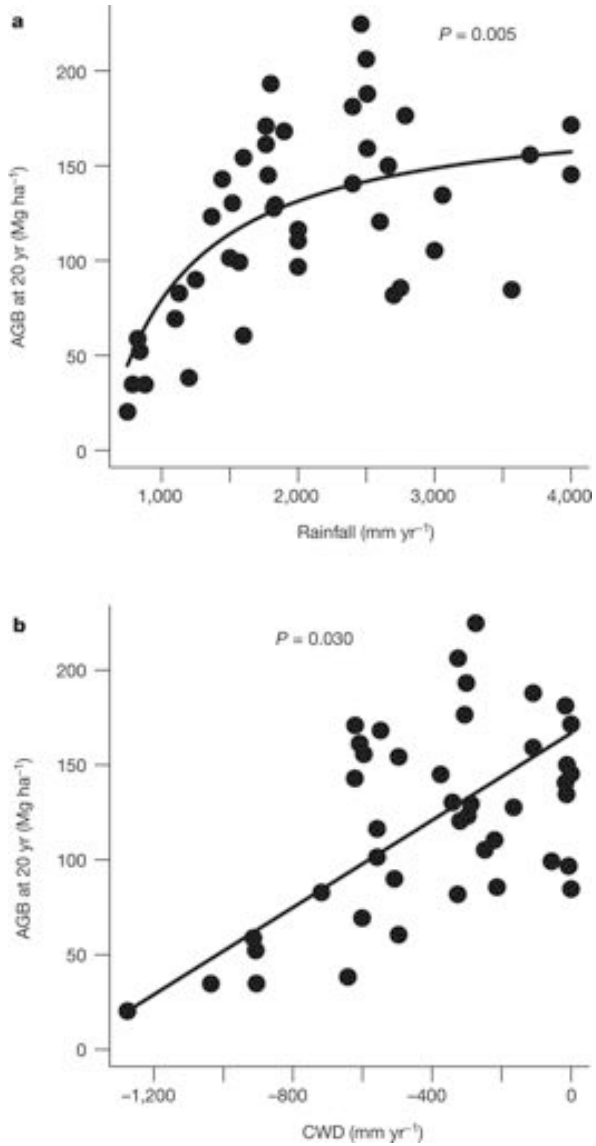
Recovery cycle and soil properties



Chazdon 2014

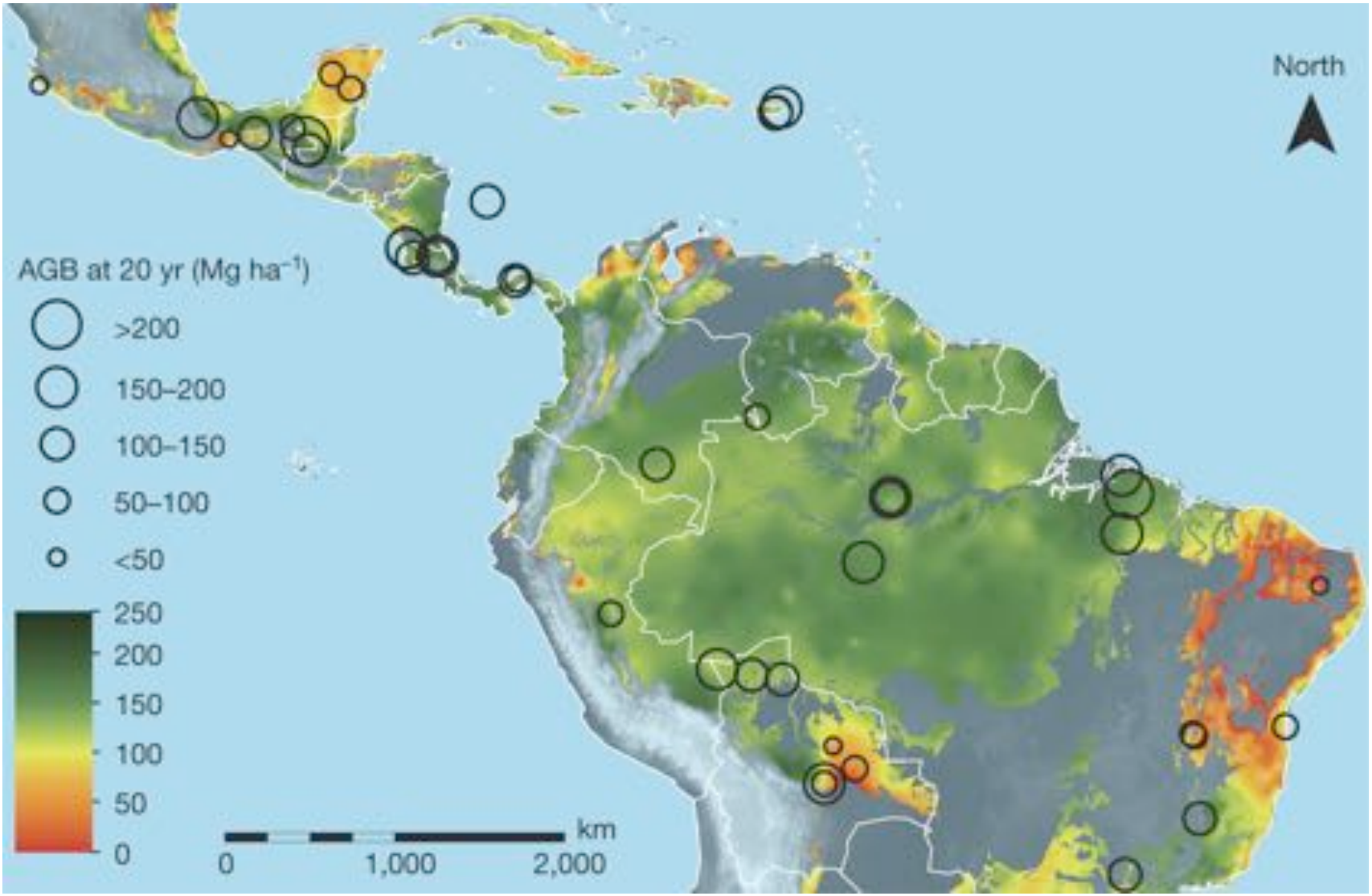
Biomass recovery in tropical America





Poorter et al. 2016 Nature 530: 211-214

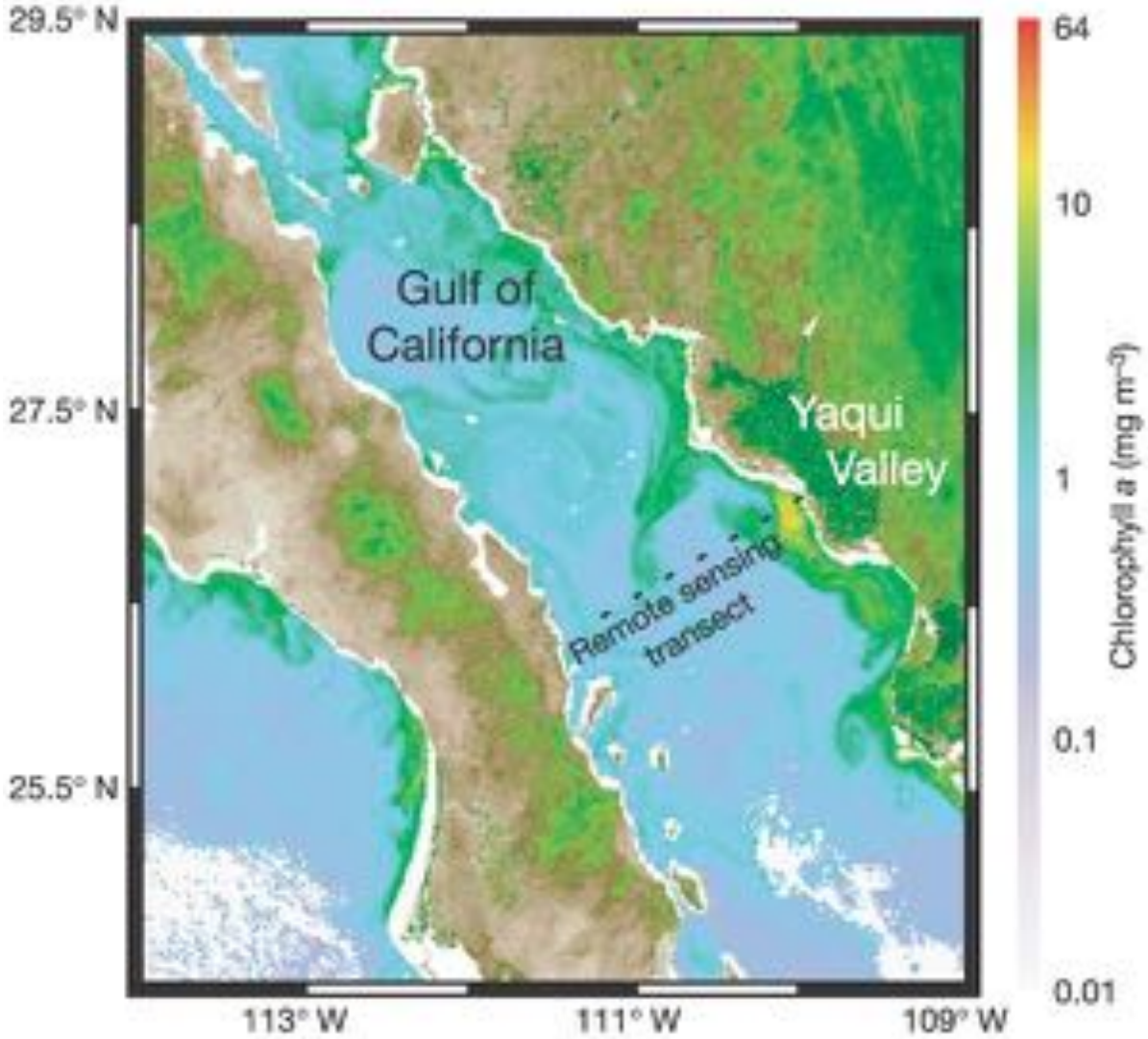
Biomass recovery in tropical America



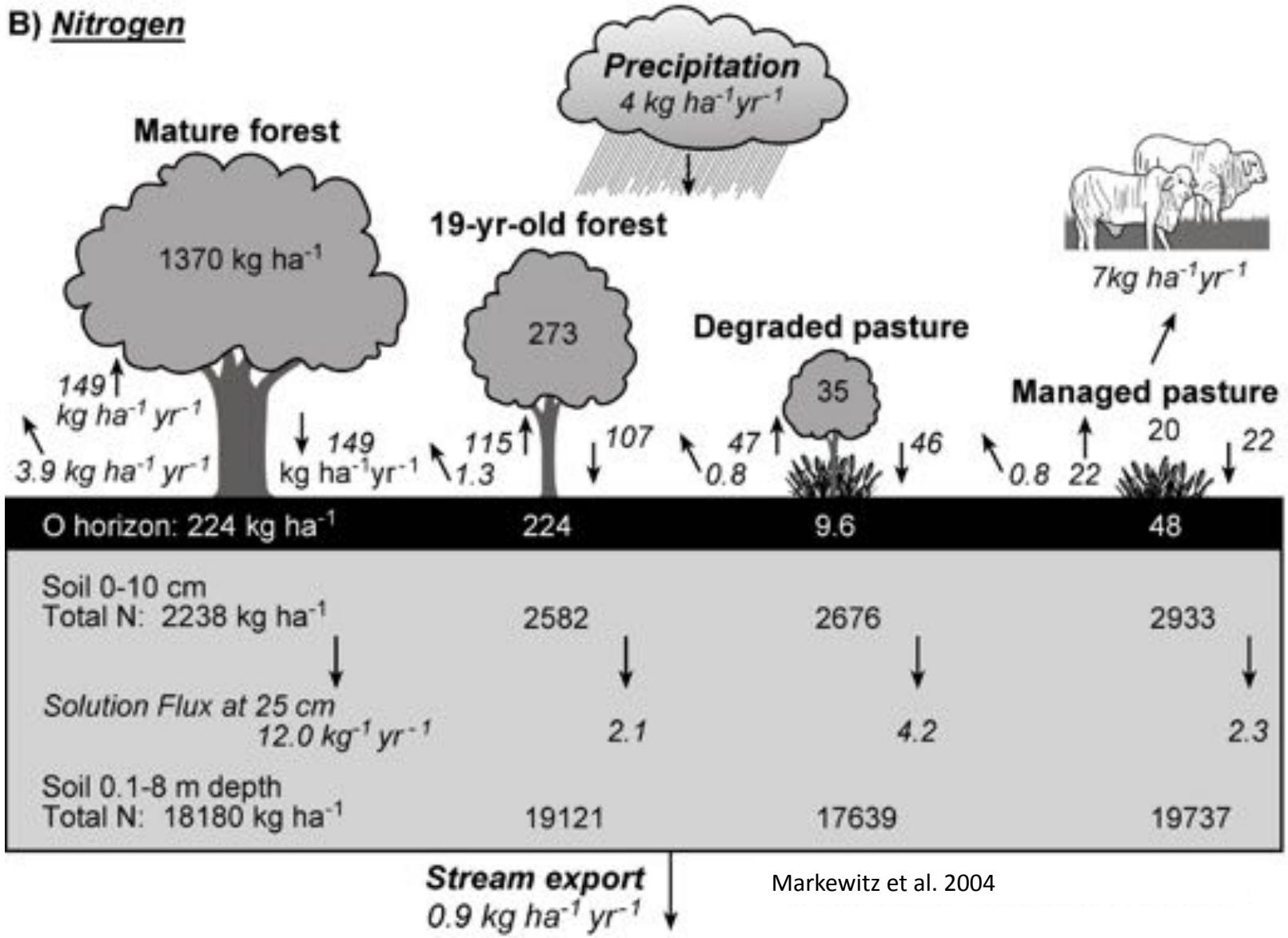
Poorter et al. 2016 Nature 530: 211-214

What are the effects of large scale deforestation on nutrient cycling?

Effects on aquatic ecosystems

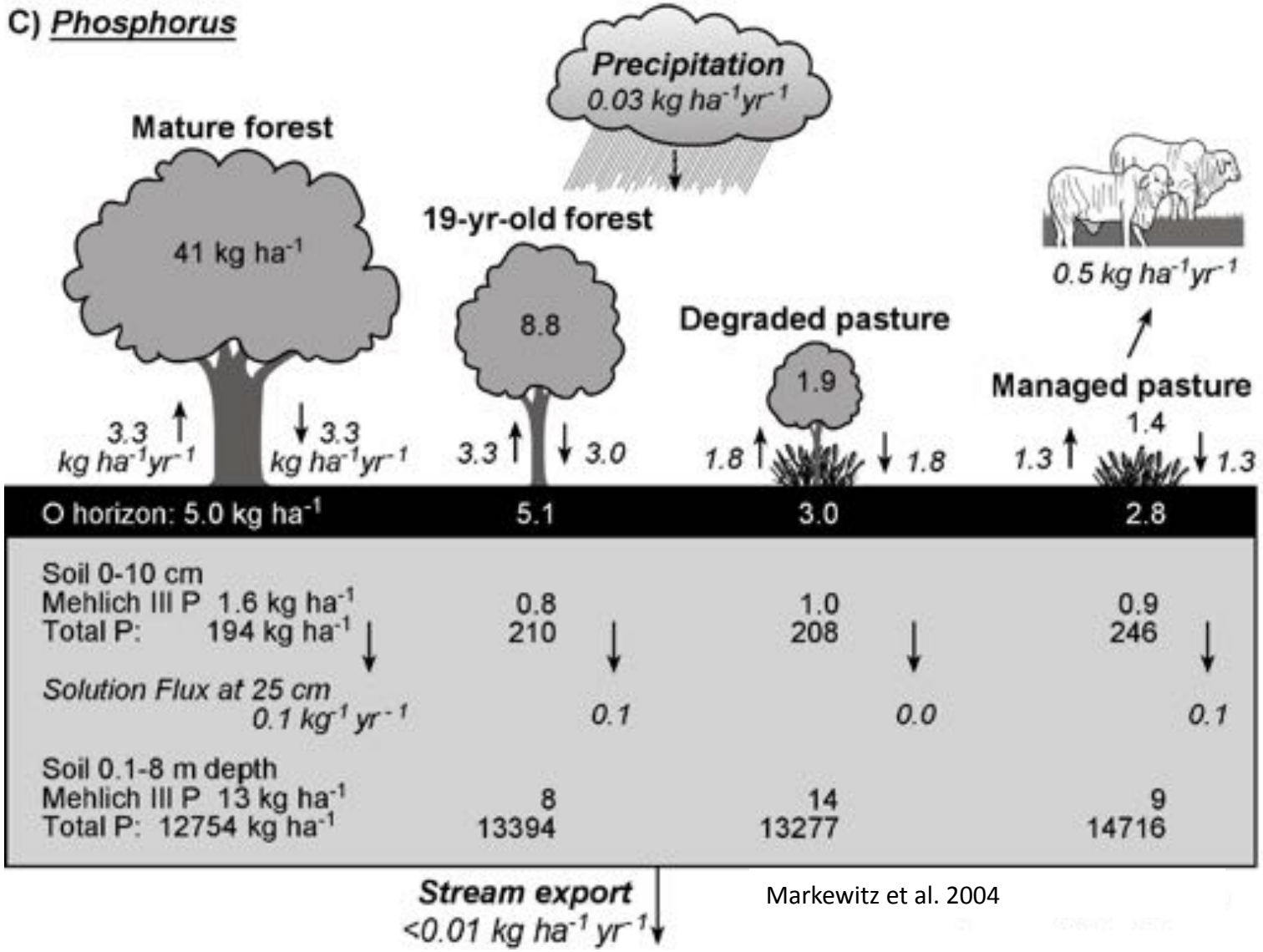


Important amounts of N are removed by deforestation, but it can recover in secondary forests



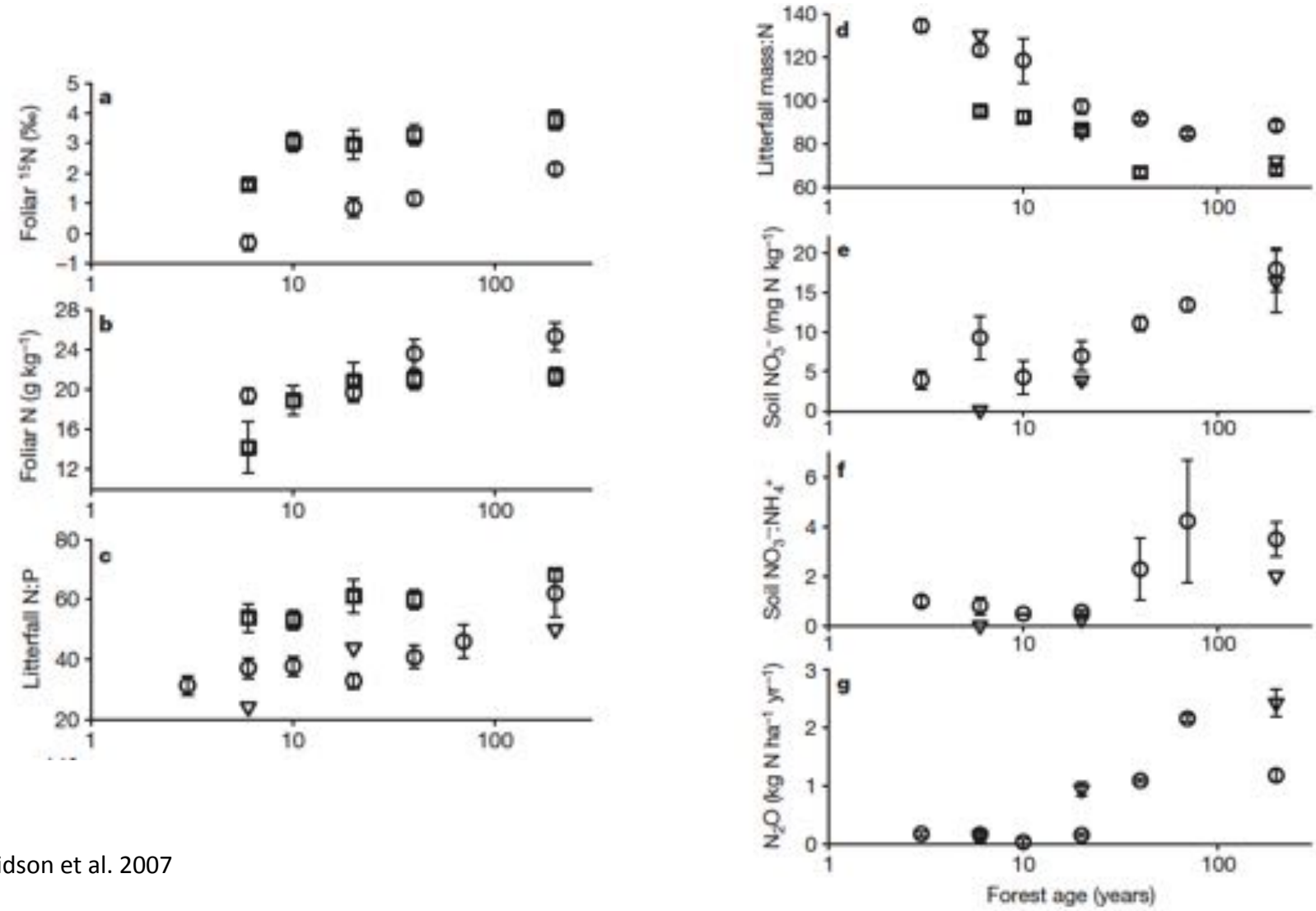
Markewitz et al. 2004

P is also removed but an important portion is retained by minerals in the soil



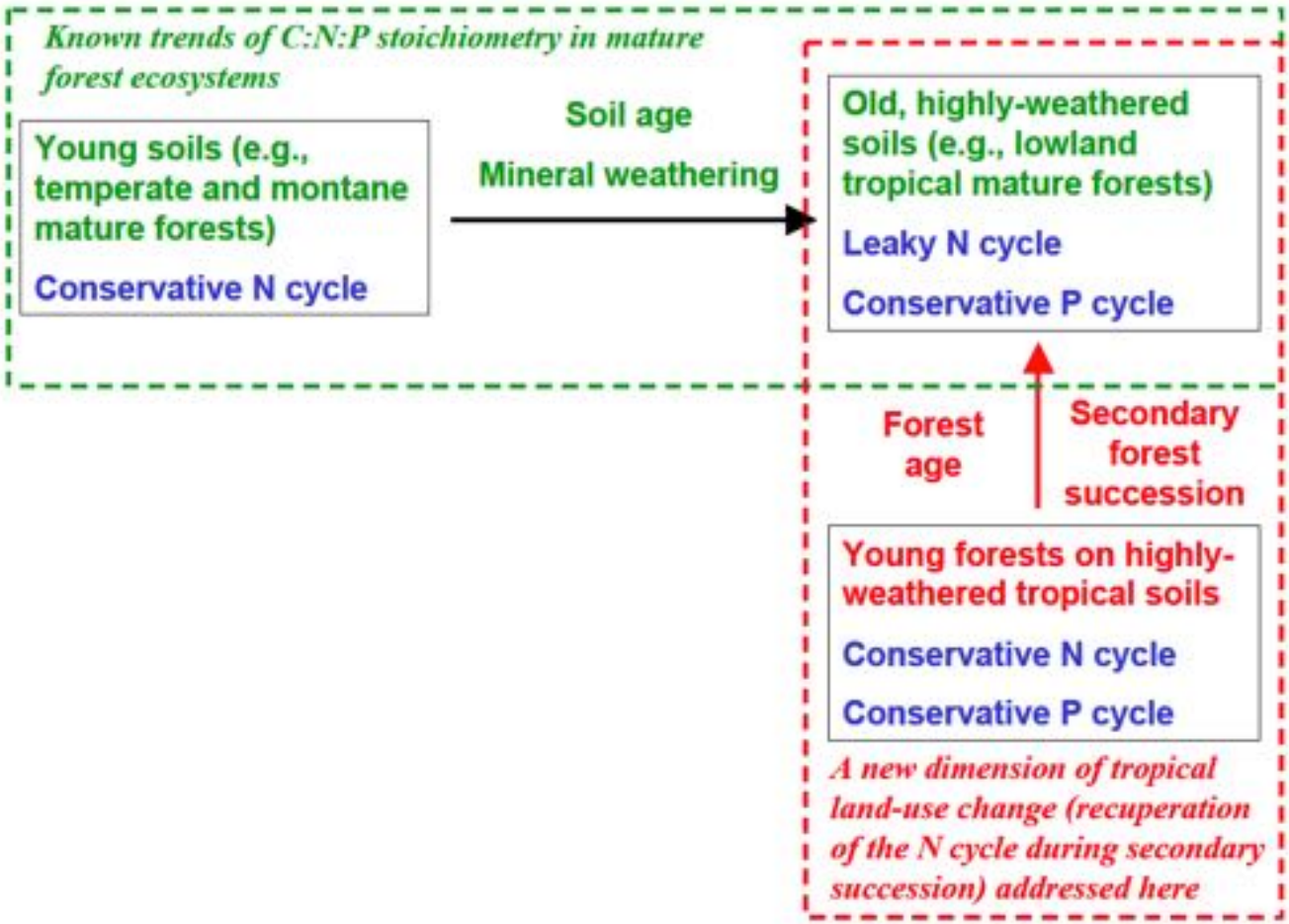
Markewitz et al. 2004

N recovers after agricultural abandonment



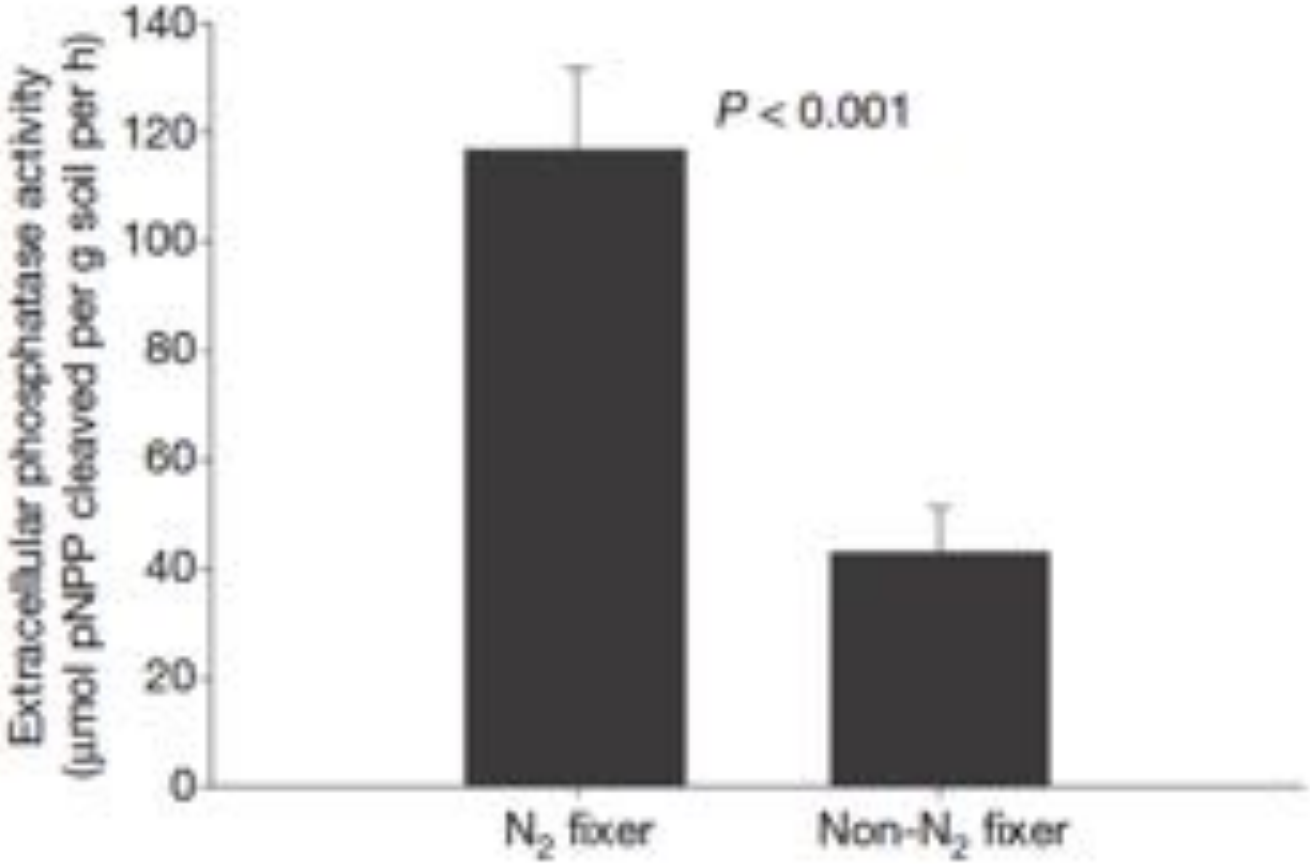
Davidson et al. 2007

A new paradigm



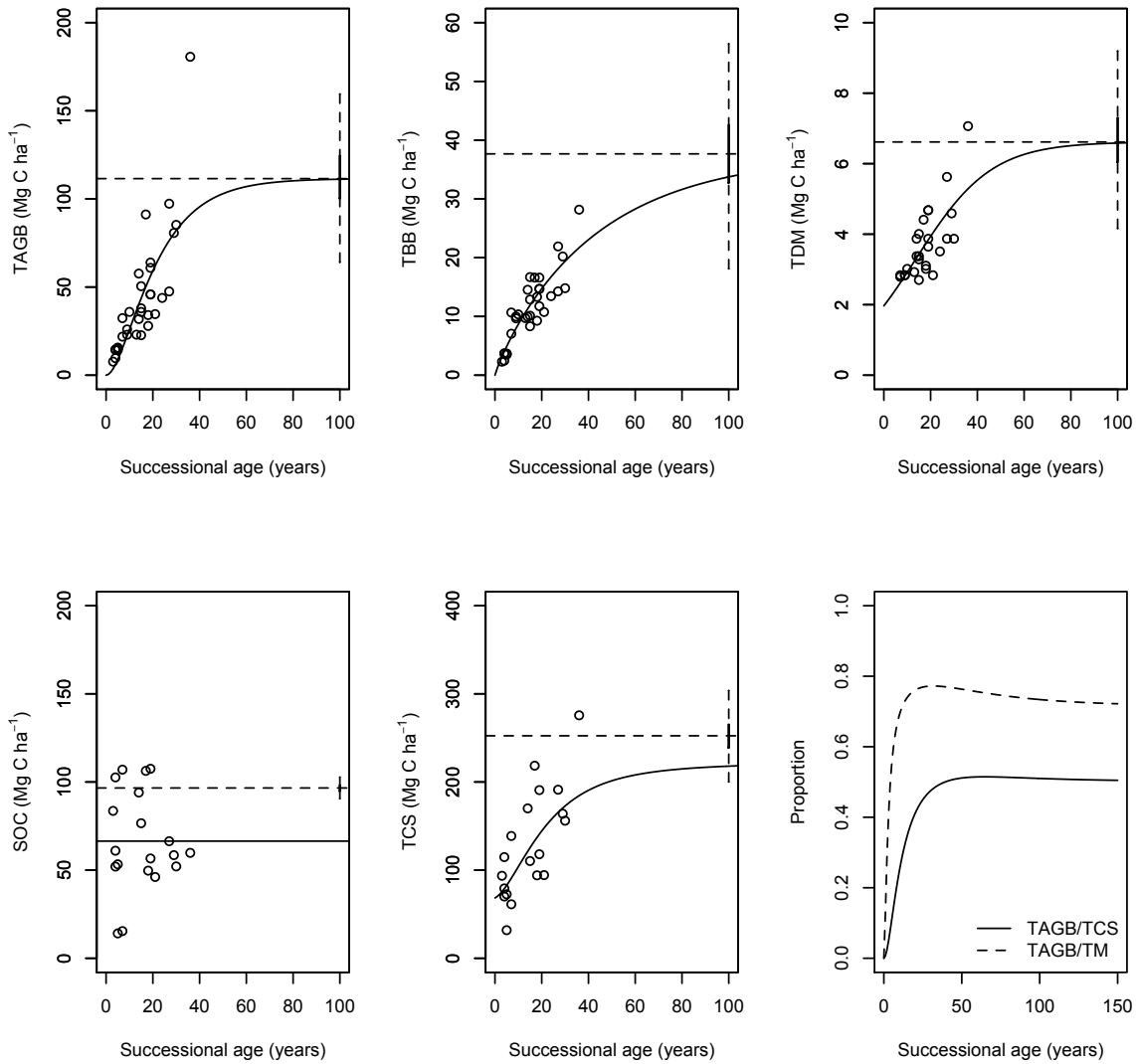
Davidson et al. 2007

N fixation seems to be key for phosphatase production



Houlton et al. 2008

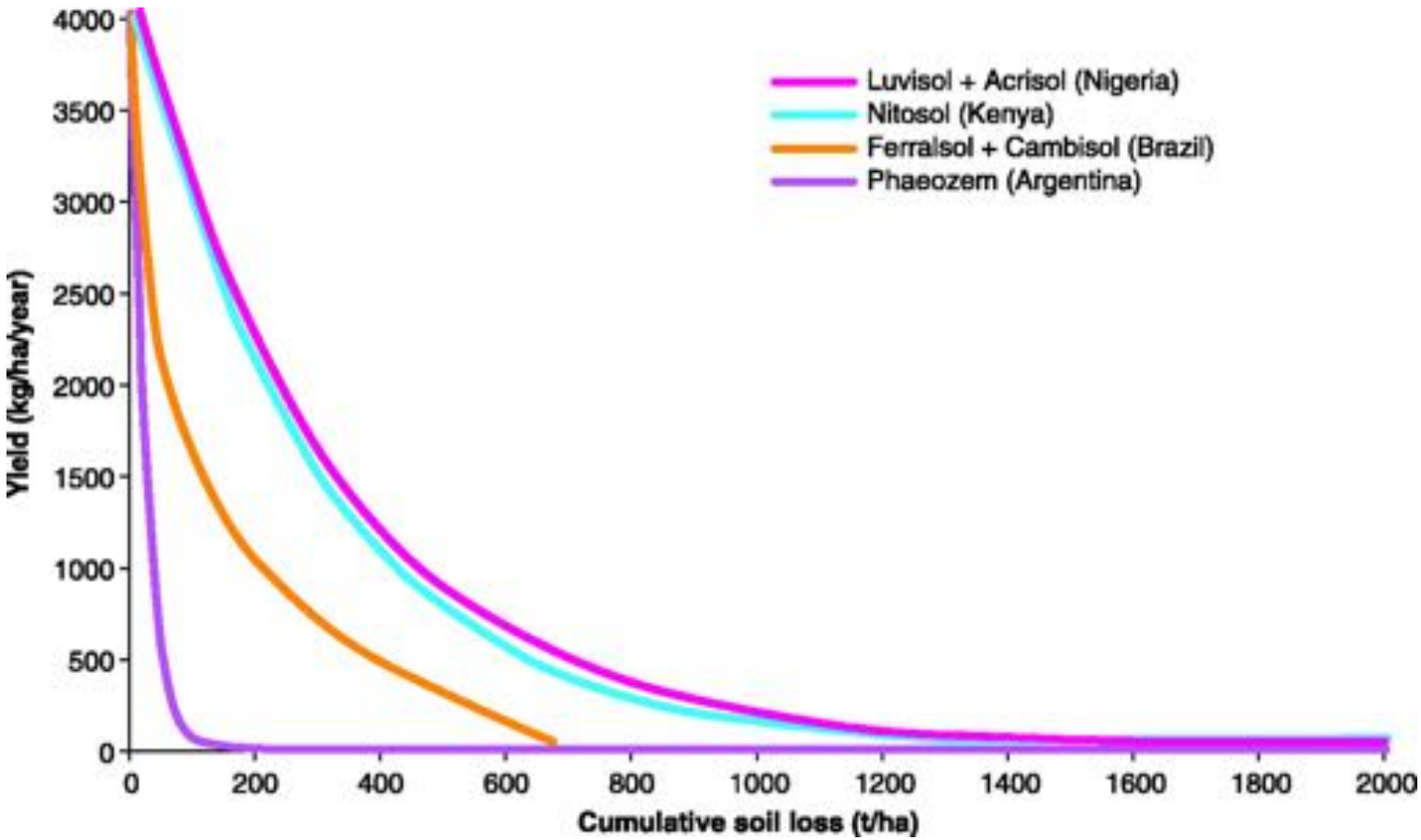
C stocks can recover after decades of land-use



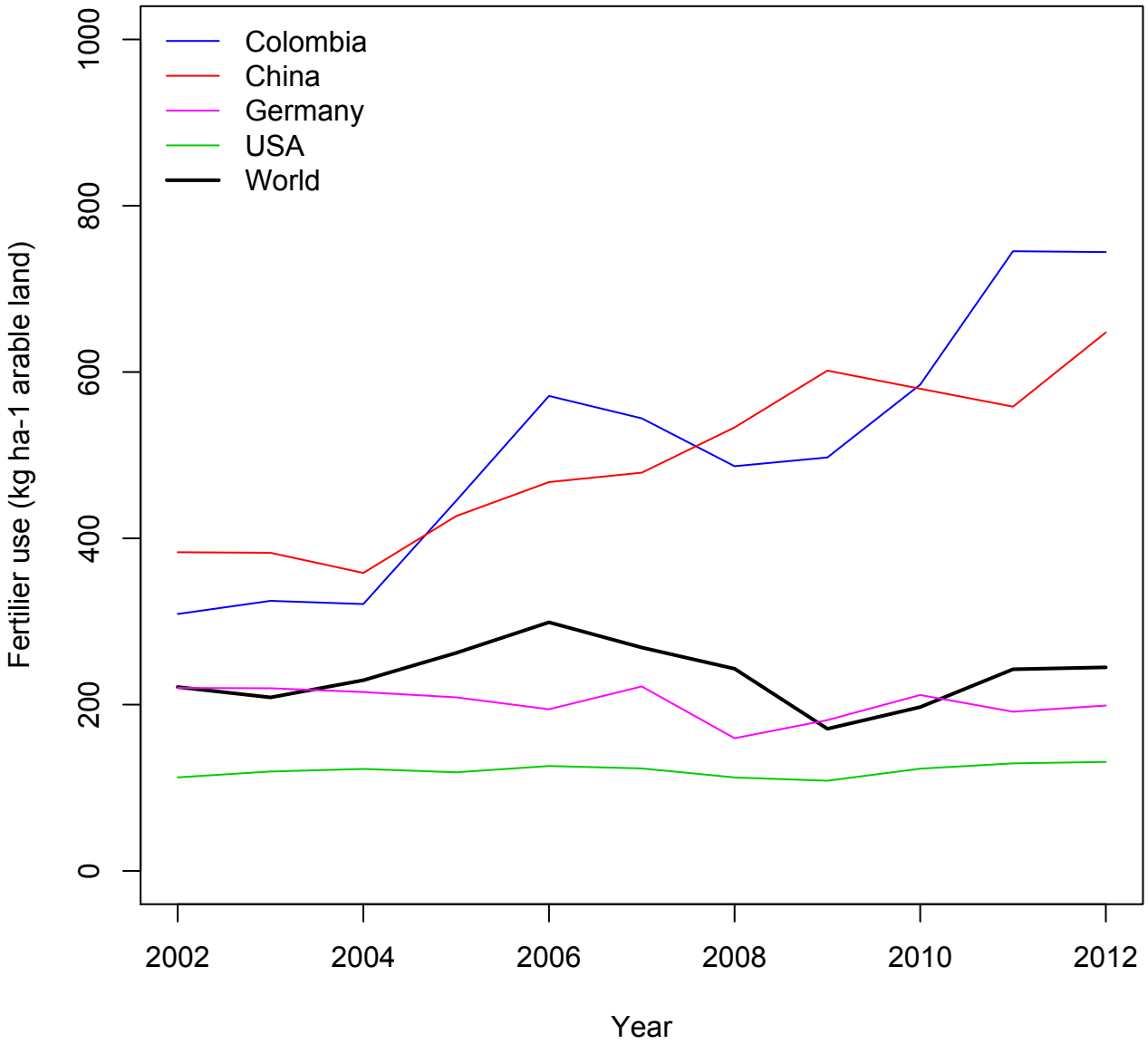
Sierra et al. 2012

Continuous cultivation and fertilization

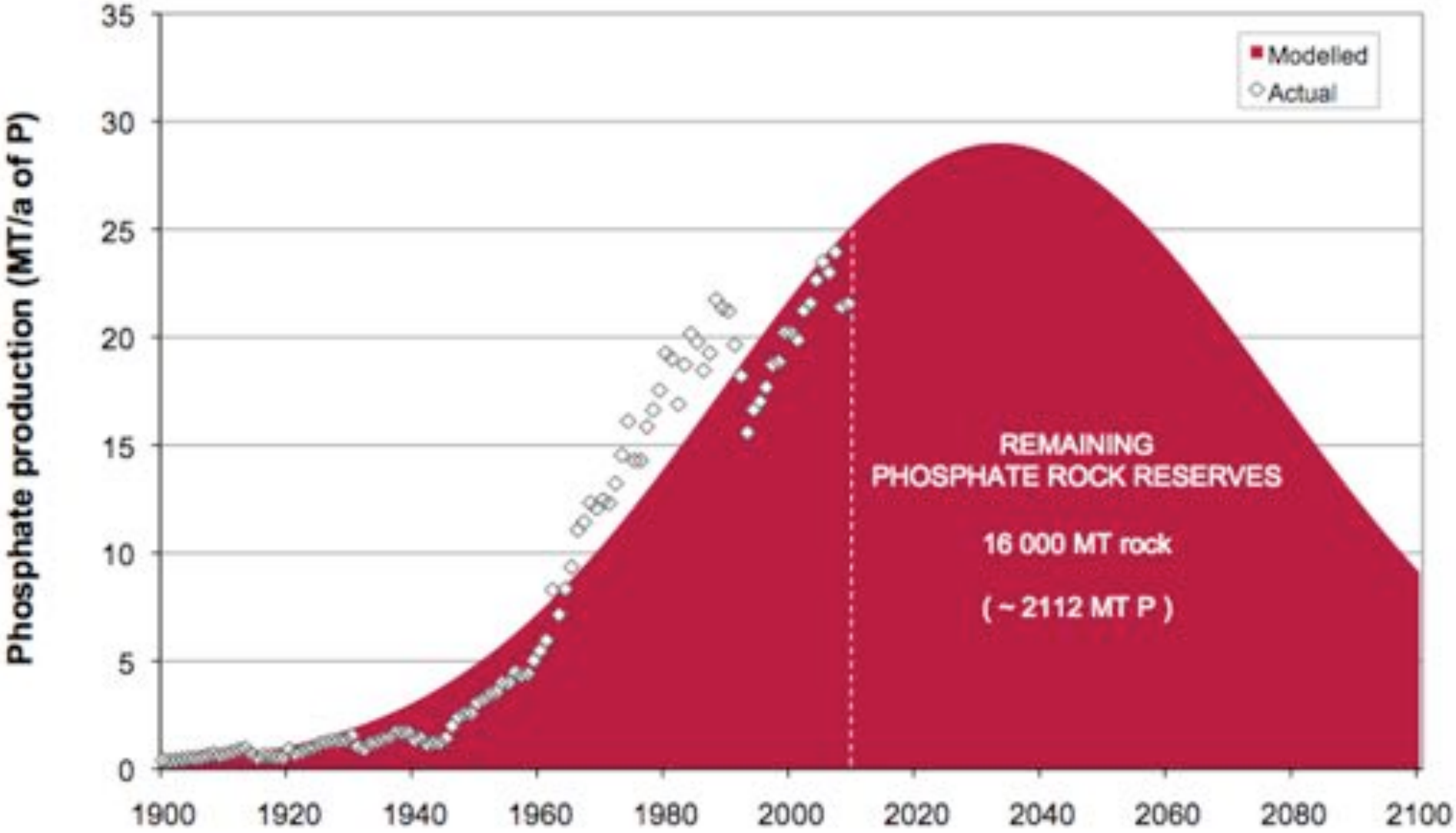
However, continuous cultivation is not sustainable

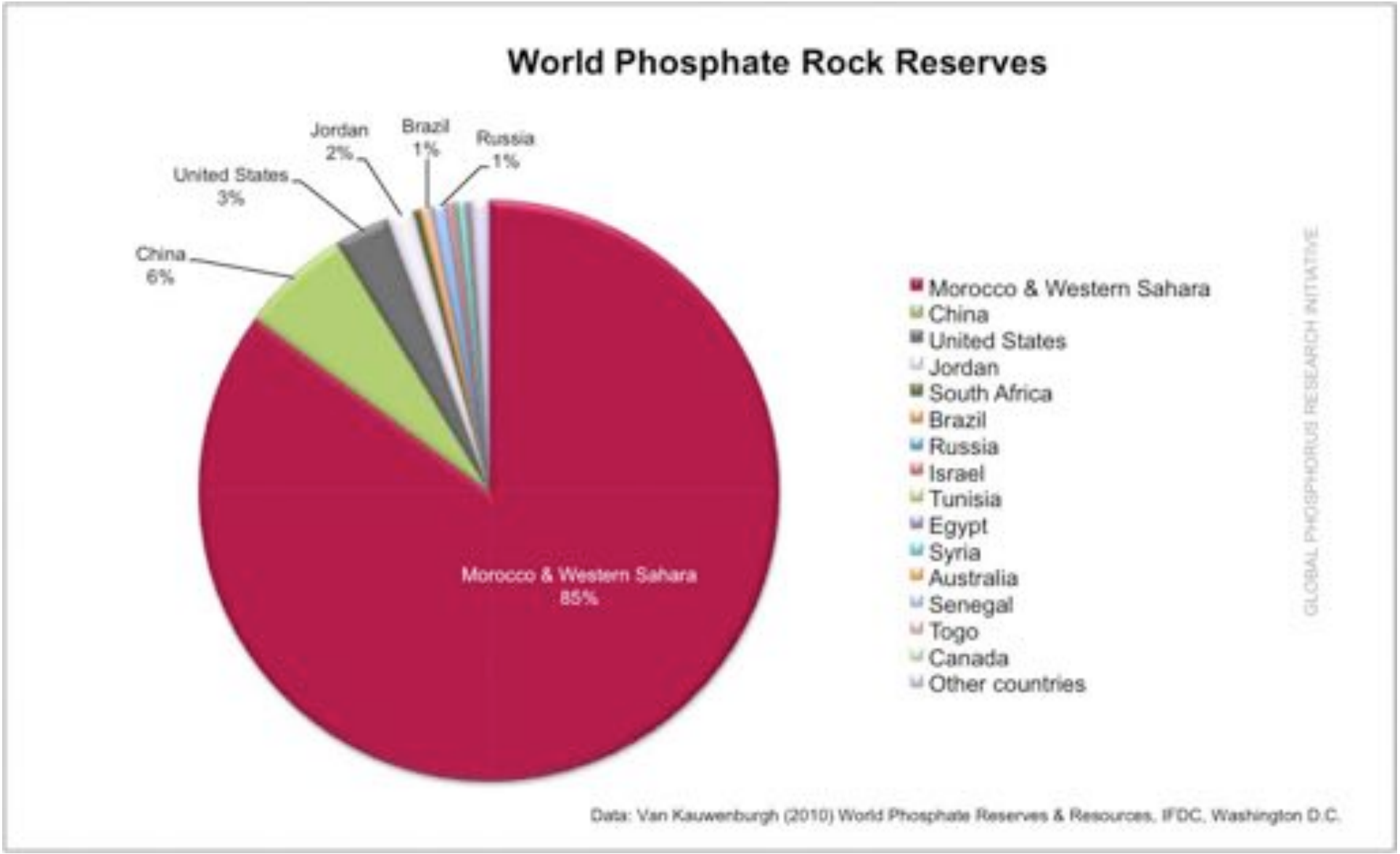


Stocking 2003

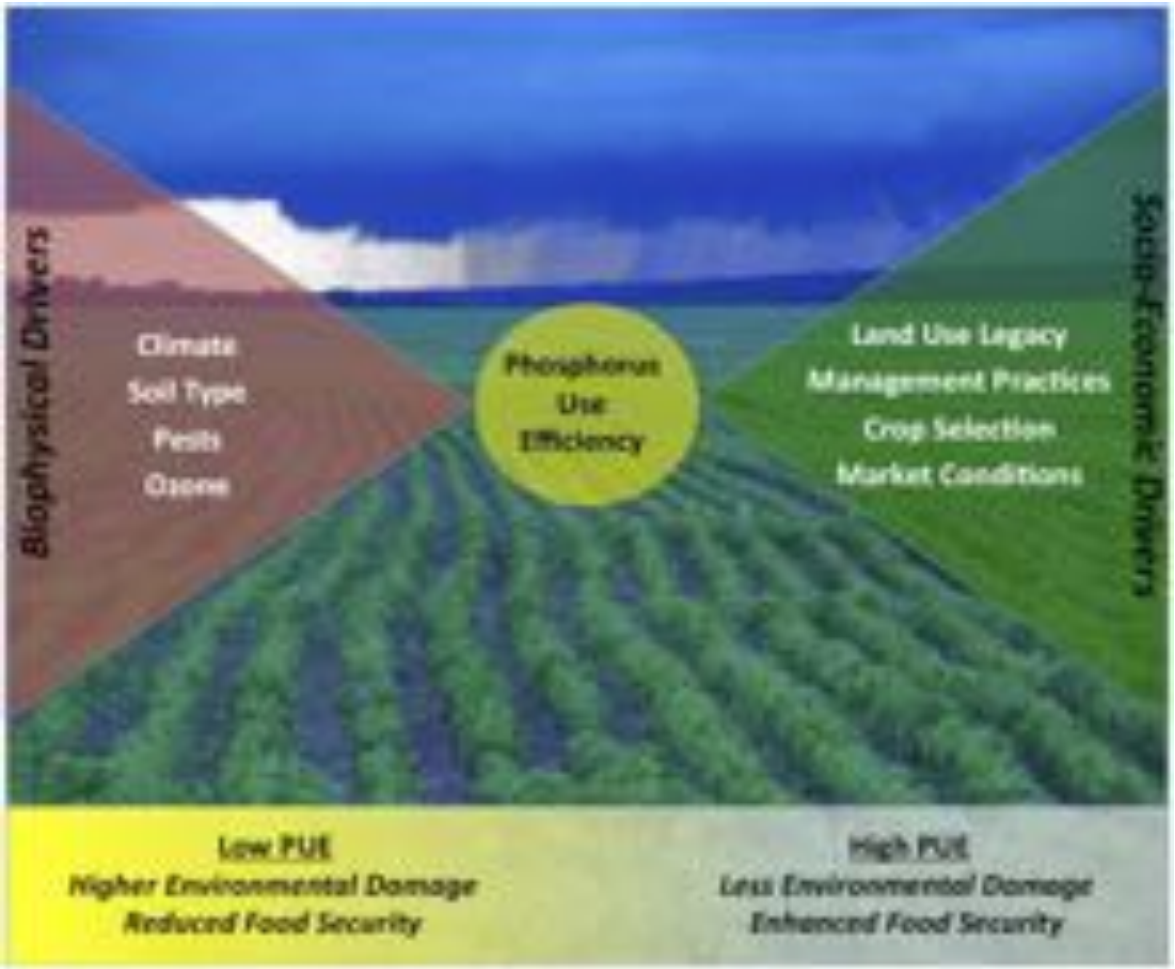

Colombia
China
Germany
USA
World
Fertilier use (kg ha-1 arable land)
0
200
400
600
800
1000
2002
2004
2006
2008
2010
2012
Year

Phosphorous peak




World Phosphate Rock Reserves
Jordan 2%
Brazil 1%
Russia 1%
United States 3%
China 6%
Morocco & Western Sahara 85%
Morocco & Western Sahara
China
United States
Jordan
South Africa
Brazil
Russia
Israel
Tunisia
Egypt
Syria
Australia
Senegal
Togo
Canada
Other countries
GLOBAL PHOSPHORUS RESEARCH INITIATIVE
Data: Van Kauwenburgh (2010) World Phosphate Reserves & Resources, IFDC, Washington D.C.

Phosphorus use efficiency



Take-home messages

- Slash-and-burn of tropical forests make nutrients available for crops, but productivity decline over time
- Regrowing forest can recover nutrient stocks over time
- N is a key nutrient for forest recovery
- Current fertilizer use is not sustainable

Topics for discussion

- Environmental consequences of large-scale conversion of tropical forests (oil palm, soy).
- Sustainability of crop production in tropical regions.
- Possible solutions to balance food production and nutrient loss.