Soils and nutrient cycling in tropical forests

Carlos A. Sierra
Max Planck Institute for Biogeochemistry
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

<table>
<thead>
<tr>
<th>Element</th>
<th>Chemical symbol</th>
<th>Atomic/ Ionic forms</th>
<th>Approximate dry concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Macronutrients</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>NO$_3^-$, NH$_4^+$</td>
<td>4.0 %</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>PO$_4^{3-}$, HPO$_4^{2-}$, H$_2$PO$_4^-$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>K$^+$</td>
<td>4.0 %</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>Mg$^{2+}$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>SO$_4^{2-}$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>Ca$^{2+}$</td>
<td>1.0 %</td>
</tr>
<tr>
<td><strong>Micronutrients</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>Fe$^{2+}$, Fe$^{3+}$</td>
<td>200 ppm</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn</td>
<td>Mn$^{2+}$</td>
<td>200 ppm</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>Zn$^{2+}$</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>Cu$^{2+}$</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Boron</td>
<td>B</td>
<td>BO$_3^{2-}$, B$_4$O$_7^{2-}$</td>
<td>60 ppm</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Mo</td>
<td>MoO$_4^{2-}$</td>
<td>2 ppm</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>Cl$^-$</td>
<td>3000 ppm</td>
</tr>
<tr>
<td><strong>Essential</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>CO$_2$</td>
<td>40 %</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>H$_2$O</td>
<td>6 %</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>O$_2$, H$_2$O</td>
<td>40 %</td>
</tr>
</tbody>
</table>

Plant tissues also contain other elements (Na, Se, Co, Si, Rb, Sr, F, I) which are not needed for the normal growth and development.
<table>
<thead>
<tr>
<th>Function</th>
<th>Elements</th>
<th>Chemical form</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>H, O, C, N, P, S, Si, B, F, Ca</td>
<td>Organic compounds</td>
<td>Biological molecules, cell walls, tissue, skeletons, etc.</td>
</tr>
<tr>
<td>Electrochemical</td>
<td>H, Na, K, Cl, HPO$_4$(^{-2})</td>
<td>Free ions</td>
<td>Message transmission, cellular signaling, energy metabolisms</td>
</tr>
<tr>
<td>Catalytic (acid base)</td>
<td>Zn, Ni, Fe, Mn</td>
<td>Complexed with enzymes</td>
<td>Digestion, hydrolisis, PO$_4$ removal in acid media</td>
</tr>
<tr>
<td>Catalytic (redox)</td>
<td>Fe, Cu, Mn, Mo, Se</td>
<td>Complexed with enzymes</td>
<td>Reactions with O$_2$, N fixation, reduction of nucleotides</td>
</tr>
</tbody>
</table>

Sterner & Elser, 2002.
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
N and P are the most important nutrients for biological activity

Sterner & Elser 2002
Different biological molecules have fixed stoichiometric proportions
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.

![Diagram showing N:P ratios and their implications]

- N:P < 14
- N:P > 16
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

![Map of Hawaii showing various islands and sites with ages in years](image)

**Table 1. Hawaiian chronosequence: site descriptions.**

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

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
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

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

\( L = \text{Light} \)
\( N = \text{Nutrients} \)
\( W = \text{Water} \)

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>
<thead>
<tr>
<th>Type of association</th>
<th>Key characteristics</th>
<th>Representative genera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heterotrophic N fixers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Associative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodulated (symbiotic)</td>
<td>Legume</td>
<td>Rhizobium</td>
</tr>
<tr>
<td></td>
<td>Non- legume woody plants</td>
<td>Frankia</td>
</tr>
<tr>
<td>Non-nodulated</td>
<td>Rhizosphere</td>
<td>Azotobacter, Bacillus</td>
</tr>
<tr>
<td></td>
<td>Phyllosphere</td>
<td>Klebsiella</td>
</tr>
<tr>
<td>Free-living</td>
<td>Aerobic</td>
<td>Azotobacter, Rhizobium</td>
</tr>
<tr>
<td></td>
<td>Facultative aerobic</td>
<td>Bacillus</td>
</tr>
<tr>
<td></td>
<td>Anaerobic</td>
<td>Clostridium</td>
</tr>
<tr>
<td>Phototrophic N fixers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Associative</td>
<td>Lichens</td>
<td>Nostoc, Calothrix</td>
</tr>
<tr>
<td></td>
<td>Liverworts (Marchantia)</td>
<td>Nostoc</td>
</tr>
<tr>
<td></td>
<td>Mosses</td>
<td>Holosiphon</td>
</tr>
<tr>
<td></td>
<td>Gymnosperms (Cycas)</td>
<td>Nostoc</td>
</tr>
<tr>
<td></td>
<td>Water fern (Azolla)</td>
<td>Nostoc</td>
</tr>
<tr>
<td>Free-living</td>
<td>Cyanobacteria</td>
<td>Nostoc, Anabaena</td>
</tr>
<tr>
<td></td>
<td>Purple non-sulfur bacteria</td>
<td>Rhodospirillum</td>
</tr>
<tr>
<td></td>
<td>Sulfur bacteria</td>
<td>Chromasrum</td>
</tr>
</tbody>
</table>
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

\[ R-\text{OPO}_3^{2-} + \text{H}_2\text{O} \longrightarrow R-\text{OH} + \text{H}^+ + \text{PO}_4^{3-} \]
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

Aboveground NPP

Belowground NPP

Total NPP

LAI index

Clay soils
Sandy soils

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

- **Shifting Cultivation**
- A clearance is made by cutting down trees and burning vegetation. This is called "Slash and Burn".
- The clearing gradually grows over and the natural forest returns.
- Crops are planted and grow well in the warm, humid conditions.
- The clearing is abandoned and the farmers move on.
- Within four or five years the soil becomes exhausted and the harvest gets poorer and poorer.
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.

<table>
<thead>
<tr>
<th></th>
<th>Plant dry mass</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kilograms per hectare</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-burn forest*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaves</td>
<td>8,647</td>
<td>160</td>
<td>5.1</td>
<td>37.7</td>
<td>14.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Stems†</td>
<td>252,318</td>
<td>785</td>
<td>26.0</td>
<td>207.2</td>
<td>194.1</td>
<td>49.3</td>
</tr>
<tr>
<td>Roots</td>
<td>48,525</td>
<td>540</td>
<td>17.1</td>
<td>43.1</td>
<td>45.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Fine litter</td>
<td>7,630</td>
<td>109</td>
<td>2.1</td>
<td>8.3</td>
<td>3.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Dead wood</td>
<td>21,200</td>
<td>128</td>
<td>1.1</td>
<td>3.4</td>
<td>6.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Total</td>
<td>338,340</td>
<td>1,722</td>
<td>51.4</td>
<td>299.7</td>
<td>261.0</td>
<td>71.4</td>
</tr>
<tr>
<td>5-yr-old regrowth forest:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaves</td>
<td>4,920</td>
<td>163</td>
<td>4.9</td>
<td>21.4</td>
<td>25.2</td>
<td>8.4</td>
</tr>
<tr>
<td>Stems†</td>
<td>35,170</td>
<td>65</td>
<td>3.5</td>
<td>58.0</td>
<td>70.7</td>
<td>18.3</td>
</tr>
<tr>
<td>Roots</td>
<td>8,250</td>
<td>61</td>
<td>2.7</td>
<td>33.7</td>
<td>22.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Fine litter</td>
<td>5,180</td>
<td>69</td>
<td>1.6</td>
<td>6.0</td>
<td>30.8</td>
<td>13.9</td>
</tr>
<tr>
<td>Dead wood</td>
<td>68,762</td>
<td>443</td>
<td>4.2</td>
<td>12.8</td>
<td>25.4</td>
<td>9.8</td>
</tr>
<tr>
<td>Total</td>
<td>122,382</td>
<td>741</td>
<td>18.9</td>
<td>131.9</td>
<td>175.9</td>
<td>53.6</td>
</tr>
<tr>
<td>Regrowth forest total live plus dead biomass ÷ pre-burn forest total mass</td>
<td>36</td>
<td>43</td>
<td>33</td>
<td>44</td>
<td>67</td>
<td>75</td>
</tr>
<tr>
<td>Regrowth forest live biomass ÷ pre-burn forest live biomass</td>
<td>16</td>
<td>15</td>
<td>23</td>
<td>39</td>
<td>48</td>
<td>45</td>
</tr>
</tbody>
</table>

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.

**B) Nitrogen**

<table>
<thead>
<tr>
<th>Mature forest</th>
<th>19-yr-old forest</th>
<th>Degraded pasture</th>
<th>Managed pasture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1370 kg ha(^{-1})</td>
<td>273 kg ha(^{-1})</td>
<td>35 kg ha(^{-1})</td>
<td>20 kg ha(^{-1})</td>
</tr>
</tbody>
</table>

**O horizon:** 224 kg ha\(^{-1}\)

- **Soil 0-10 cm:** 2238 kg ha\(^{-1}\)
- **Solution Flux at 25 cm:** 2582 kg ha\(^{-1}\)
- **Soil 0.1-8 m depth:** 19121 kg ha\(^{-1}\)

**Stream export:** 0.9 kg ha\(^{-1}\) yr\(^{-1}\)

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

Known trends of C:N:P stoichiometry in mature forest ecosystems

- Young soils (e.g., temperate and montane mature forests)
  - Conservative N cycle

Soil age

Mineral weathering

Old, highly-weathered soils (e.g., lowland tropical mature forests)

- Leaky N cycle
- Conservative P cycle

Forest age

Secondary forest succession

- Young forests on highly-weathered tropical soils
  - Conservative N cycle
  - Conservative P cycle

A new dimension of tropical land-use change (recuperation of the N cycle during secondary succession) addressed here

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
Continuous cultivation and fertilization
However, continuous cultivation is not sustainable
Phosphorous peak

REMAINING PHOSPHATE ROCK RESERVES
16 000 MT rock
( ~ 2112 MT P )
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.