Tropical Ecosystem and Soil Development

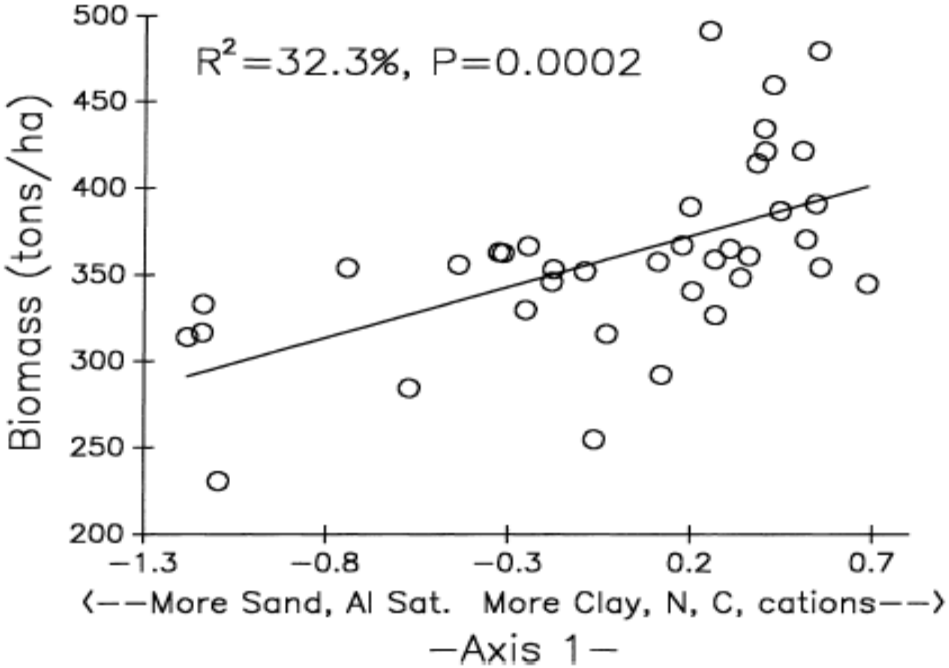
Joost van Haren

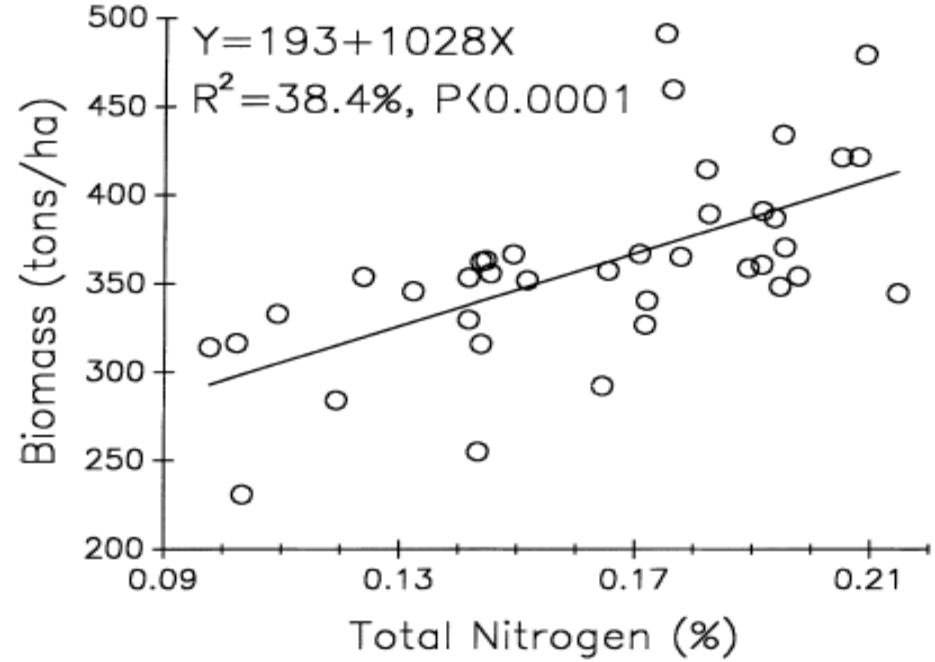
Ecology 596L

09/03/10

Ecosystem biomass strongly dependent on soil

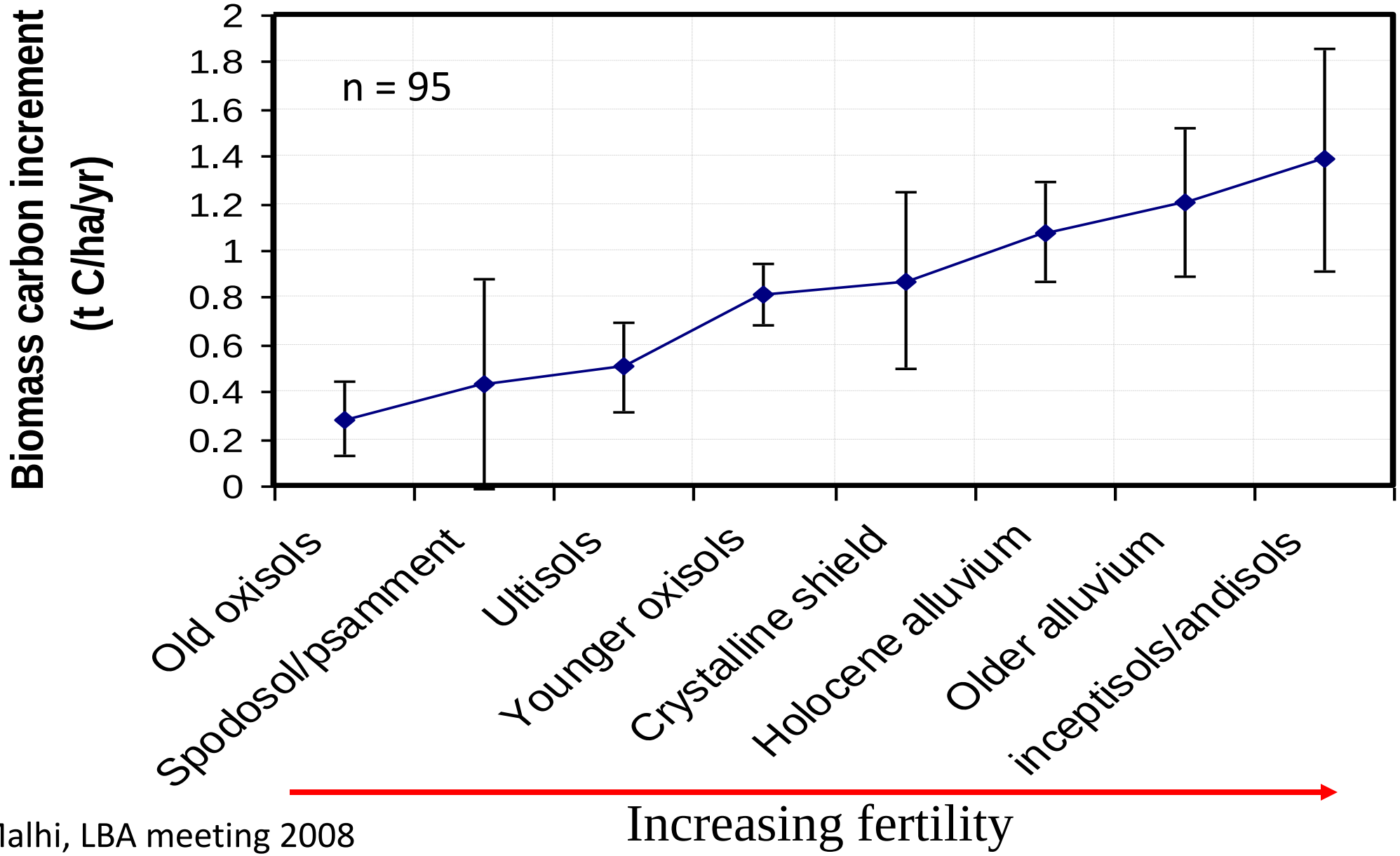
W.F. Laurance et al. / Forest Ecology and Management 118 (1999) 127–138





Manaus, BDFF plots

Ecosystem growth strongly dependent on soil



Malhi, LBA meeting 2008

Main questions I'll address

- How do necessary ecosystem ingredients (C, H, O, N, P, S, and micro nutrients) get into organisms?
- What factors influence soil formation?
  - Effect of time, parent material, and land-use change on soil nutrient content and ecosystem development
  - How does soil nutrient content vary over time
- Do soils influence tree diversity or do plants influence soil evolution?
- Final grab bag:
  - influence of land use change and fertilization
  - Do plant species really care what nutrient source is available?
  - Why do so many legumes not fix nitrogen?

How do necessary ecosystem ingredients get into above ground organisms?

Organisms need:	Ultimate source
• **Carbon**	Atmosphere (CO_2) (via biological photosynthesis)
• **Nutrients**	
– **N**	Atmosphere (N_2 is 80%) (via biological fixation and deposition)
– **S**	Atmosphere (SO_4^{2-} wet deposition)
– **P**	**Parent rock material** (via chemical weathering)
– **Cations (Ca^+, Mg^+, K^+ , ...)**	Atmospheric deposition (from dust storms & fire)
– **Micro nutrients (Fe, Cu, Mn, Zn, …)**	
• **Water**	Ocean (via evaporation & recon-densation as precip.)

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• **ENERGY**	**Sun** and chemical reactions

How do necessary ecosystem ingredients get into soil/below ground organisms?

Organisms need:	Ultimate source
• **Carbon**	Atmosphere (CO_2) (from plants via photosynthesis)
• **Nutrients**	
– **N**	Atmosphere (N_2 is 80%) (via biological fixation and deposition)
– **S**	Atmosphere (SO_4^{2-} wet deposition)
– **P**	**Parent rock material** (via chemical weathering)
– **Cations (Ca^+, Mg^+, K^+ , ...)**	Atmospheric deposition (from dust storms & fire)
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• **Water**	Ocean (via evaporation & recon-densation as precip.)
• **ENERGY**	**Sun** and chemical reactions

Plant compounds

What are nutrients used for in plants?

- N: chlorophyll, nucleic acids (DNA, RNA), amino acids, enzymes, proteins, vitamins, and hormones
- P: nucleic acids (DNA, RNA), phospholipids (cell wall), adenosine triphosphate (ATP, energy storage and transfer), and phosphopyridine nucleotides (NAD+, NADP+)
- S: proteins, polysaccharides, vitamins, and hormones
- Metal micronutrients: enzymes

Main questions I'll address

Soil nutrient dynamics

- How do necessary ecosystem ingredients (C, H, O, N, P, S, and micro nutrients) get into organisms?
- What factors influence soil formation?
  - Effect of time, parent material, and land-use change on soil nutrient content and ecosystem development

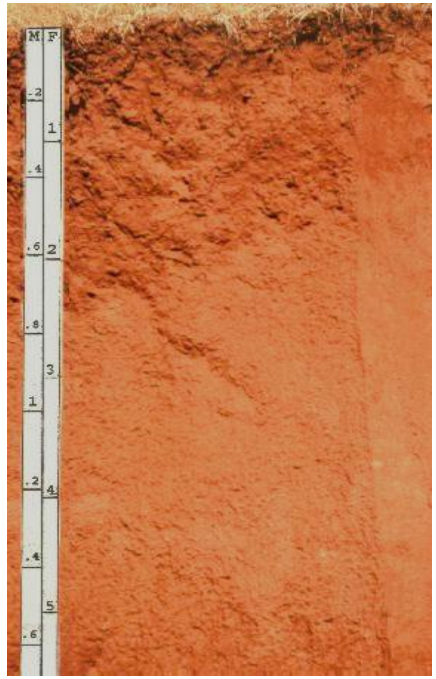
How is soil generated from rocks?

Weathering

dark, "humus"

clay, Fe-oxides, $CaCO_3$

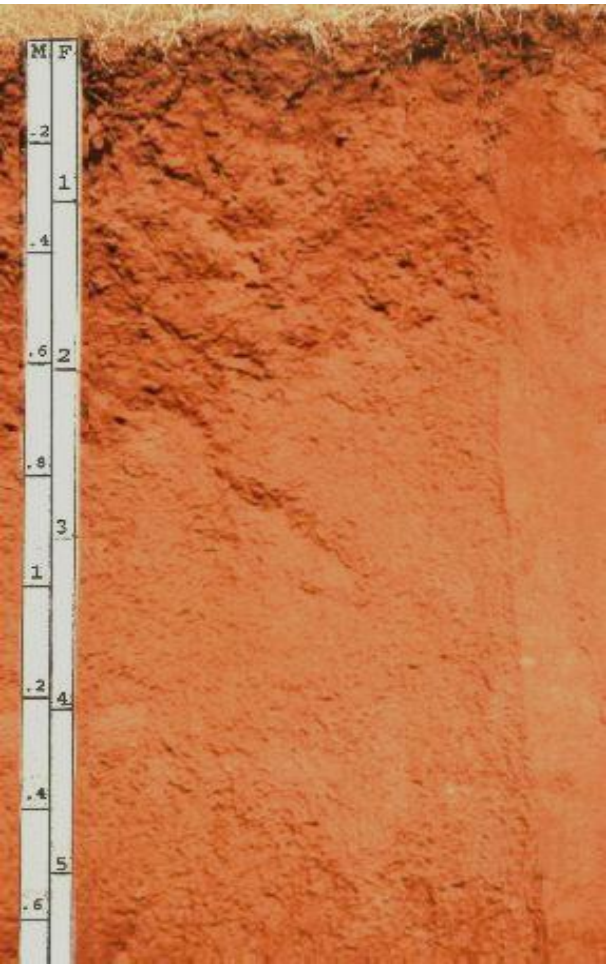
FIGURE 11-5. The designation of horizons for a hypothetical soil profile that could represent a forest soil in a cool, moist climate.



Soil Formation

Independent variables or soil-forming factors

Climate	(cl')
Organisms	(o')
Topography	(r')
Parent material	(p)
Time	(t)



$$s = f'(cl', o', r' p, t) \qquad (3)$$

S is any soil variable such as pH, texture, porosity, Ca content, etc.

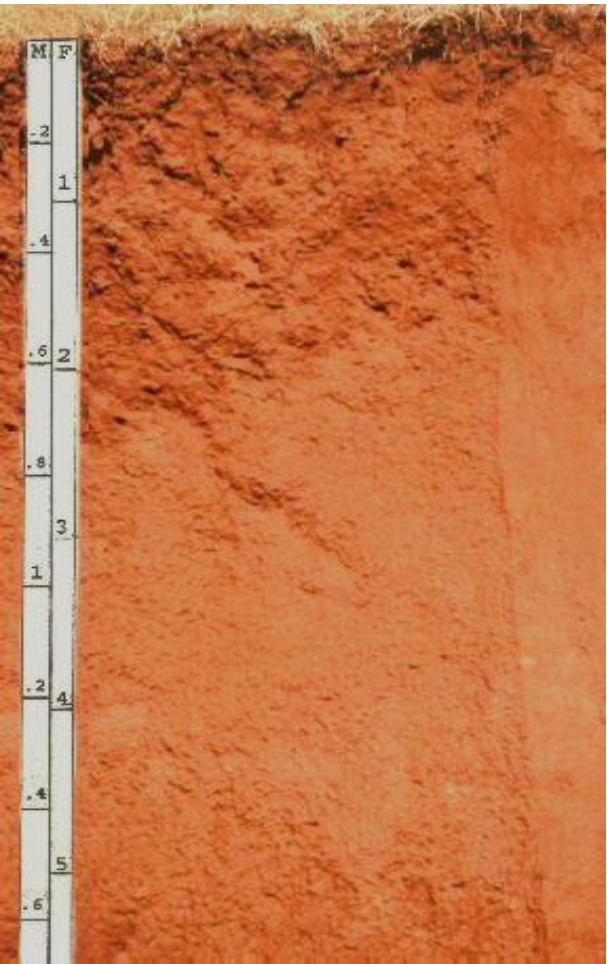
Jenny 1941

Soil Formation

Independent variables or soil-forming factors

Climate	(cl')
Organisms	(o')
Topography	(r')
Parent material	(p)
Time	(t)

All important in ecosystem development and diversity



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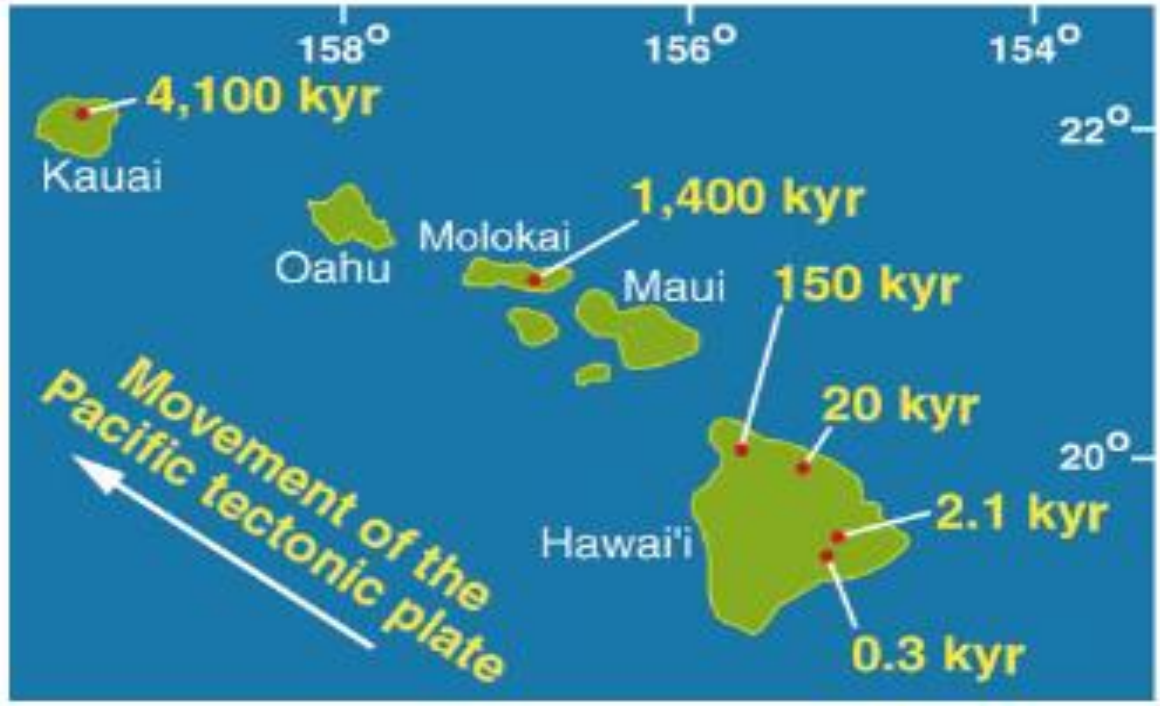
Jenny 1941

Tropical soil and ecosystem development over time: example from Hawaii

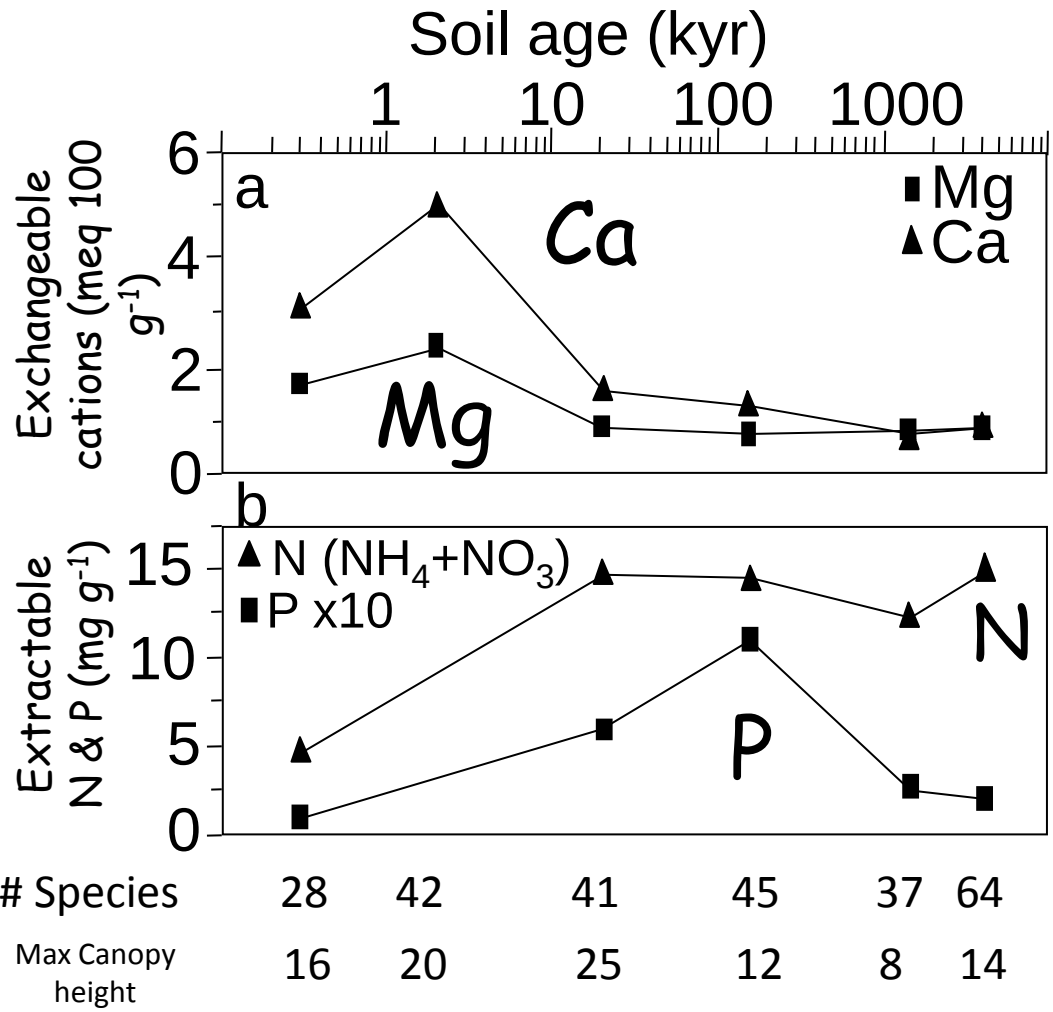
Hawaii as a model of ecosystem development over 4.1 Myrs



Hawaiian islands are extraordinary natural laboratory allowing chronosequences in which (ideally) all factors except time are held constant

Chadwick et al. (1999)

Soil evolution over time



None of the native Hawaiian tree species are legumes.
N trend without legume trees!

- Easily exchangeable rock-derived cations (Mg, Ca) drop off through time due to leaching.
- Atmospheric source nutrient (N) increases with time.
- P is not as easily weathered off as Mg and Ca (see below) – available P rises as weathering proceeds, then falls off due to leaching.

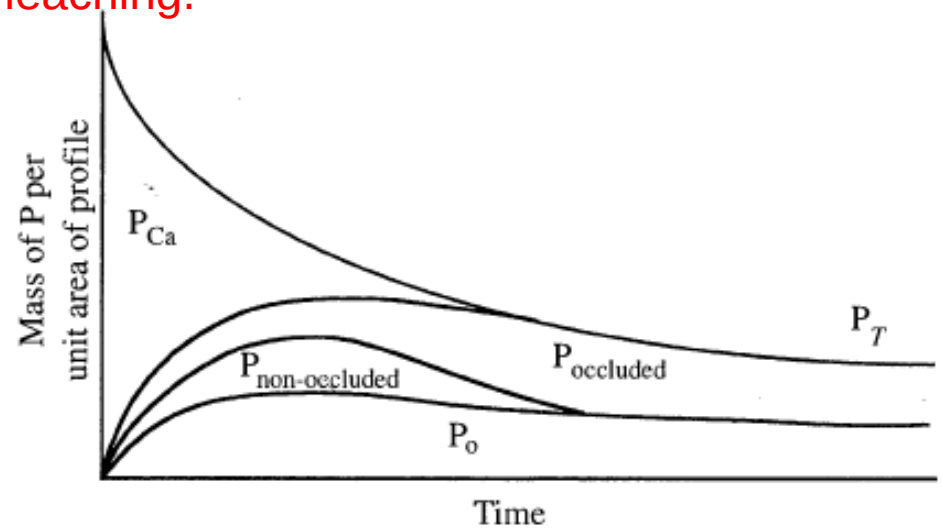
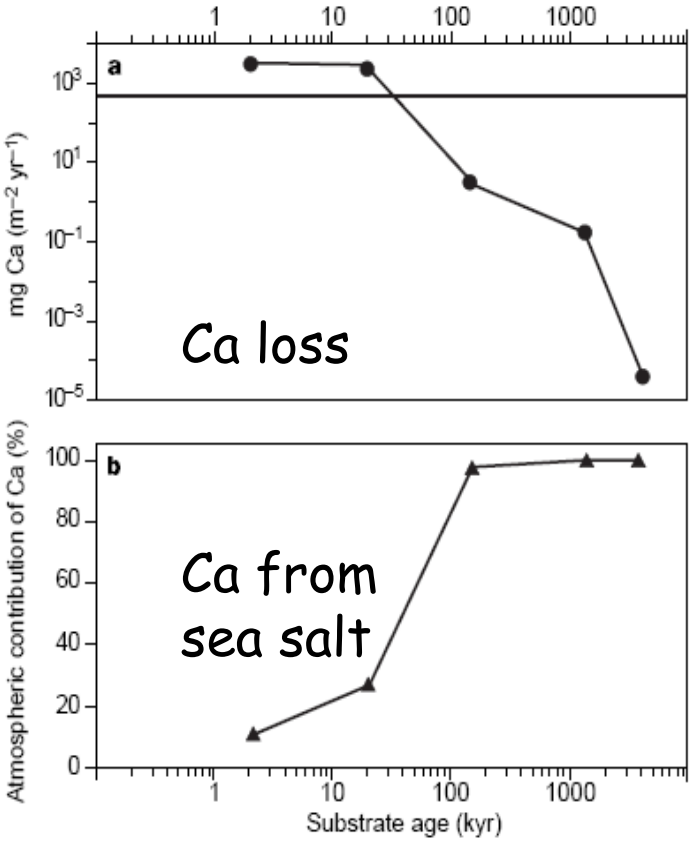
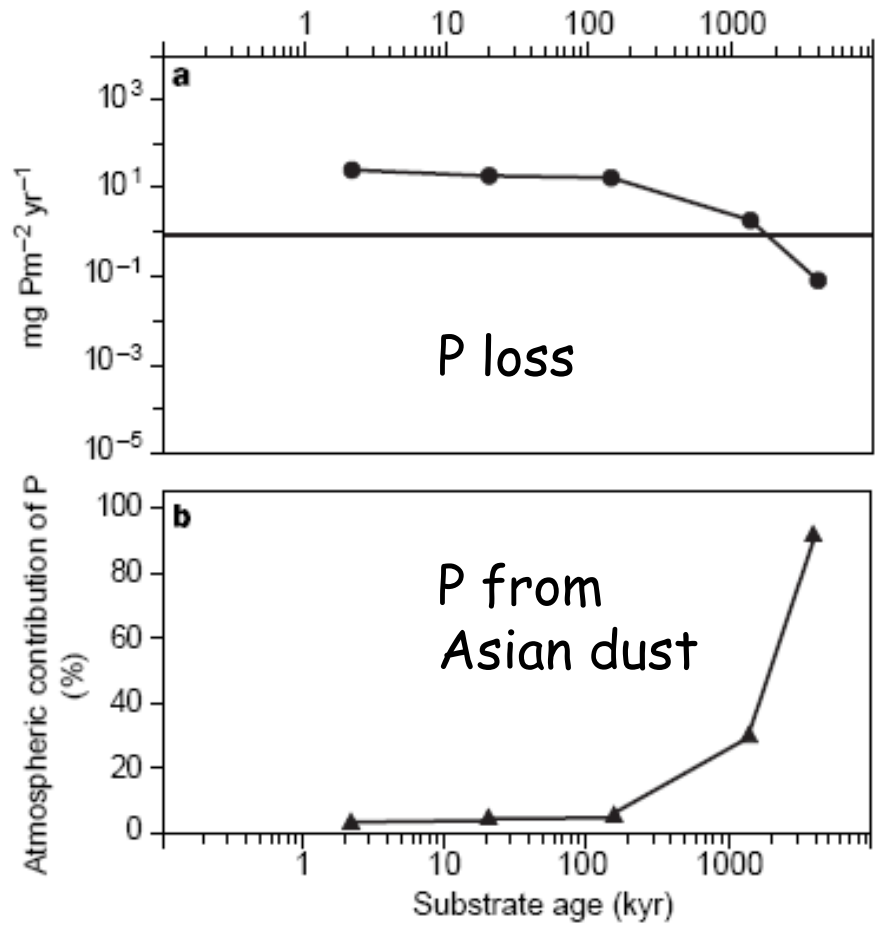


FIG. 1. Walker and Syers' (1976) diagram of P transformations with time. P_{Ca} = calcium phosphates, P_T = total phosphorus, P_o = P bound to organic matter.

Chadwick et al. 1999: Soil evolution over time

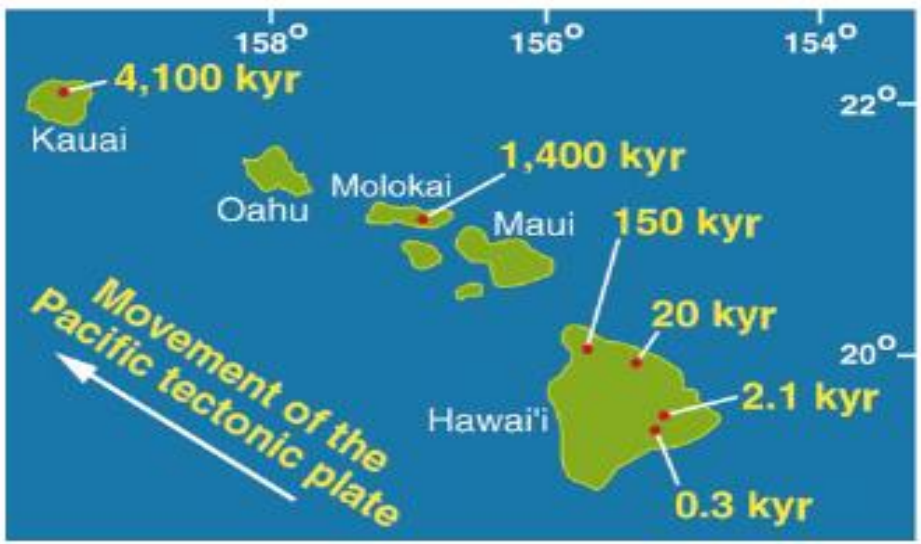


- Ca drops off through time (main source is parent rock)
- Importance of atmospheric deposition as source increases

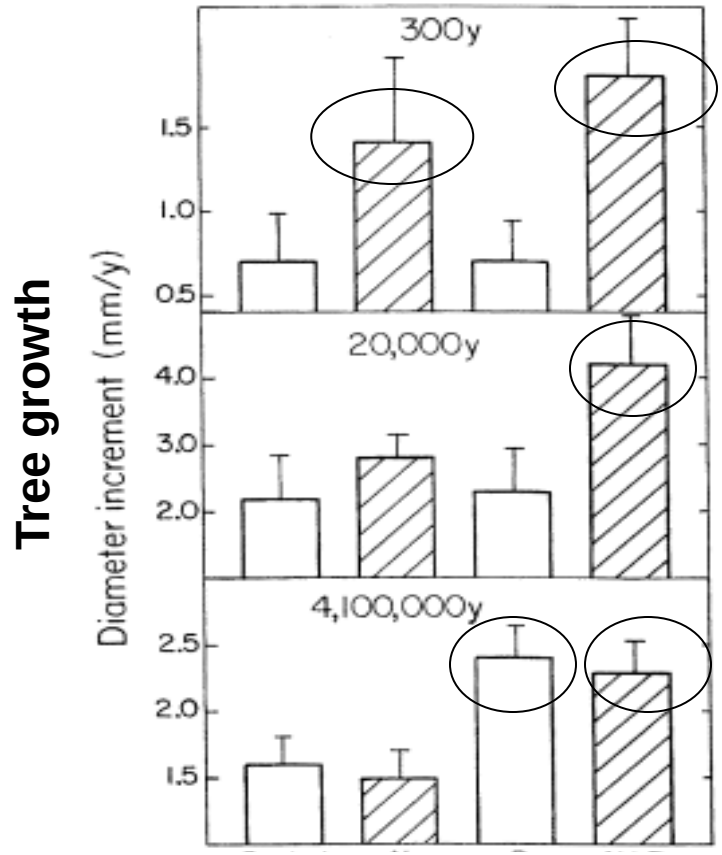


- P drops off through time (main source is parent rock)
- In oldest soils, most is from atmospheric dust (a source likely 10X stronger in ice ages than interglacials), though bird poop cannot be excluded

Hawaii as a model of ecosystem development over 4.1 Myrs



Fertilization Experiments on Chronosequence



Young sites N-limited

Middle sites jointly-limited

Old sites P-limited

Chadwick et al. (1999)

Vitousek & Farrington (1997)

Ecosystem development

How do young and old soils differ?

- Young soils:
  - should be **rich in rock-derived elements** (P, cations)
  - should be **poor in atmospherically derived elements and those from organic matter degradation**
- Older soils:
  - should be **poor in rock-derived elements**, due to leaching and soil erosion
  - should be **richer in elements from atmospheric deposition and those from organic matter** degradation

Based on the Hawaii story what would you expect for the nutrient status of Amazon basin soils?

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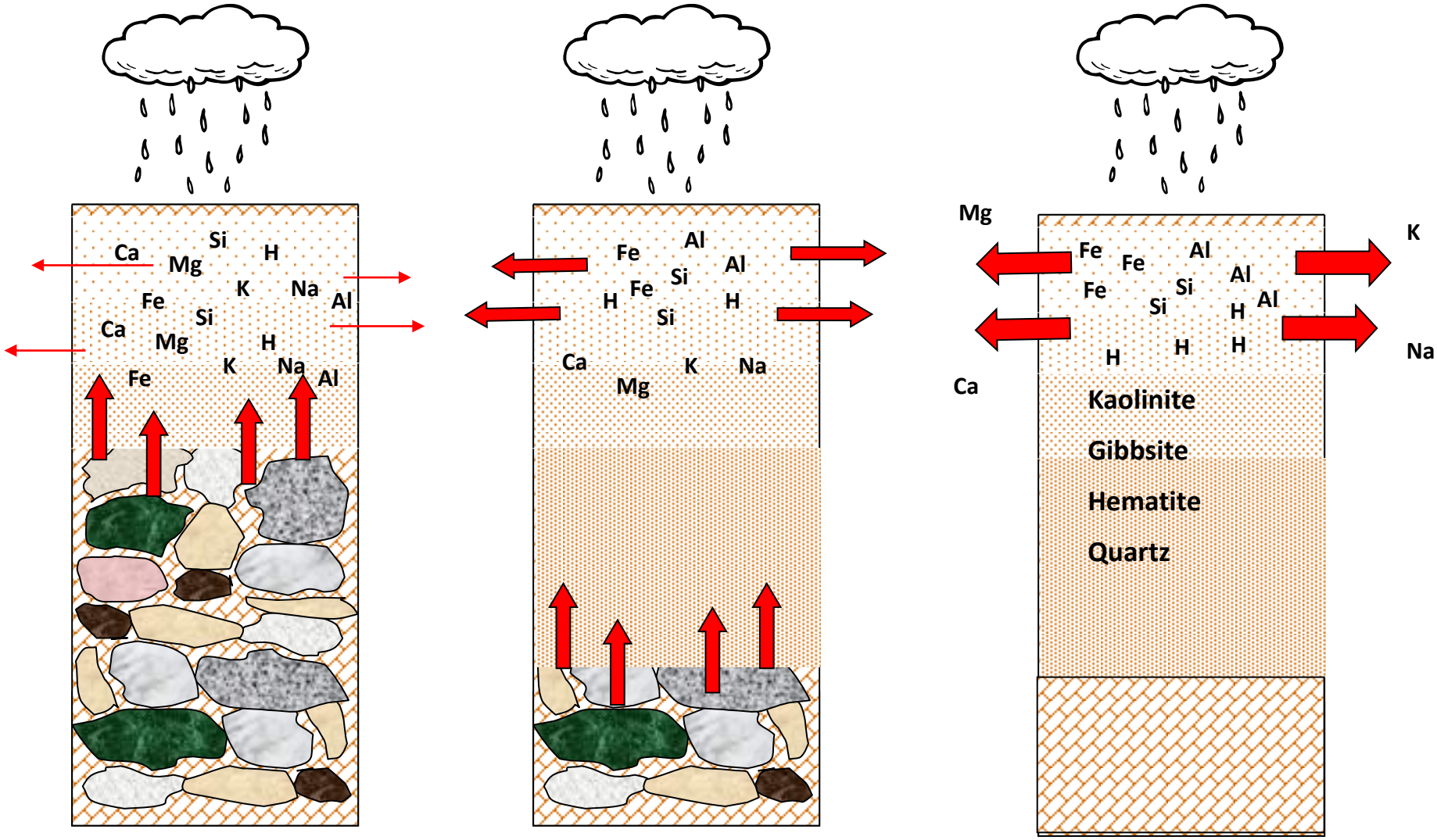
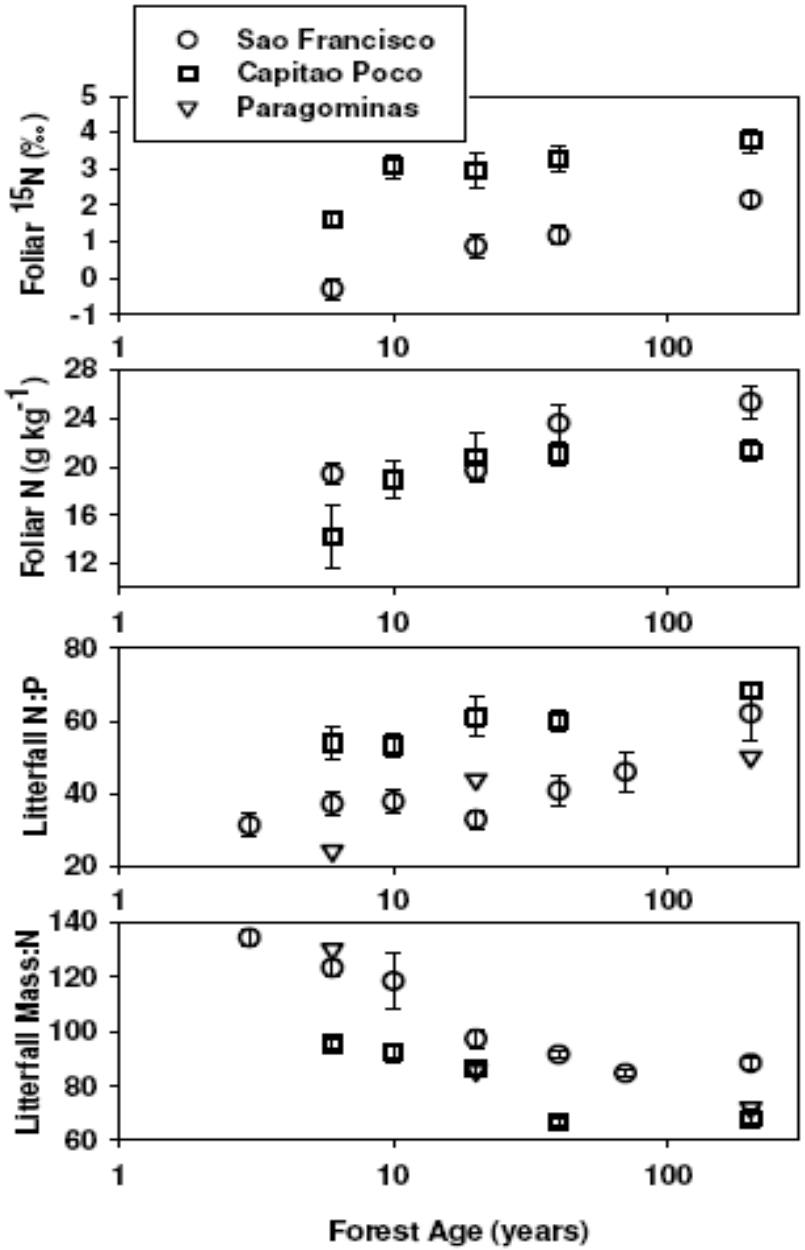


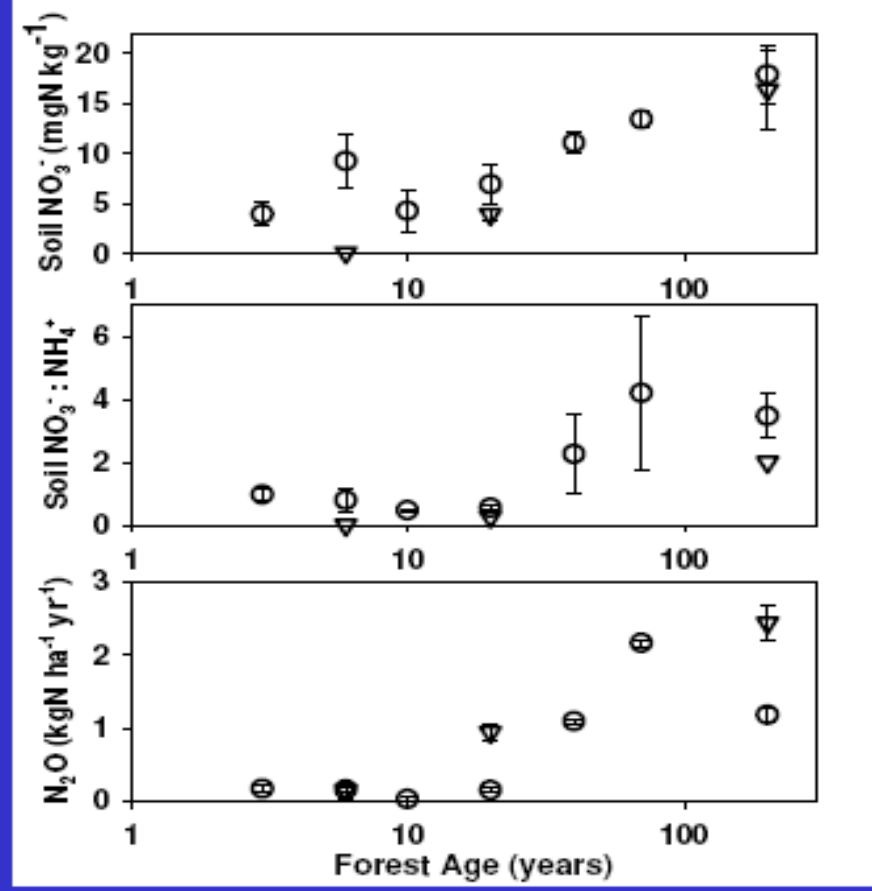
End of Miocene
10-15 million years ago

End of Pleistocene
1 -3 million years ago

Present

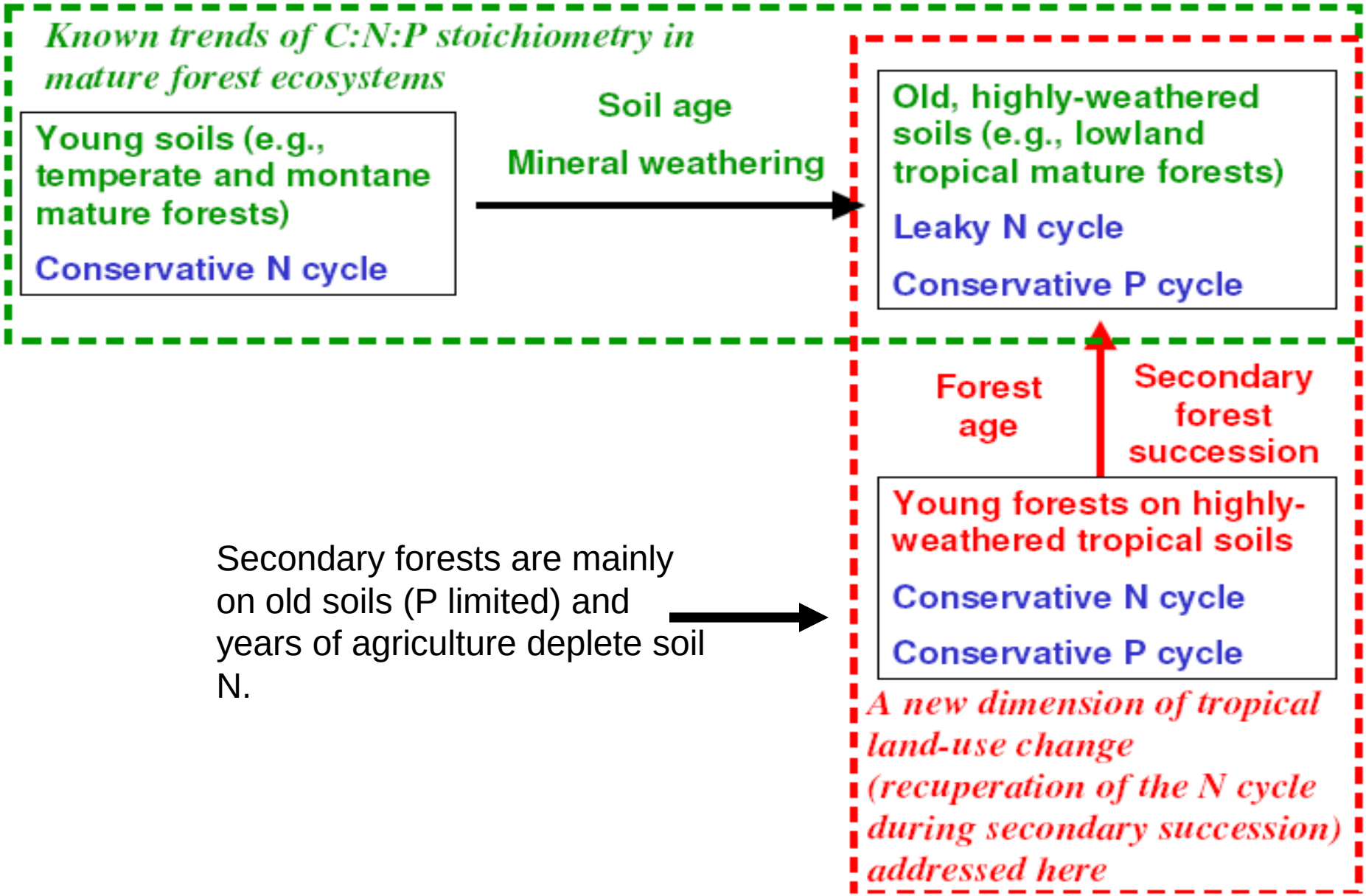
Rapid N-recovery in secondary forest





N-recovery secondary forests is rapid due to high levels of N-fixation

Davidson et al. 2007.
Nature 447:995-998



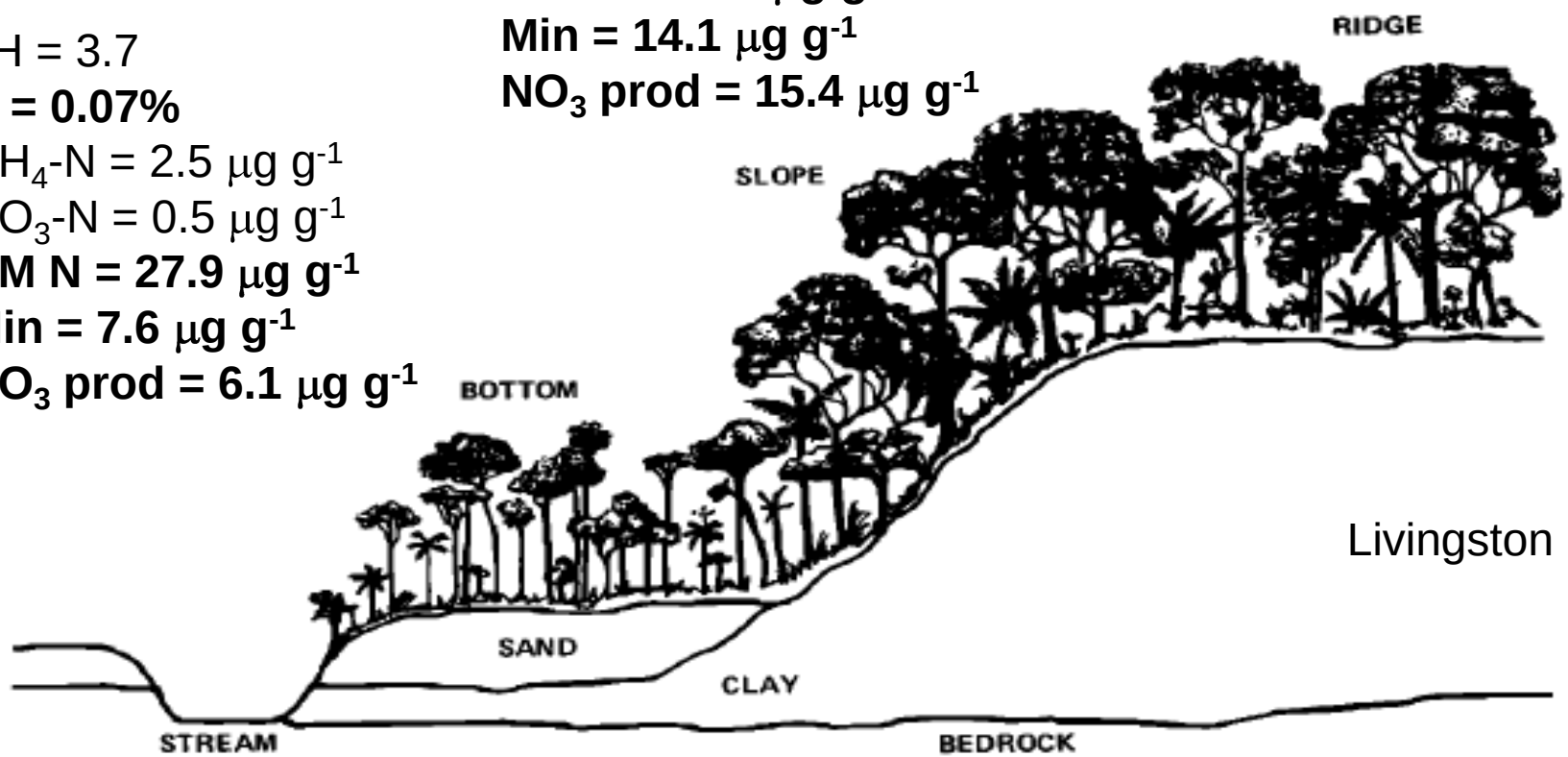
Secondary forests are mainly on old soils (P limited) and years of agriculture deplete soil N.

Spatial variability soil texture and fertility: Influence of topography

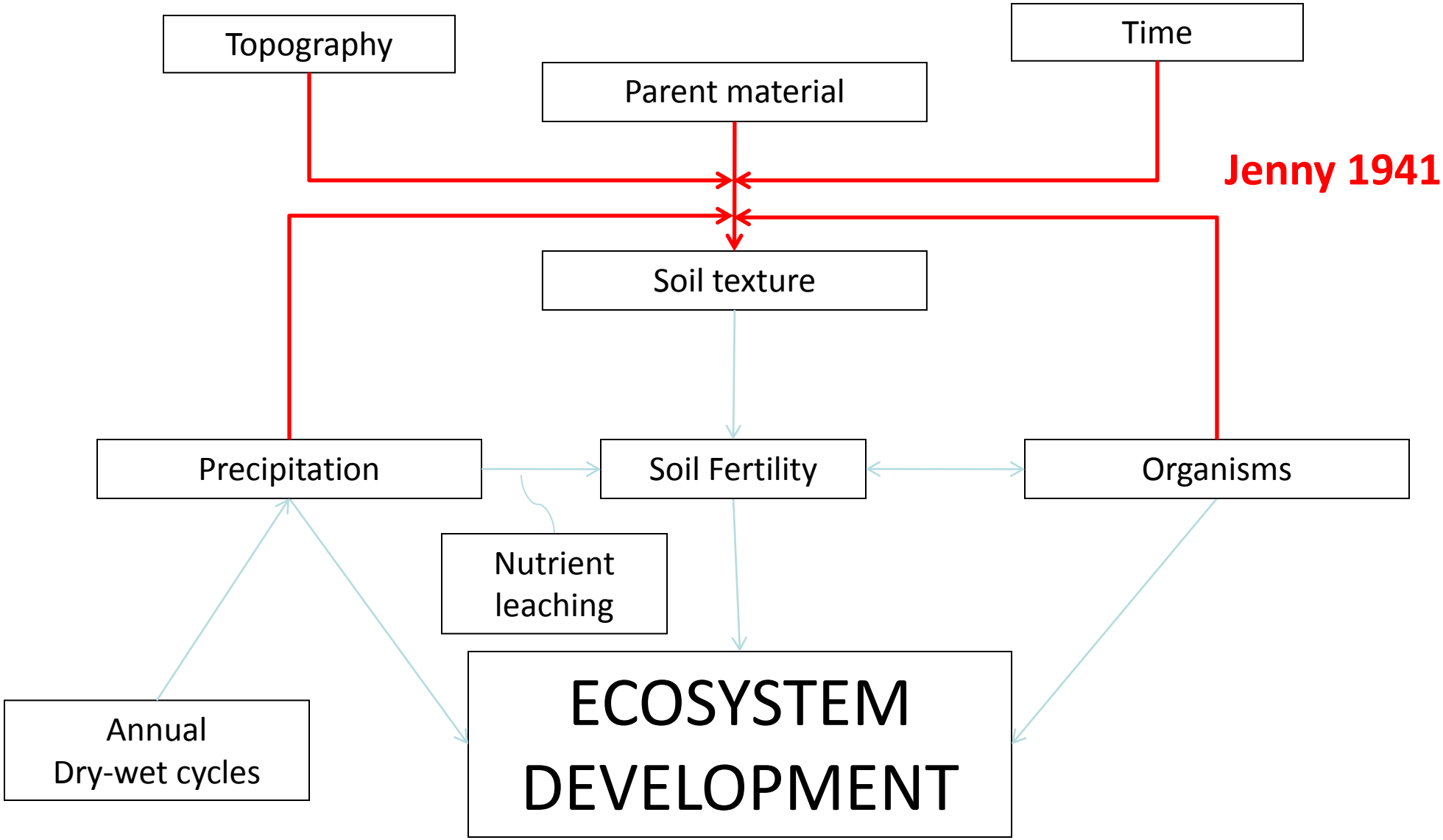
pH = 4.0
N = 0.22%
NH_4-N = 4.2 μg g^{-1}
NO_3-N = 1.3 μg g^{-1}
BM N = 119.6 μg g^{-1}
Min = 19.3 μg g^{-1}
NO_3 prod = 21.6 μg g^{-1}

pH = 4.0
N = 0.13%
NH_4-N = 2.7 μg g^{-1}
NO_3-N = 1.4 μg g^{-1}
BM N = 72.3 μg g^{-1}
Min = 14.1 μg g^{-1}
NO_3 prod = 15.4 μg g^{-1}

pH = 3.7
N = 0.07%
NH_4-N = 2.5 μg g^{-1}
NO_3-N = 0.5 μg g^{-1}
BM N = 27.9 μg g^{-1}
Min = 7.6 μg g^{-1}
NO_3 prod = 6.1 μg g^{-1}



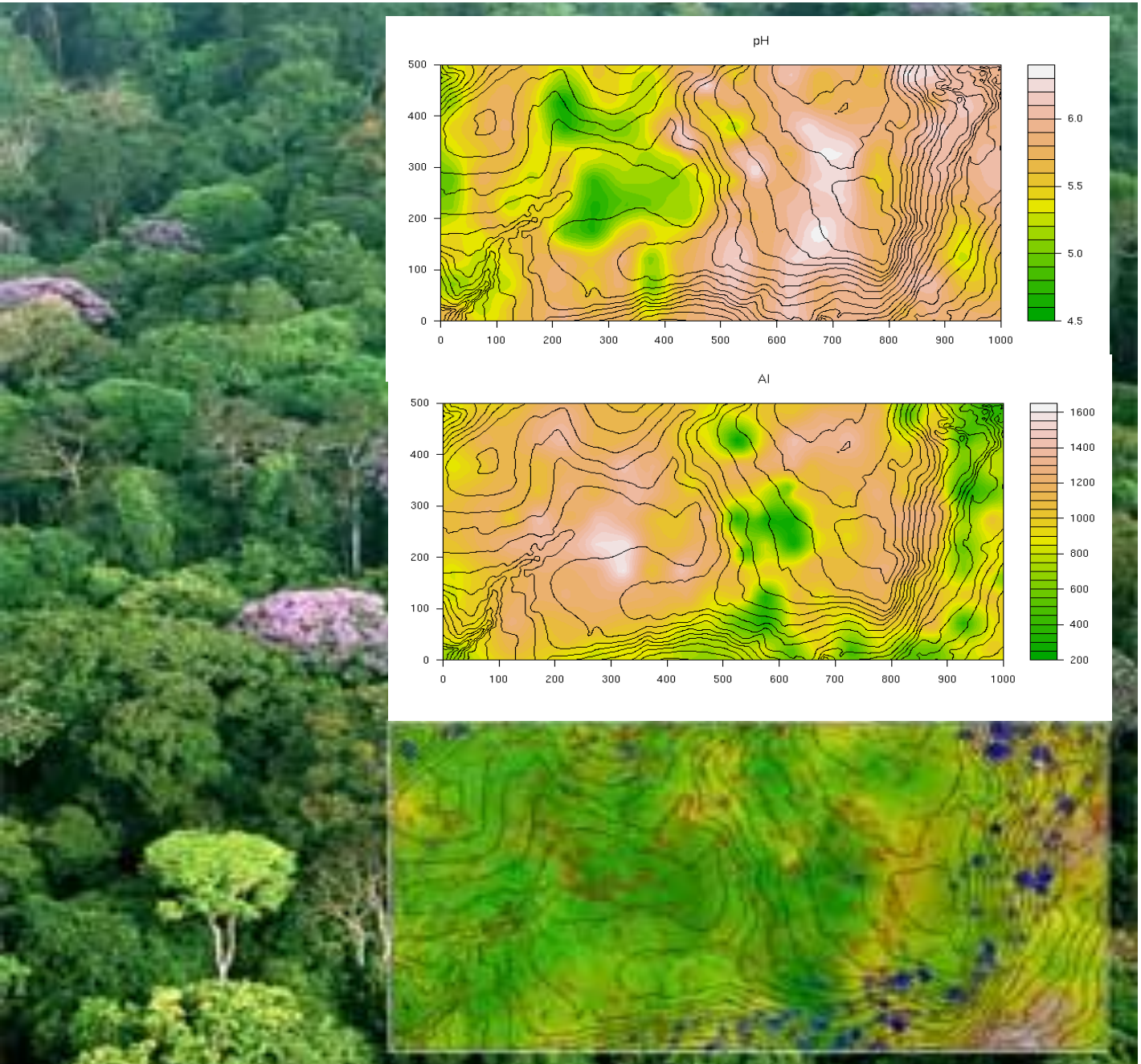
Livingston et al. 1988


Topography
Time
Parent material
Jenny 1941
Soil texture
Precipitation
Soil Fertility
Organisms
Nutrient leaching
Annual Dry-wet cycles
ECOSYSTEM DEVELOPMENT

Soil Nutrient content Forest diversity

- Temperate forests:
  - Old russian scientists already noticed that soils under broadleaf vs needleleaf forests were different.
  - Led to incorporation of organisms into the soil development function of Jenny (1941)
    - S = f(parent material, topography, time, climate, organisms, …..)
- High diversity in tropical forests makes analyses difficult

John et al. (2007) Soil chemistry and forest diversity



Per plot 300 soil samples are taken from 0-10cm; 1 per 20x20m block (composite of 3 samples taken at the center, 2 and 8m away from the center).

Used PC analyses for soil nutrients to correlate with plant species with either a minimum of 5 or 50 individuals.

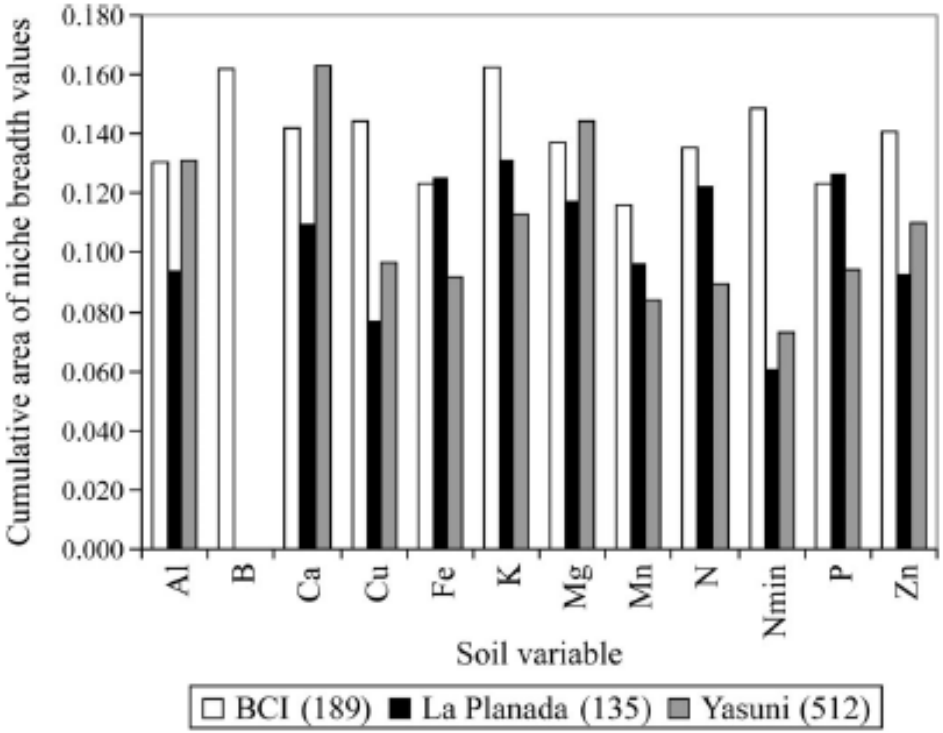


Fig. 3. The influence of soil nutrients on niche structure in the three forest dynamics plots. The values on the *y* axis are areas under the cumulative curves of species niche breadth values for each soil variable. The greater the area for a given soil variable, the greater the effect of that variable on niche structure. The values in parentheses are the total number of species analyzed at each site.

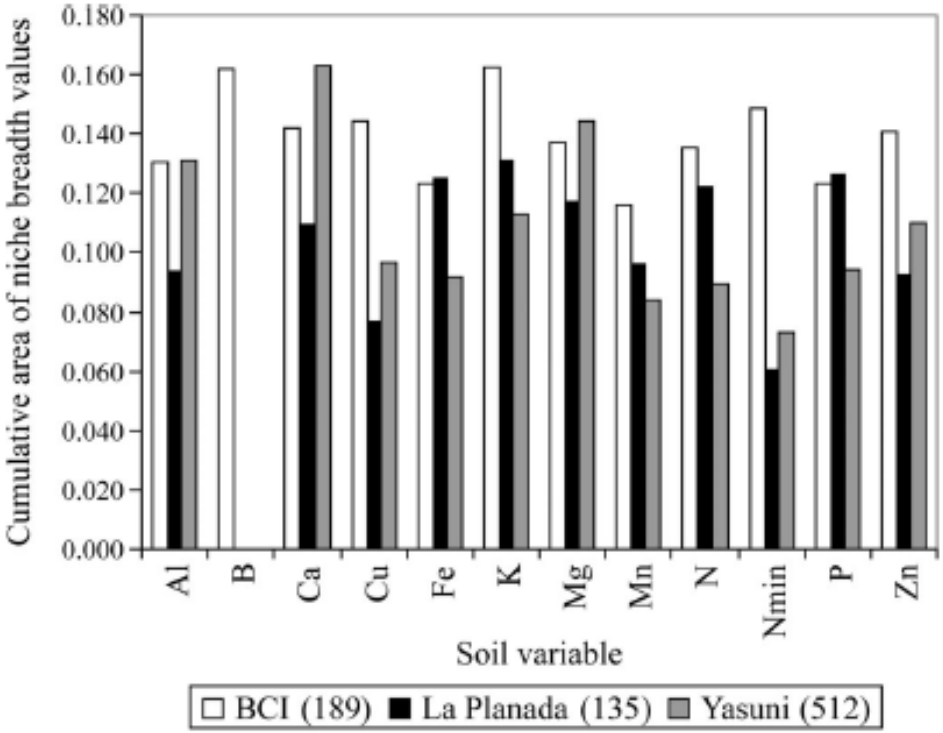
- Niche breaths indicate different nutrients most influential on species distribution

Conclusion: soil nutrient content influences plant diversity

Table 2. Soil nutrient concentrations and pH values in the three forest dynamics plots

Site	Al	B	Ca	Cu	Fe	K	Mg	Mn	N	N_{min}	P	Zn	pH
BCI	1,013.8	0.944	1732.5	8.08	178.5	171.8	298.9	370.7	25.92	17.84	2.90	5.66	5.66
	(233.3)	(0.536)	(743.2)	(2.04)	(46.2)	(74.7)	(128.0)	(155.6)	(7.96)	(12.82)	(1.62)	(4.14)	(0.34)
La Planada	3,732.4	—	168.6	2.20	562.2	62.5	26.1	3.9	22.71	−5.91	20.20	1.28	4.46
	(234.3)	(63.78)	(0.43)	(219.1)	(18.0)	(7.5)	(5.5)	(4.2)	(7.11)	(12.89)	(0.48)	(0.29)	
Yasuni	1,796.7	—	409.9	1.06	284.1	99.8	112.5	139.8	10.84	−0.21	6.34	1.44	4.63
	(278.8)	(275.4)	(0.49)	(82.4)	(112.0)	(65.2)	(95.0)	(3.01)	(4.08)	(2.35)	(0.55)	(0.31)	

For each plot, the top row gives plot-wide mean values (mg/kg) of 10 × 10 m quadrats, and the values in parentheses are standard deviations. N_{min}, N mineralization rates (mg/kg per 28 days).



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Problems:

- Causality problem, also possible: soil nutrient differences due to plant species composition
- Strongest influence of K and Ca on niche structure at La Planada and Yasuni, respectively is surprising.
- Only 0-10cm of soil sampled. Depth most strongly influenced by vegetation.

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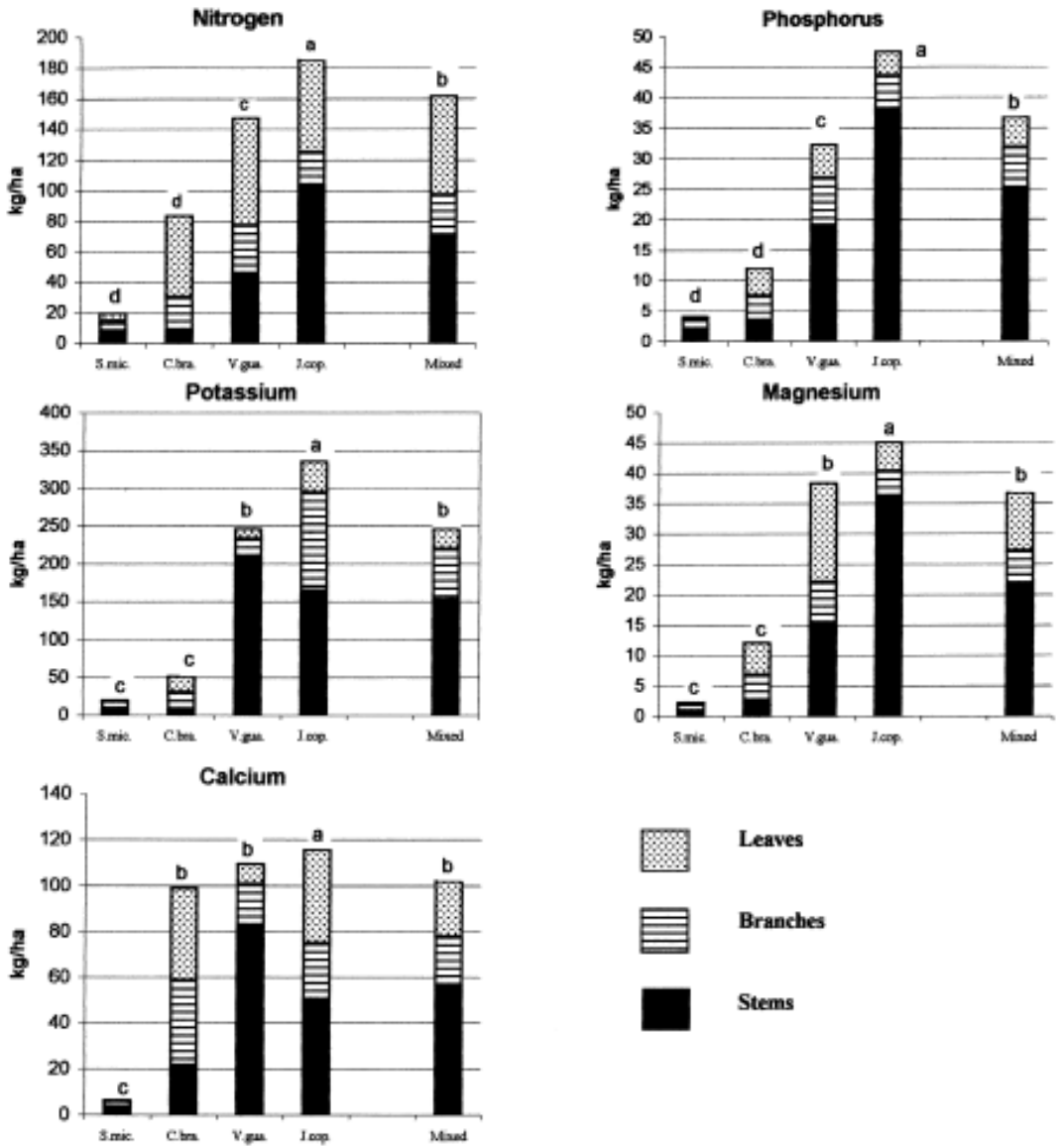
Contrary evidence

F. Montagnini / Forest Ecology and Management 134 (2000) 257–270



Plantation La Selva, CR:

-Monoculture or mixed species

-32x32m plots

-3 Randomized blocks with 4 replicates and 6 treatments (4 monocultures, mixed, and fallow)

Main conclusions:

-above-ground biomass and nutrient mass species very different

-Main nutrient differences in stem biomass, i.e., strongly related to GR

-**5 years** after planting significant effects on soil P concentration (to 35 cm depth)

Montagnini 2000

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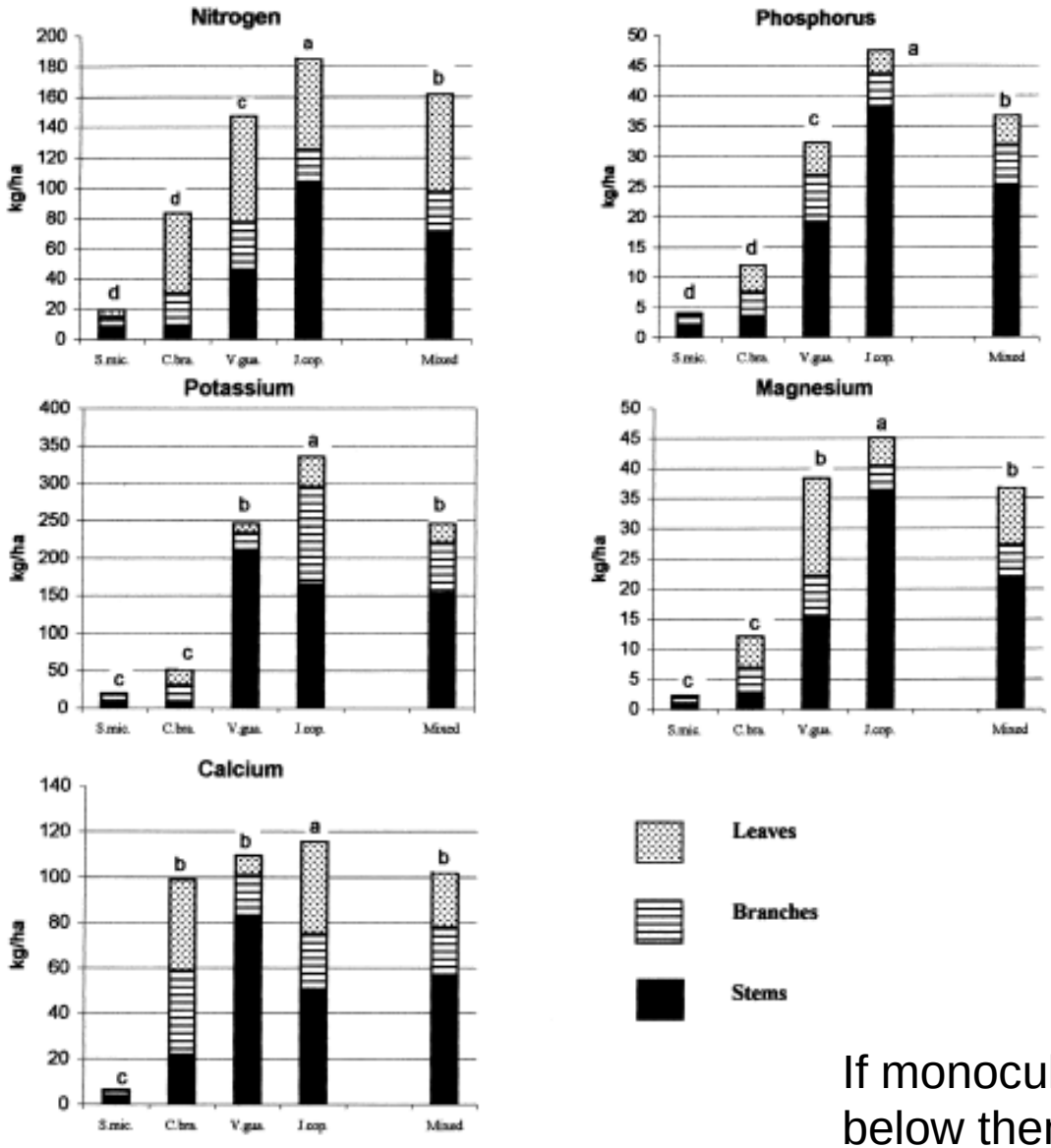

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Montagnini 2000

If monocultures already influence soil P below them after 5 years, why not large (>300 yr old) trees in diverse forests?

Summary

- Soil nutrient variability in three tropical forest plots appears to influence 36-51% of species distribution
- Multiple nutrients most influential at different sites

- I am not convinced that the John et al. paper really represents soil nutrient influence on tree species distribution

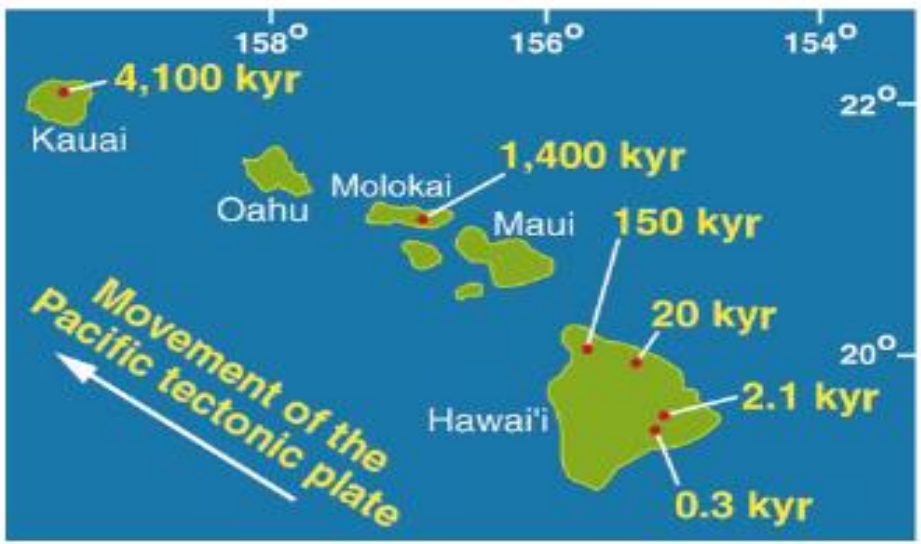
Land-use Fertilization effects

- Forest growth?
- Species effects?
- Nutrient cycling?

Land-use change leads to

- dust N and P fertilization from agriculture
- fire adds NH3, P, and micronutrients to natural ecosystems

Hawaii as a model of ecosystem development over 4.1 Myrs



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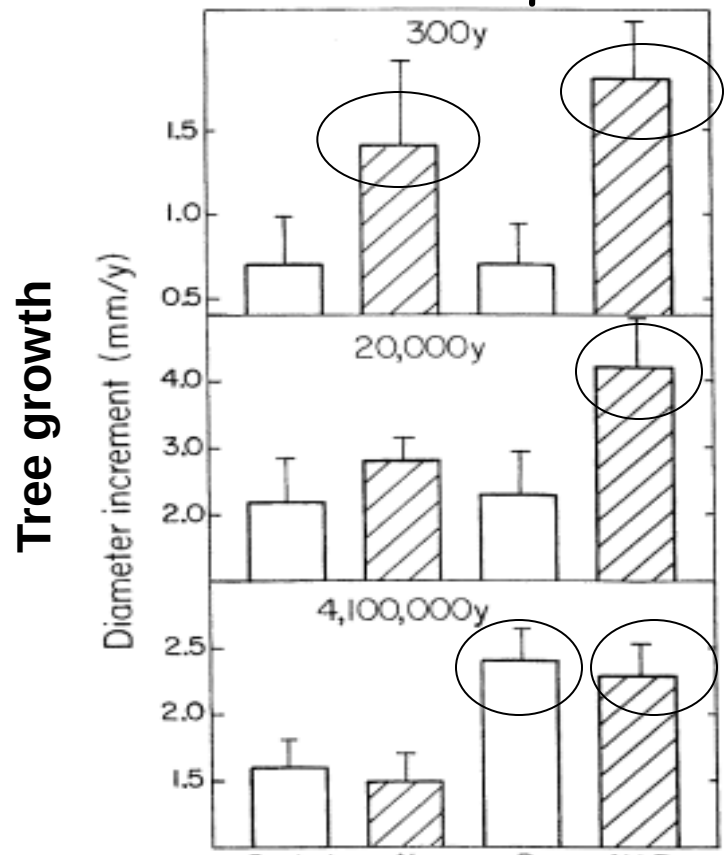


Young sites
N-limited

Middle sites jointly-limited

Old sites
P-limited

Treatment: Control N P N+P

Chadwick et al. (1999)

Vitousek & Farrington (1997)

Effect of soil nutrient status on Ecosystem response to fertilization

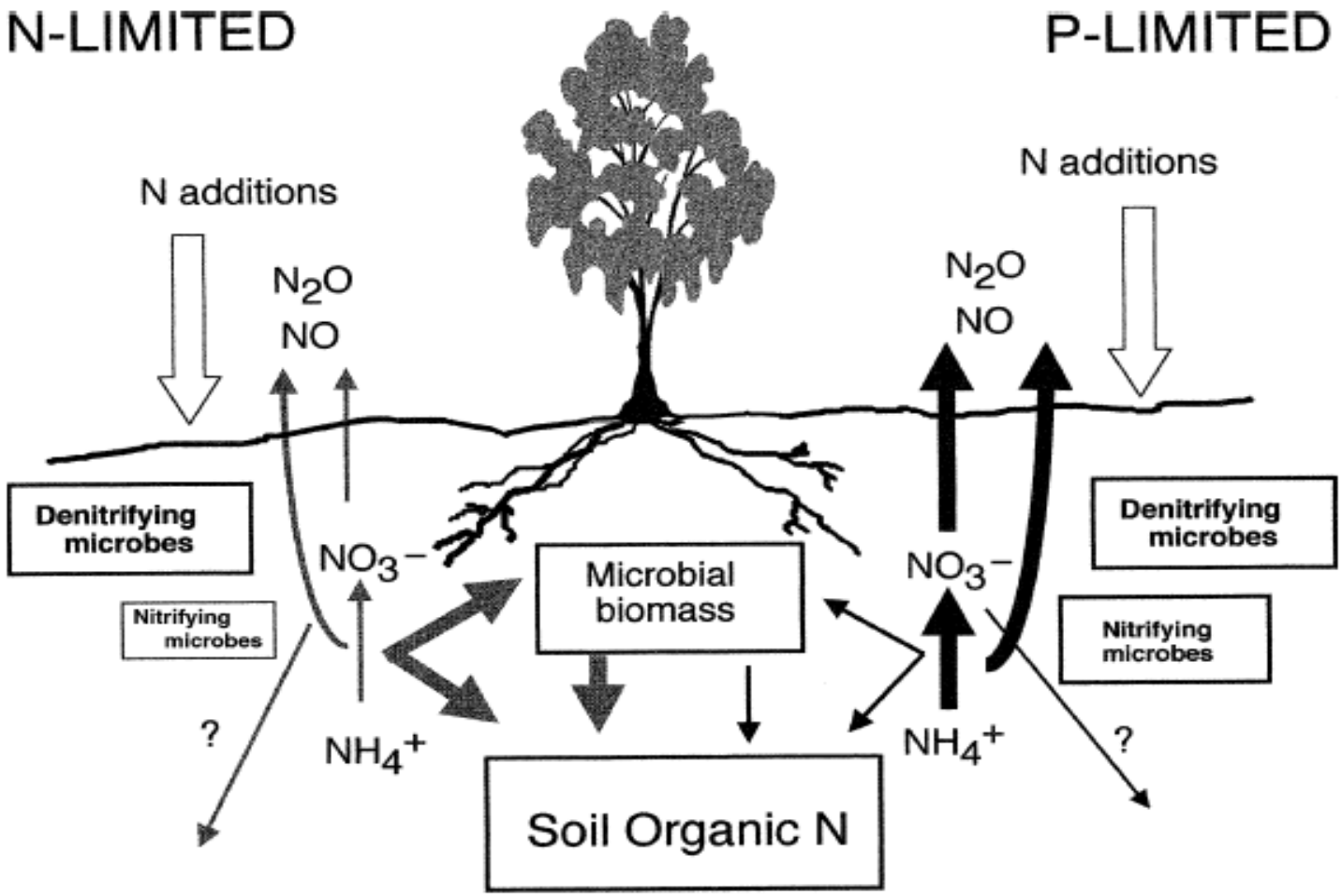


FIG. 12. N cycles in N-limited (left side of figure, gray arrows) and P-limited (right side of figure, black arrows) tropical forests. Only processes and pools related to soil N-oxide emissions in this study are shown. The size of arrows represents the relative rate of each process; the size of boxes represents the relative size of each pool.

P fertilization

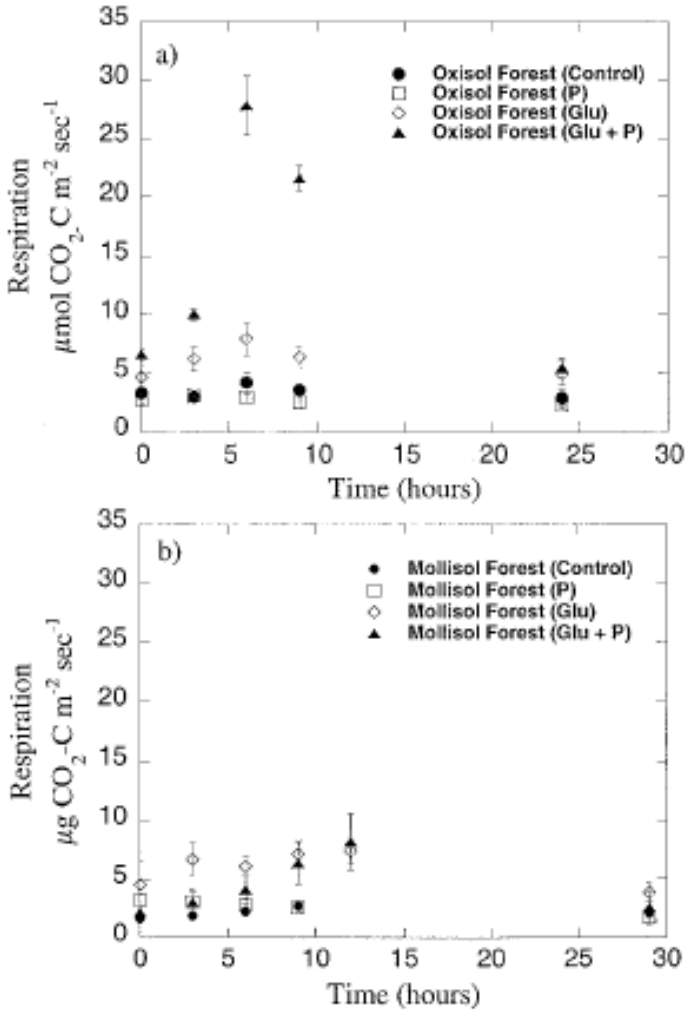


Figure 4. In situ soil respiration rates following Glu, P, or Glu + P fertilization in both (a) P-poor oxisol forest and (b) P-rich mollisol forest (b). Error bars are ± 1 SE.

Cleveland et al. (2005)

P fertilization in CR

•Microbial growth in P-poor soils is P limited

•Respiration increases only when both C and P added

N, P, and M fertilization

Methods:

•Continuously fertilized forest plots with N, P, and M (mix of micronutrients)

•Measured litter decomposition on litter sampled over a period of 6 yrs

Findings:

•Enhanced reproductive litter on N fertilized plots

•K and P enhance cellulose and litter decomposition

Conclusions:

•Tropical forests subject to multiple nutrient limitation

•N fertilization could change species reproductive investment and potentially long-term competition

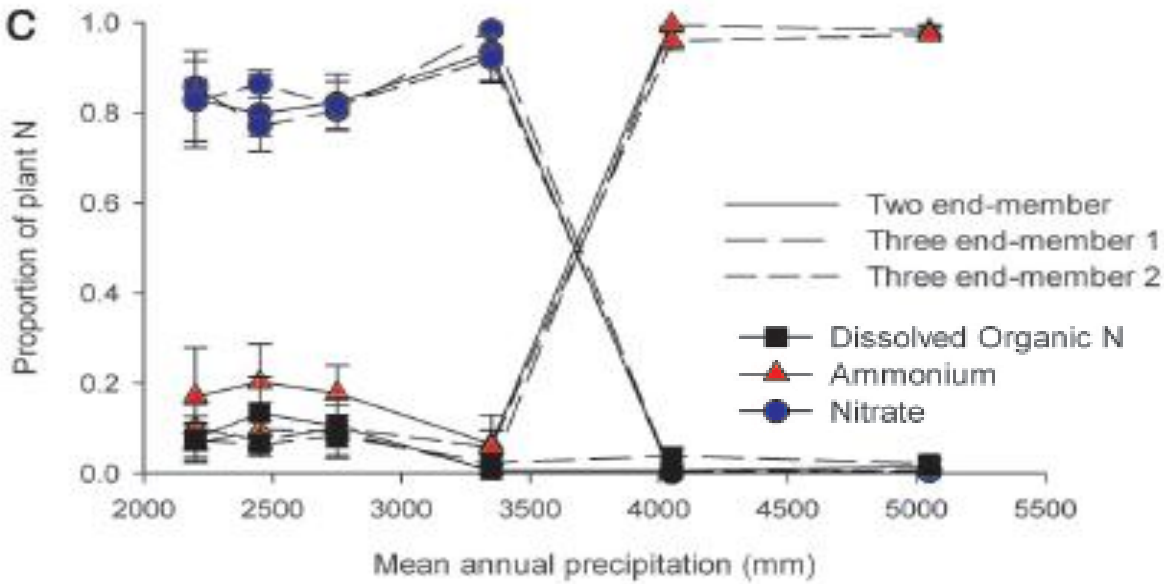
Kaspari et al. 2008

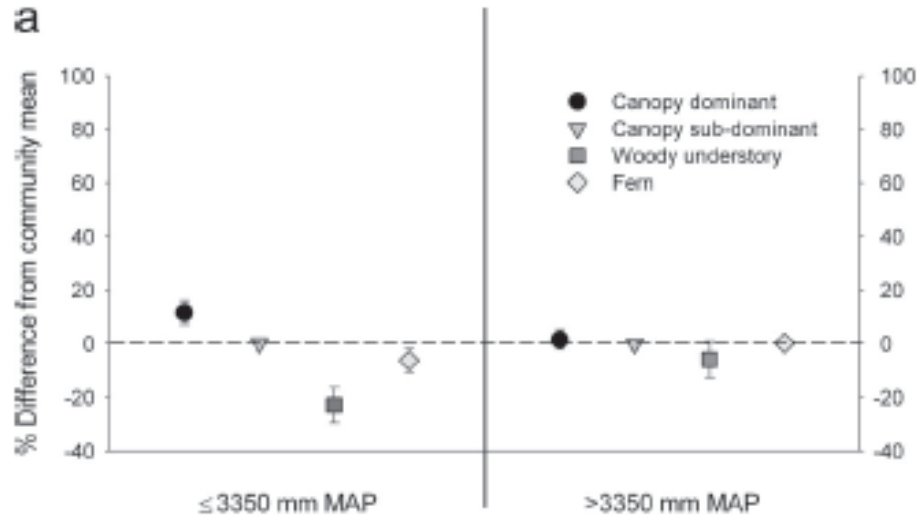
Fertilization summary

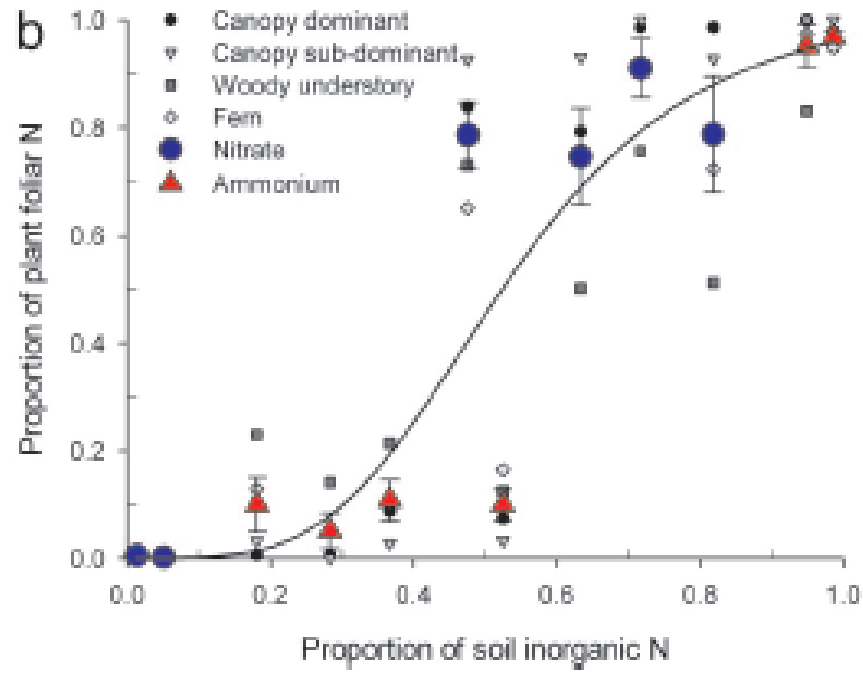
- Limited data suggest that fertilization effects can change
  - Forest carbon and nutrient uptake
  - species competition
  - Litter decomposition rates
  - N cycling

Davidson et al. (2007) paper suggest that this can have strong effects within present day human life-times

Houlton Climate driven switch N uptake







Plant species do not care what source of nitrogen they use!

Legume abundance explained?

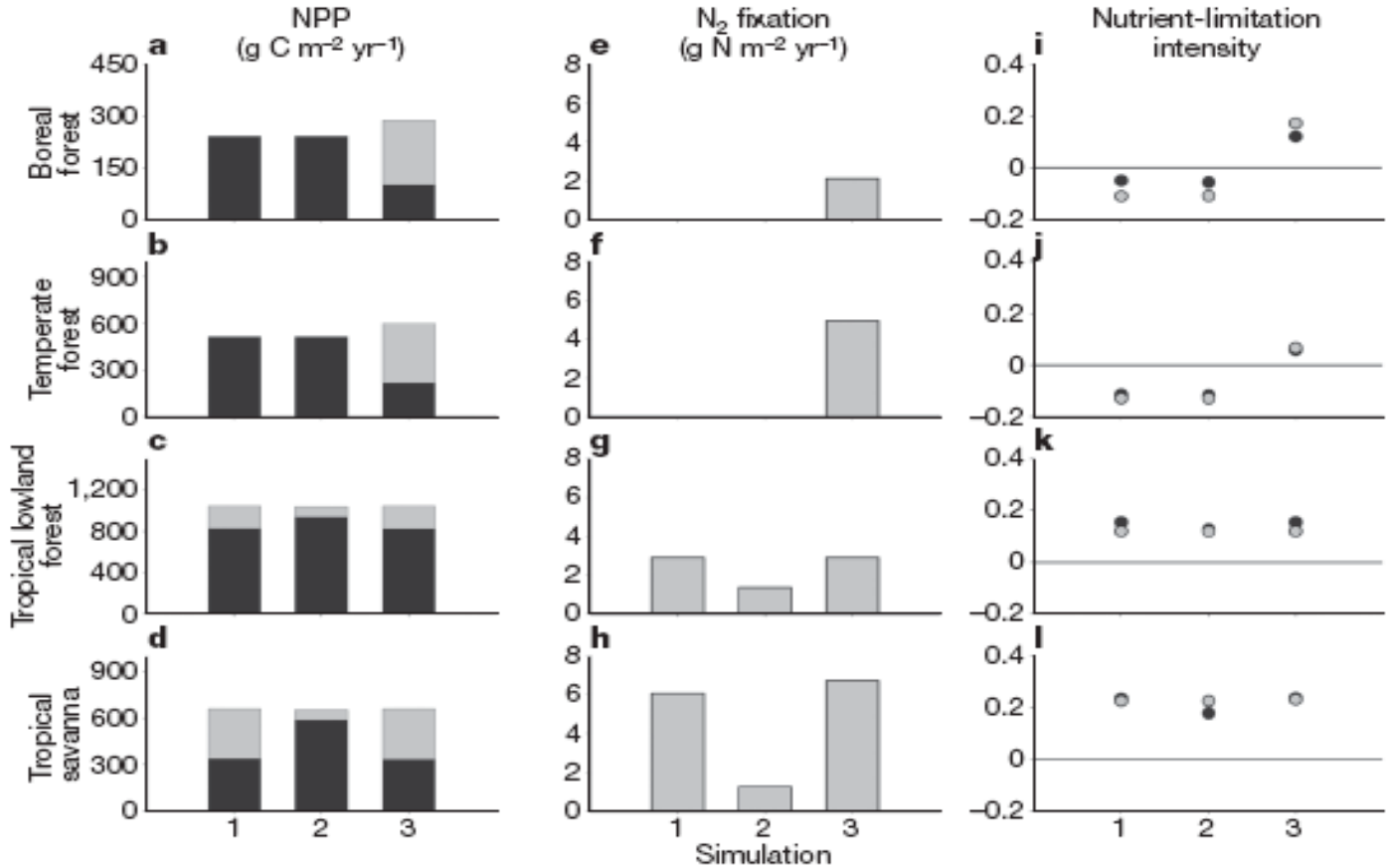
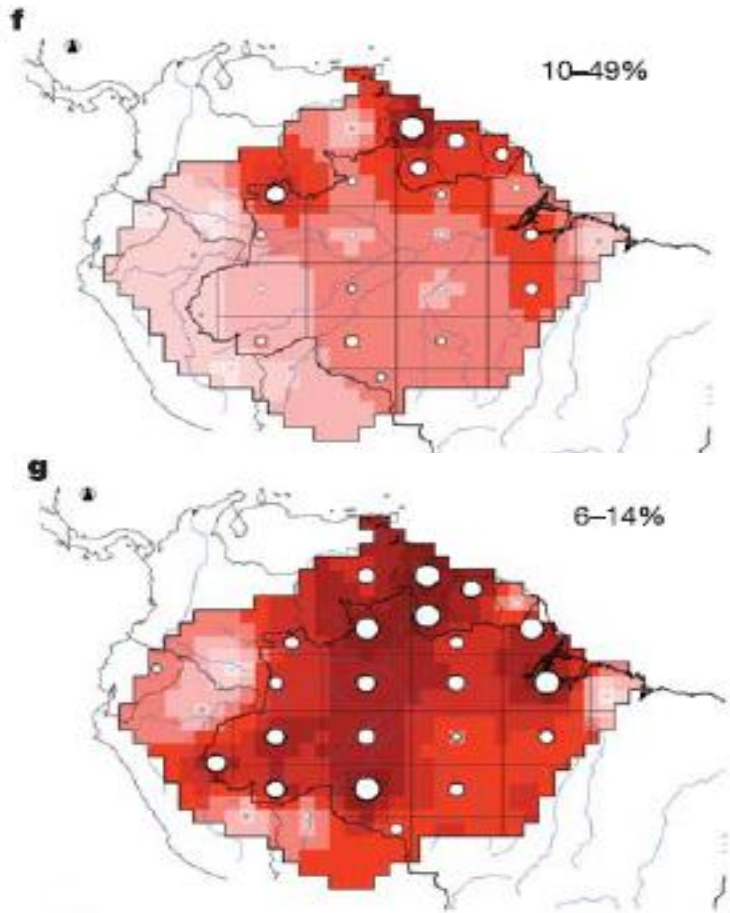
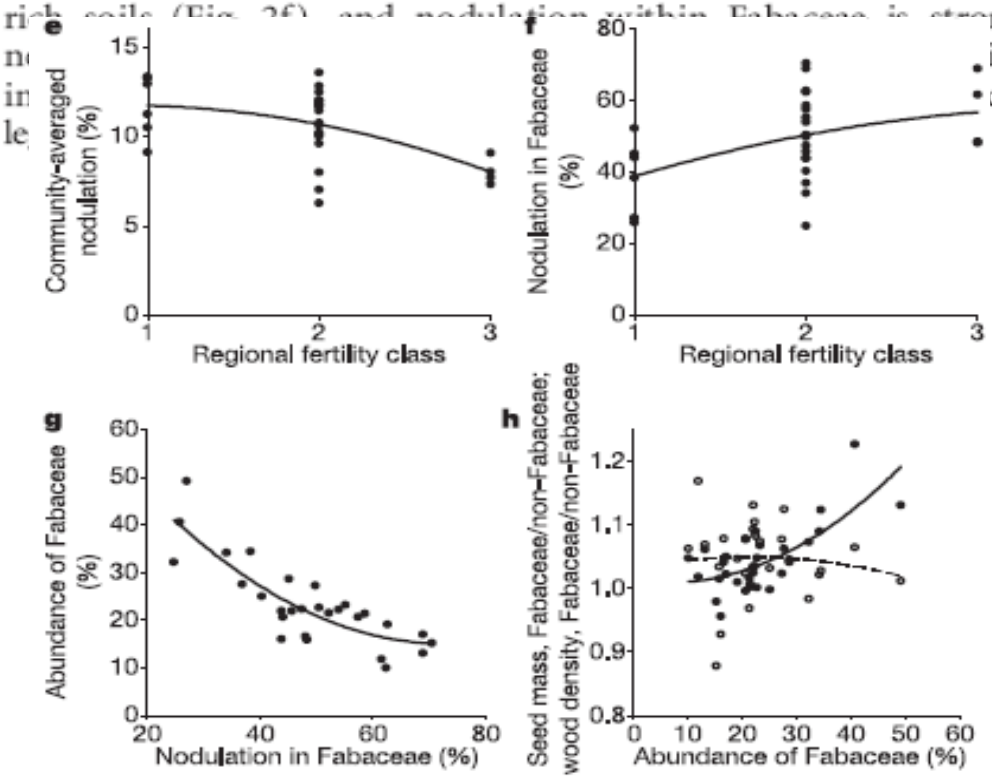


Figure 3 | Model results for different hypotheses across terrestrial biomes at steady state. **a–l**, The hypotheses tested are: (1), temperature-dependent N_2 fixation and individual-based P acquisition strategy (consistent with our proposed framework); (2), temperature-dependent N_2 fixation and global-commons P acquisition strategy; and (3), constant N_2 fixation (no temperature effect) and individual-based P acquisition strategy. **a–d**, NPP by N_2 fixers (grey) and non-fixers (black); **e–h**, the N_2 fixation rate; **i–l**, the nutrient-limitation intensity for N_2 fixers (grey) and non-fixers (black). Nutrient-limitation intensity was calculated as the difference in N availability minus P availability, such that positive values indicate P limitation and negative values indicate N limitation.

Neotropical legume occurrence

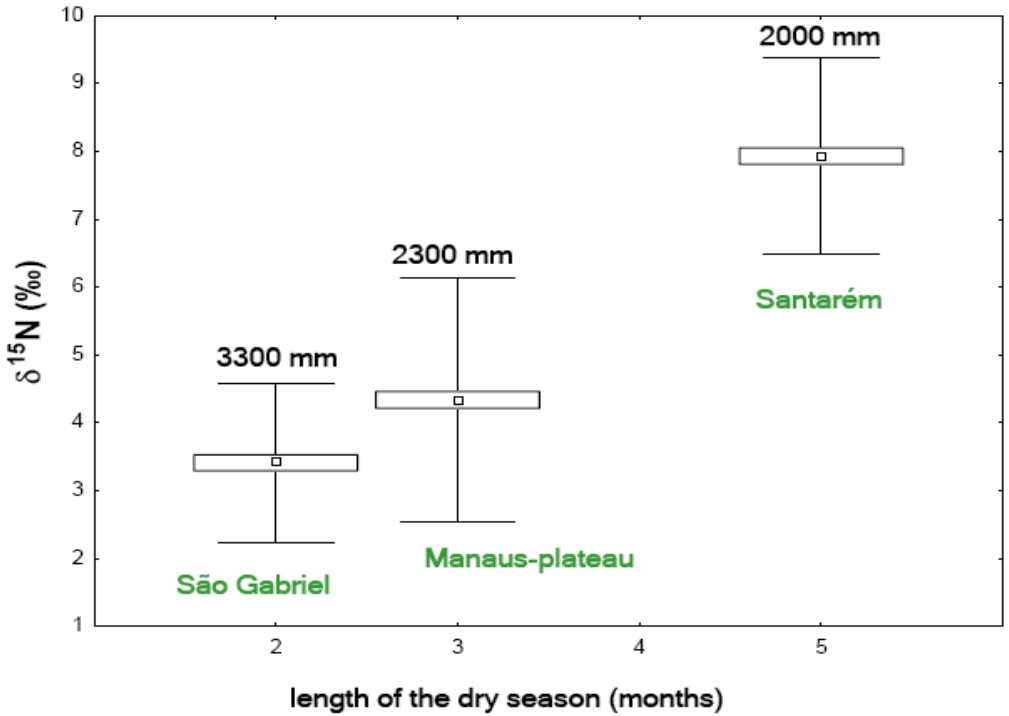


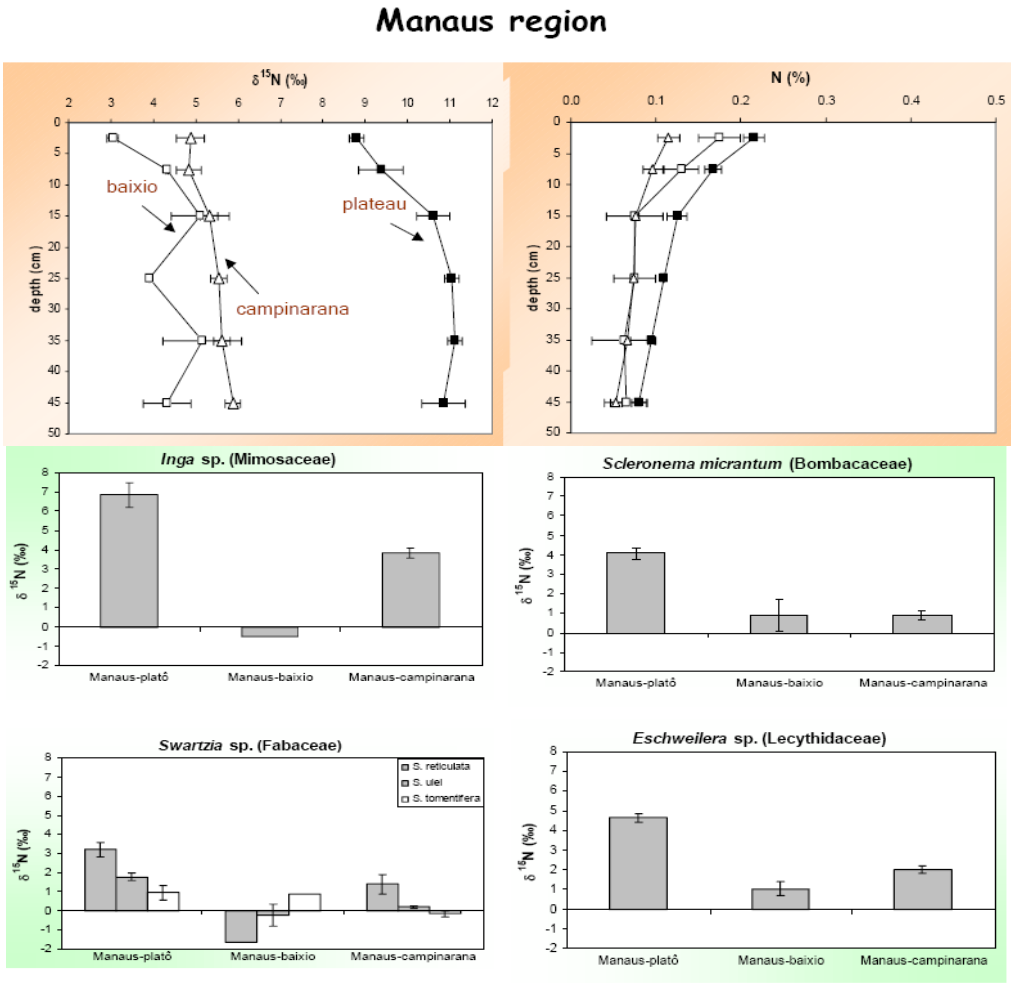
Because the first gradient is so strongly associated with the abundance of legumes (Fabaceae; Fig. 1f), we investigated the geographical distribution of two characteristics commonly associated with the family: nitrogen-fixing nodulation and ectomycorrhizal associations, both assumed adaptations to low-fertility soils[17]. Ectomycorrhizal association is apparently insignificant in northern South America (Fig. 1e), apart from small areas in Guyana (where the ectomycorrhizal genus *Dicymbe* is common) and the upper Rio Negro (where the ectomycorrhizal genus *Aldina* is common). Not surprisingly, individuals of nodulating genera are more common on poor soils (Figs 1g and 2e). However, individuals of nodulating genera represent a smaller fraction of all Fabaceae on poor soils than they do on



ter Steege et al. (2006)

$\delta^{15}N$ evidence





Nardoto (2005)

So why do legumes not fix N?

- Too carbon intensive?
- Too P intensive?

But why are they so abundant then?

- Are very important as early colonizers
- Relatively fast growers
- Are more versatile

Soil development summary

- Organisms need both soil and atmosphere derived nutrients
- Under natural conditions soil nutrient changes are relatively fast for atmospheric derived nutrients, but slow for soil derived nutrients
- Time frame of soil derived nutrients depends on soil depth and nutrient retention

Supporting evidence

Table 1. Means ± 95% confidence intervals of soil variables (0–15 cm depth mineral soil) sampled underneath the crowns of four tree species and neighbouring *Pentaclethra* trees (data for the paired *Pentaclethra* trees are listed beneath each focal tree species).

	Ca	K	Mg				
		(cmol(+)kg^{-1})		P (μg g^{-1})	%C	%N	pH($CaCl_2$)
Albizia	0.04 (0.02)	0.24 (0.03)	0.35 (0.05)	31.11 (7.98)	6.00 (0.79)	0.46 (0.05)	3.52 (0.18)
Pentaclethra	0.06 (0.05)	0.21 (0.03)	0.30 (0.04)	20.67 (4.38)	5.13 (1.07)	0.40 (0.07)	3.59 (0.17)
Dipteryx	0.13 (0.06)	0.26 (0.04)	0.46 (0.12)	28.51 (11.59)	5.72 (0.68)	0.45 (0.04)	3.66 (0.16)
Pentaclethra	0.08 (0.04)	0.51 (0.66)	0.42 (0.28)	26.06 (12.14)	5.14 (1.12)	0.42 (0.08)	3.72 (0.14)
Hyeronima	0.16 (0.10)	0.35 (0.14)	0.48 (0.15)	52.31 (48.54)	5.55 (1.15)	0.46 (0.09)	3.74 (0.20)
Pentaclethra	0.14 (0.23)	0.29 (0.08)	0.58 (0.40)	49.88 (31.15)	5.05 (0.87)	0.43 (0.09)	3.80 (0.26)
Lecythis	0.13 (0.07)	0.25 (0.03)	0.35 (0.10)	21.18 (6.17)	4.94 (0.48)	0.39 (0.03)	3.63 (0.20)
Pentaclethra	0.05 (0.04)	0.24 (0.08)	0.28 (0.13)	23.29 (6.96)	4.78 (0.58)	0.38 (0.04)	3.60 (0.23)

La Selva, CR:
-8 trees per species
-8 samples combined per tree
-Pair wise comparison to avoid soil specific variability

P and K suggest soil variability, though large uncertainty

Powers et al. 2005

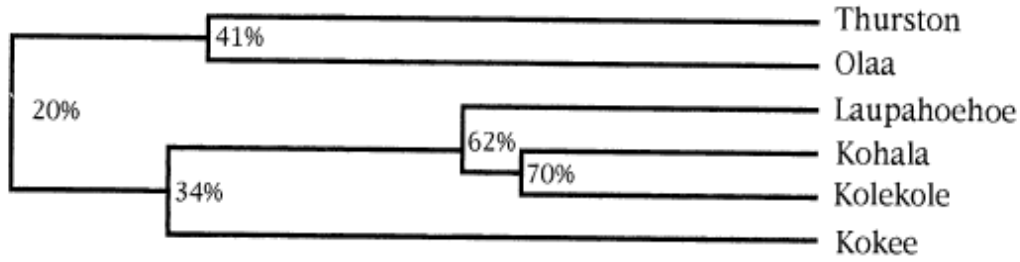


FIG. 8. Unweighted pair-group cluster analysis of quantitative species composition of chronosequence sites. Percentage values refer to similarities among sites based on percentage similarity coefficient (Kovach 1990).

Results from the DECORANA and cluster analyses (Figs. 7 and 8) suggest that factors related to soil development, such as site fertility, are important in determining the abundance and coverage of dominant species at different sites. The strong relationship be-

Crews et al. 1995