Geology and Soils

• Objectives
  – To gain a general understanding of:
    • 5 state factors and how they influence soil development
    • General types of soils & their defining characteristics
    • Soil physical, chemical, and biological properties

Additional Readings:
Geology and Soils

• Why should we talk about geology and soils in a class on ecosystem ecology?
  – Within a given climatic regime, soil properties are the major control over ecosystem distribution and processes
  – Source of 2 of the 3 major plant resources (H₂O & nutrients)
  – Provide a physical support system (i.e., rooting medium) for plants, and habitat for soil micro-, meso- and macroorganisms
  – Soil physical/chemical/biological properties influence ecosystems which, in turn, influence soil physical/chemical/biological properties
  – Intersection of bio, geo, and chemistry (i.e., biogeochemistry) occurs largely in soil
    • All in a very thin film over Earth’s surface
Geology and Soils

• What is soil composed of?
  – Roughly 15-35% H₂O and 15-35% air (30-70% pore space)
  – ~45-50% minerals
  – 1-5% OM

  – Where does the mineral component of soils come from?
Geology and Soils

• Weathering (parent rocks/minerals → more stable forms)
  – **Physical**: disintegration of parent material into smaller and smaller particles (no chemical change)
    • Important for soil structure
    • Increases the surface area : volume ratio
  
  – **Chemical**: minerals in parent material and soils react with acidic and oxidizing agents to change chemical form
    • Primary minerals (feldspars, micas) → secondary minerals (silicate clays) → other secondary minerals
    • Important source of nutrients (P, K, Ca, Mg; but not N)
State Factors

Soil formation = \( f(\text{development, deposition, erosion}) \)
Parent material – The Rock Cycle

- Rock Cycle: Formation & weathering of parent material
- Important source of nutrients
- Lithosphere cycles every 100-200 million years
Parent material – Plate tectonics

Mountain ranges and volcanoes

Crumpled sedimentary and metamorphic rocks

Granite

Trench

Lithosphere
Climate

• Physical weathering (Direct)
  – Leaching and erosion
  – Expansion/contraction (wet/dry & freeze/thaw)
  – Abrasion (wind, ice, water)

• Chemical weathering rates (Indirect)
  – Process rates

• Biological activity (Indirect)
  – Productivity, decomposition, nutrient cycling
Climate

Global Soil Regions

Annual Total Precipitation

Average Annual Temperature
Climate
Topography

• Topography influences soil formation through 2 main processes
  1. Climate effects
     • Solar radiation → differences in temperature and moisture → differences in weathering rates & chemical processes
Topography

- Topography influences soil formation through 2 main processes
  2. Differential transport of fine soil particles via erosion and deposition
Potential biota

• Physical weathering (plant roots)

• Chemical weathering (carbonic acid)
  – \(\text{H}_2\text{O} + \text{CO}_2 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \leftrightarrow \text{H}_2\text{CO}_3\)

• Primary production \(\rightarrow\) organic matter quantity and quality
  – OM is an important component of soils
    • Distributed through soil profile by biological (roots, micro- and macrofauna) and physical (leaching) forces
  – OM \(\rightarrow\) organic acid \(\rightarrow\) chemical weathering

• Geologic pumps
  – Redistribute bio-essential elements to surface soils
Time

- Weathering preferentially removes Si, Ca, Na, Mg, and enriches Fe and Al
  - Susceptibility to weathering: Cl > SO₄ > Na > Ca > Mg > K > Si > Fe > Al
- Biota enrich soils in C, O, H, N

Table 4.1  Approximate Mean Composition of the Earth’s Continental Crust

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percentage composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>28.8</td>
</tr>
<tr>
<td>Al</td>
<td>7.96</td>
</tr>
<tr>
<td>Fe</td>
<td>4.32</td>
</tr>
<tr>
<td>Ca</td>
<td>3.85</td>
</tr>
<tr>
<td>Na</td>
<td>2.36</td>
</tr>
<tr>
<td>Mg</td>
<td>2.20</td>
</tr>
<tr>
<td>K</td>
<td>2.14</td>
</tr>
<tr>
<td>Ti</td>
<td>0.40</td>
</tr>
<tr>
<td>P</td>
<td>0.076</td>
</tr>
<tr>
<td>Mn</td>
<td>0.072</td>
</tr>
<tr>
<td>S</td>
<td>0.070</td>
</tr>
</tbody>
</table>

*Data from Wedepohl (1995).*
Time

- Most soil processes occur slowly, and time interacts with other state factors

Walker and Syers (1976)
Human Activities

• Are humans a 6th state variable?

• Direct impacts
  – Nutrient and sediment inputs, irrigation, land use change (modification of biota), acceleration of erosion and deposition, reductions in SOM (e.g., ag fields), etc.

• Indirect
  – Changes in atmospheric composition (climate), and alteration of microenvironment
Soil profile development

- Soil properties are the result of a dynamic balance in continual flux determined by:
  1. Additions to and losses from soil
  2. Transformations and transfers within soil
Additions to soils

• Inputs from outside ecosystem
  – Atmospheric inputs: Precipitation, dust
  – Horizontal inputs: Floods, deposition

• Inputs from within ecosystem
  – Weathering of parent material
  – Organic matter
    • Primary production
    • Litterfall and root turnover
Soil losses

1. Leaching (driven by movement of H$_2$O)
   - Monovalent cations (Na$^+$, K$^+$) and anions (Cl$^-$, NO$_3^-$) lost most easily

2. Gaseous loss (driven by microbial activity and diffusion gradients)
   - Loss of organic matter as CO$_2$ and CH$_4$, N trace gases, etc.

3. Erosion and mass wasting
Transformations - Physical

• Predominate in severe environments
• Cracks (e.g., roots) or abrasion (e.g., glaciers)
• No chemical change
• Produces coarse textured soils
• Importance lies in creation of new surfaces for chemical weathering
  – Increases surface area : volume ratio
Transformations - Chemical

- Involves chemical change
  - Conversion from primary to secondary minerals
- Promoted by water and heat (i.e. climate)
- Varies with parent material
- Stimulated by acidity
  - What are main acids in soils?
Soil transfers

• Vertical movement largely determines soil profiles
  – Downward leaching driven by water
  – Upward capillary rise (e.g., salinization)
  – Distribution of plant roots; plants as geochemical pumps
  – Soil mixing by animals

![Soil profile diagram showing average leaching depth and carbonate accumulation.](image)
Typical Soil Profile

- Driven by additions, transformations, transfers, accumulations, and losses

[Diagram showing soil profile with labeled horizons and descriptions]

- **O** Organic, slightly decomposed
  - **Oe** Organic, moderately decomposed
  - **Oa** Organic, highly decomposed

  - Mineral, mixed with humus, dark colored

  - Horizon of maximum leaching of silicate clays, Fe, Al oxides, etc.

  - Zone of Fe and Al accumulation

  - Zone of least weathering and accumulation; contains unweathered parent material

- **R** Bedrock
Typical Soil Profile

- Presence/absence and degree of formation of profiles is used to classify soils into broad soil orders
Soil Orders

• Soil order is determined largely by degree of weathering
U.S. Soil Orders

- ~40% of ice-free surface has minimal development
- 12% associate with very dry areas
- <50% of soils responsible for vast majority of biological activity
- What are the important soil orders in Hawaii, and why?

![Table 3.3](image)

Table 3.3 Names of the soil orders in the U.S. soil taxonomy and their characteristics and typical locations

<table>
<thead>
<tr>
<th>Soil order</th>
<th>Area (% of ice-free land)</th>
<th>Major characteristics</th>
<th>Typical occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock and sand</td>
<td>14.1</td>
<td>No well-developed horizons</td>
<td>Sand deposits, plowed fields</td>
</tr>
<tr>
<td>Entisols</td>
<td>16.3</td>
<td>Weakly developed soils</td>
<td>Young or eroded soils</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>9.9</td>
<td>Highly organic; low oxygen</td>
<td>Peatland, bog</td>
</tr>
<tr>
<td>Histosols</td>
<td>8.6</td>
<td>Presence of permafrost</td>
<td>Tundra, boreal forest</td>
</tr>
<tr>
<td>Andisols</td>
<td>0.7</td>
<td>From volcanic ejecta; moderately developed horizons</td>
<td>Recent volcanic areas</td>
</tr>
<tr>
<td>Aridisols</td>
<td>12.1</td>
<td>Dry soils with little leaching</td>
<td>Arid areas</td>
</tr>
<tr>
<td>Mollisols</td>
<td>6.9</td>
<td>Deep, dark-colored A horizon with &gt;50% base saturation</td>
<td>Grasslands, some deciduous forests</td>
</tr>
<tr>
<td>Vertisols</td>
<td>2.4</td>
<td>High content (&gt;30%) of swelling clays; crack deeply when dry</td>
<td>Grassland with distinct wet and dry seasons</td>
</tr>
<tr>
<td>Alfisols</td>
<td>9.7</td>
<td>Enough precipitation to leach clays into a B horizon; &gt;50% base saturation</td>
<td>Moist forests; shrublands</td>
</tr>
<tr>
<td>Spodosols</td>
<td>2.6</td>
<td>Sandy leached (E) horizon; acidic B horizon; surface organic accumulation</td>
<td>Cold, wet climates, usually beneath conifer forests</td>
</tr>
<tr>
<td>Ultisols</td>
<td>8.5</td>
<td>Clay-rich B horizon, low base saturation</td>
<td>Wet tropical/subtropical climate; forest or savanna</td>
</tr>
<tr>
<td>Oxisols</td>
<td>7.6</td>
<td>Highly leached horizon on old landforms</td>
<td>Hot, humid tropics beneath forests</td>
</tr>
</tbody>
</table>

Data from Miller and Donahue (1990) and Brady and Weil (2008)
HI Soil Orders

- 39% in andisols (volcanic ejecta)
- 26% in histosols (highly organic)
  - Peatlands and bogs
  - Young substrate
- 10% in oxisols (highly weathered)

Deenik & McClellan (2007)
HI Soil Orders

**Andisols**
- Volcanic ejecta
- 13-28% OM
- Low BD, High WHC
- Amorphous clay
- Developed horizons
- Very Fertile (but high P adsorption)

**Histosols**
- >50% OM
- Low BD, High WHC
- Prod > Decomp
- Atypical in Hawaii
- Little horizon dev.
- Fertile

**Oxisols**
- Highly weathered
- Very little OM
- Well drained
- Little horizon dev.
- Very infertile, but good physical prop.
- Common in tropics
Young Island

Old Island
Soil physical properties

- Physical properties → availability and cycling of H₂O and nutrients
  - Texture
  - Structure
  - Bulk density
  - Water-holding capacity
Soil physical properties

- Texture
  - %sand, silt, and clay
    - Sand and silt mainly unweathered primary minerals
    - Clay mainly secondary minerals
  - Surface area / unit volume
    - Small particles $\rightarrow$ high SA/V $\rightarrow$ high WHC

Clay: <0.002mm
Silt: 0.002 – 0.05mm
Sand: 0.05 – 2.0mm
Soil physical properties

• Texture
  – What determines texture?

• 5 state factors
  – Parent material is typically most important
  – Time and climate also very important
  – Ultimately a balance between soil development (parent material and climate), and deposition vs. erosion (topography)
Soil physical properties

• Soil structure
  – Arrangement of soil particles
  – Single-grained, massive, etc.
  – “glued” by OM, roots, and microorganisms into soil aggregates

• Cracks and channels
  – Physical weathering
  – Biological activity
Soil physical properties

• Bulk density
  – Ratio of mass to total soil volume (solids + pores)
  – Mineral soils (1-2 g cm\(^{-3}\)), organic soils 0.05-0.4 g cm\(^{-3}\)
  – Fine texture < coarse textured
  – Influences H\(_2\)O filtration, nutrient content (% conc. X B.D.)
  – Influenced by: mineralogy, chemical composition, compaction, soil animals
Soil physical properties

• Water holding capacity (WHC)
  \[ \text{WHC} = \text{Field Capacity (FC)} - \text{Permanent Wilting Point (PWP)} \]
  - FC = amount of water left after drainage from gravity
  - PWP = point at which roots can no longer remove water from particle surfaces (~-1.5 MPa for crops)
  - WHC enhanced by clay and OM (large surf. area : vol.)

• Soil Water Potential (Ψ; bars or MPa)
  - Index of plant available water
  - \[ \Psi_{\text{soil}} = \Psi_{\text{grav}} + \Psi_{\text{osmotic}} + \Psi_{\text{matrix}} \]
Soil chemical properties

- Chemical properties → availability and cycling of nutrients
  - Redox potential
  - pH
  - OM content
  - Ion exchange Capacity
Soil chemical properties

- **Redox potential**
  - Electrical potential of a system due to tendency of substances in the system to gain or lose electrons

- **pH**
  - Negative log of $H^+$ ion activity in solution (0-14)
  - pH declines (more acidic) as $H^+$ increases
  - **Strongly** affects nutrient availability via CEC, and solubility of phosphate and micronutrients

- **Organic content**
  - Important for WHC, structure, BD, nutrient retention, soil formation and development, etc.
Soil chemical properties

- **Cation exchange capacity (CEC)**
  - Capacity of a soil to hold exchangeable cations (+ ions)
  - Driven by negatively charged sites on minerals and OM
  - Exchange occurs when a loosely held cation exchanges with one in solution
  - $\text{Al}^{3+} > \text{H}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ \approx \text{NH}_4^+ > \text{Na}^+$
    - Can be altered by large quantities of a weaker cation
  - Base saturation is % of total exchangeable cation pool accounted for by base cations (any cations but $\text{Al}^{3+}$ or $\text{H}^+$)
  - Buffering capacity to keep soils from becoming acidic
Soil chemical properties

- Anion exchange capacity (AEC)
  - Capacity of a soil to hold exchangeable anions (- ions)
  - Common in highly weathered tropical soils
    - Fe and Al oxides have slight positive charges in acidic soils
  - \( \text{PO}_4^{3-} > \text{SO}_4^{3-} > \text{Cl}^- > \text{NO}_3^- \)
    - Can be altered by large quantities of a weaker anions
    - Results in leaching of nitrate (\( \text{NO}_3^- \))
Soil biological properties

- Biological properties $\rightarrow$ availability and cycling of nutrients
  - Soil organisms
    - Roots
    - Microflora (bacteria, archaea, fungi, actinomycetes)
    - Microfauna (nematodes, protozoa)
    - Macrofauna (earthworms, rodents)
  - Microbially mediated transformations (C, N, S, P, etc.)
  - Rhizosphere processes
  - Mycorrhizal symbioses
  - Soil-borne pathogens