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:

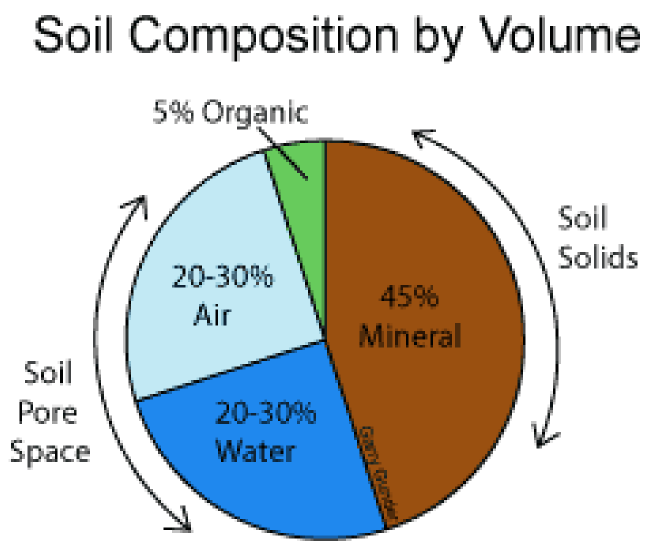
1) Coleman, D.C. *et al*. 2004. Fundamentals of Soil Ecology.
2) Hillel, D. 2004. Introduction to Environmental Soil Physics.

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 (H_2O & 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% H_2O and 15-35% air (30-70% pore space)
  – ~45-50% minerals
  – 1-5% OM



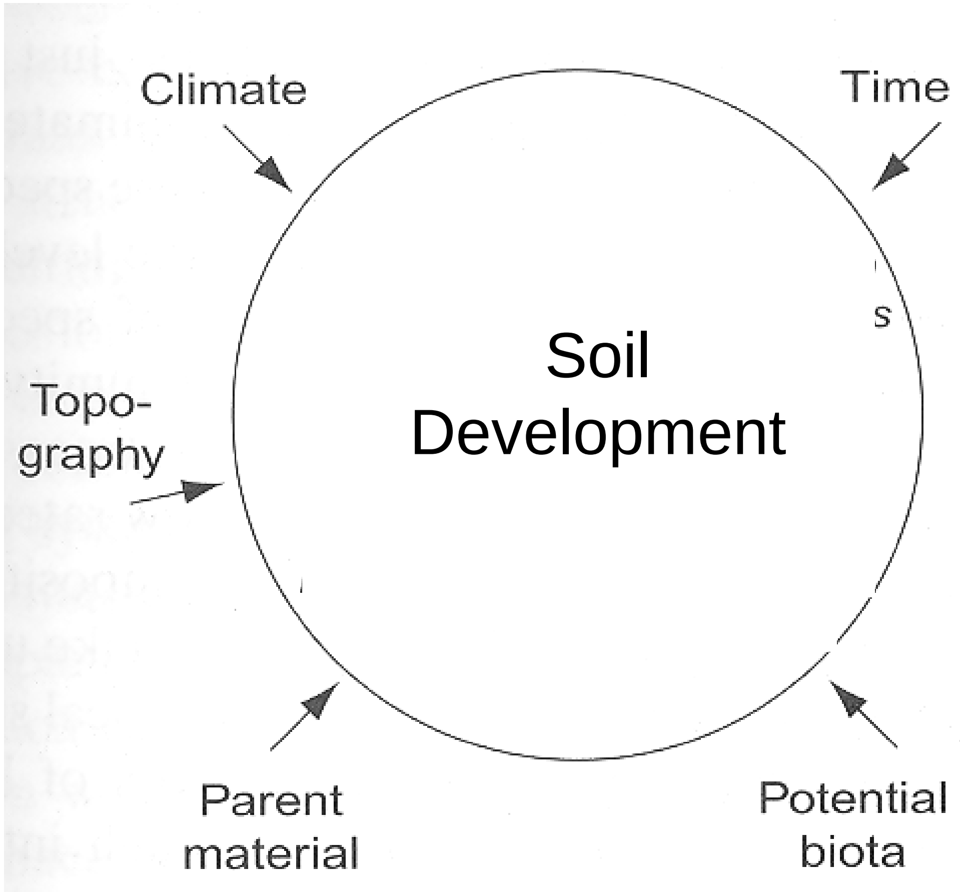
– Where does the mineral component of soils come from?

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)

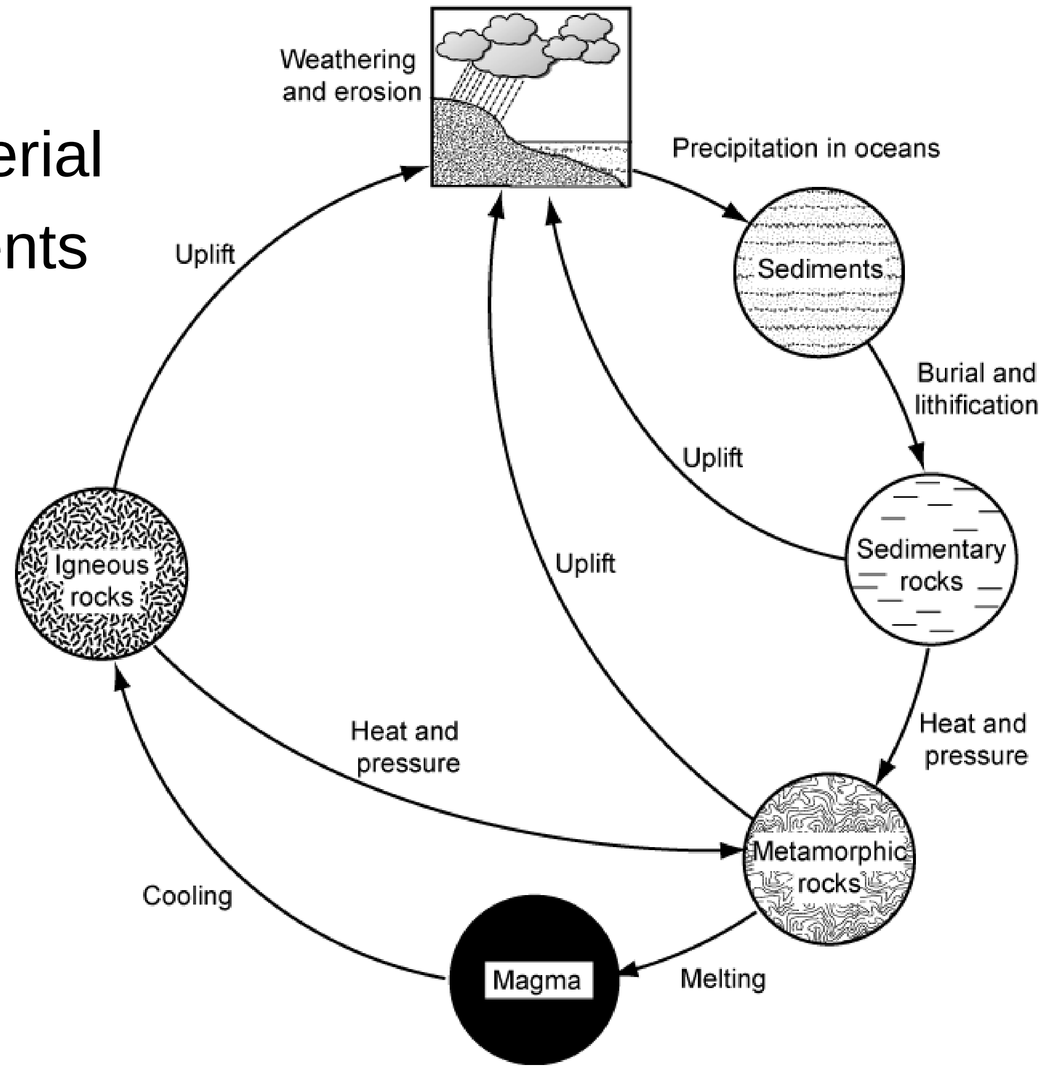
State Factors



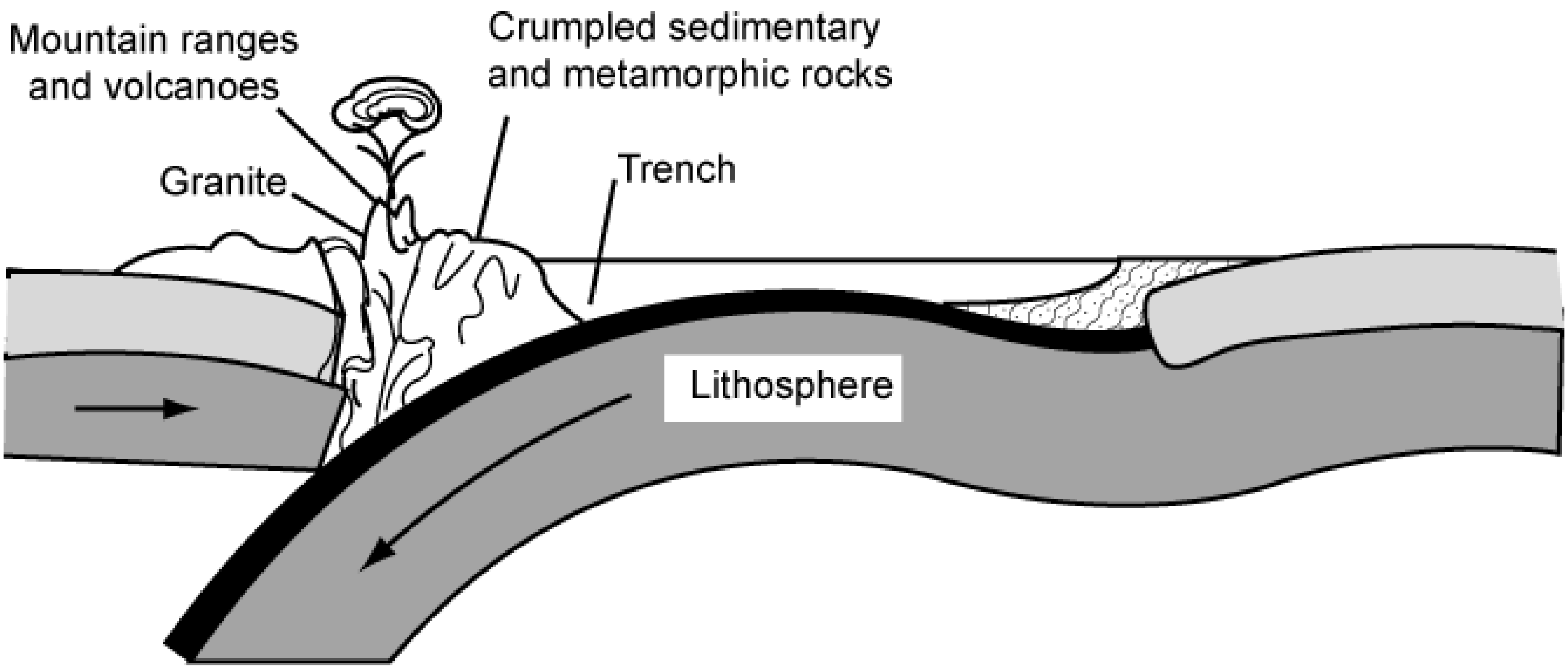
Soil formation = ¦ (development, deposition, erosion)

Parent material – The Rock Cycle

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



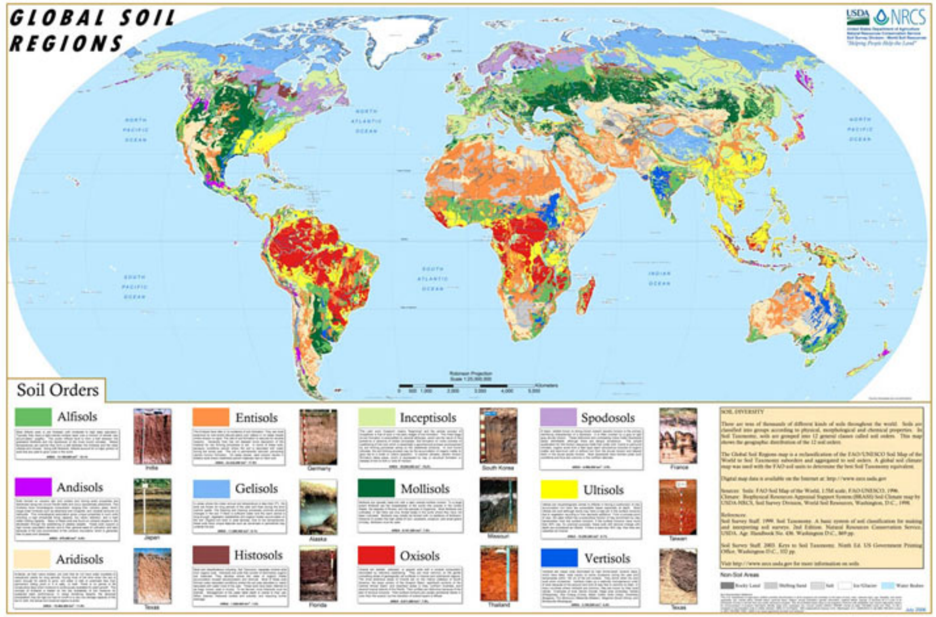
Parent material – Plate tectonics



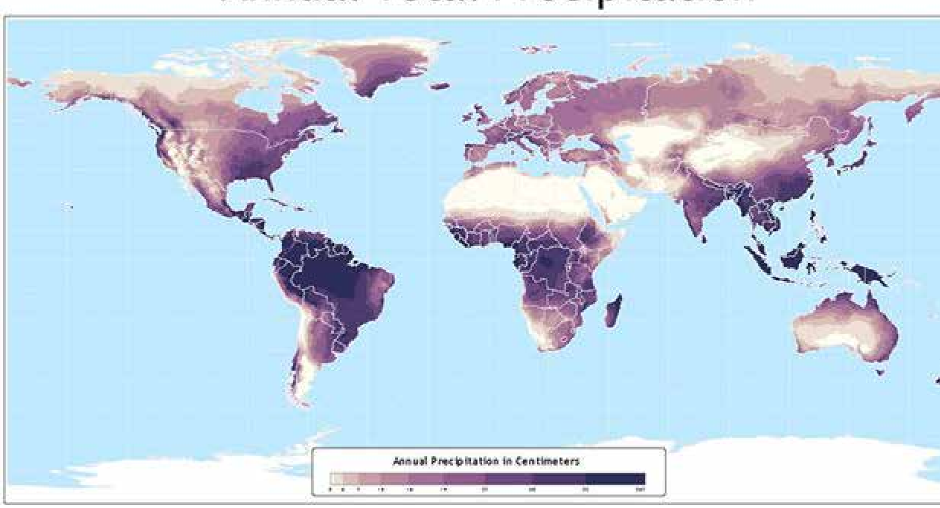
Climate

- 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

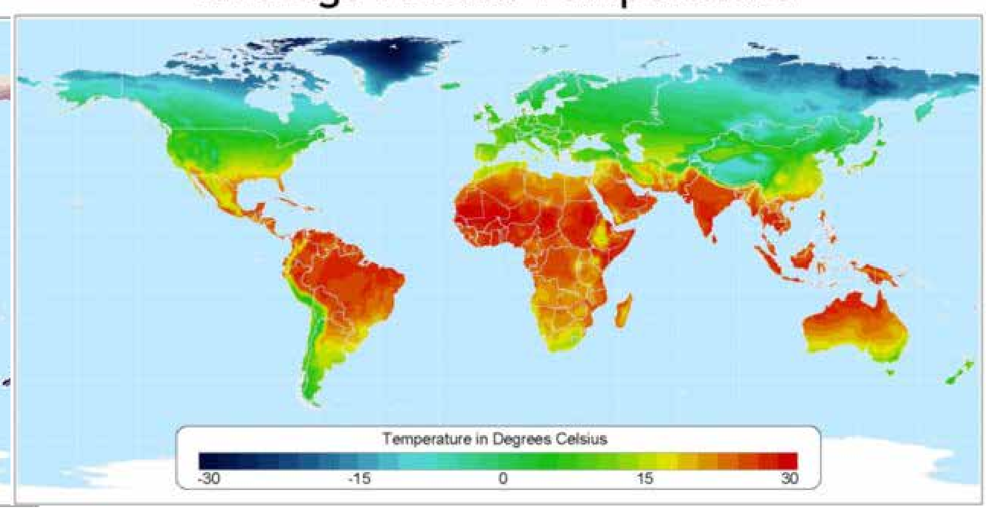
Climate



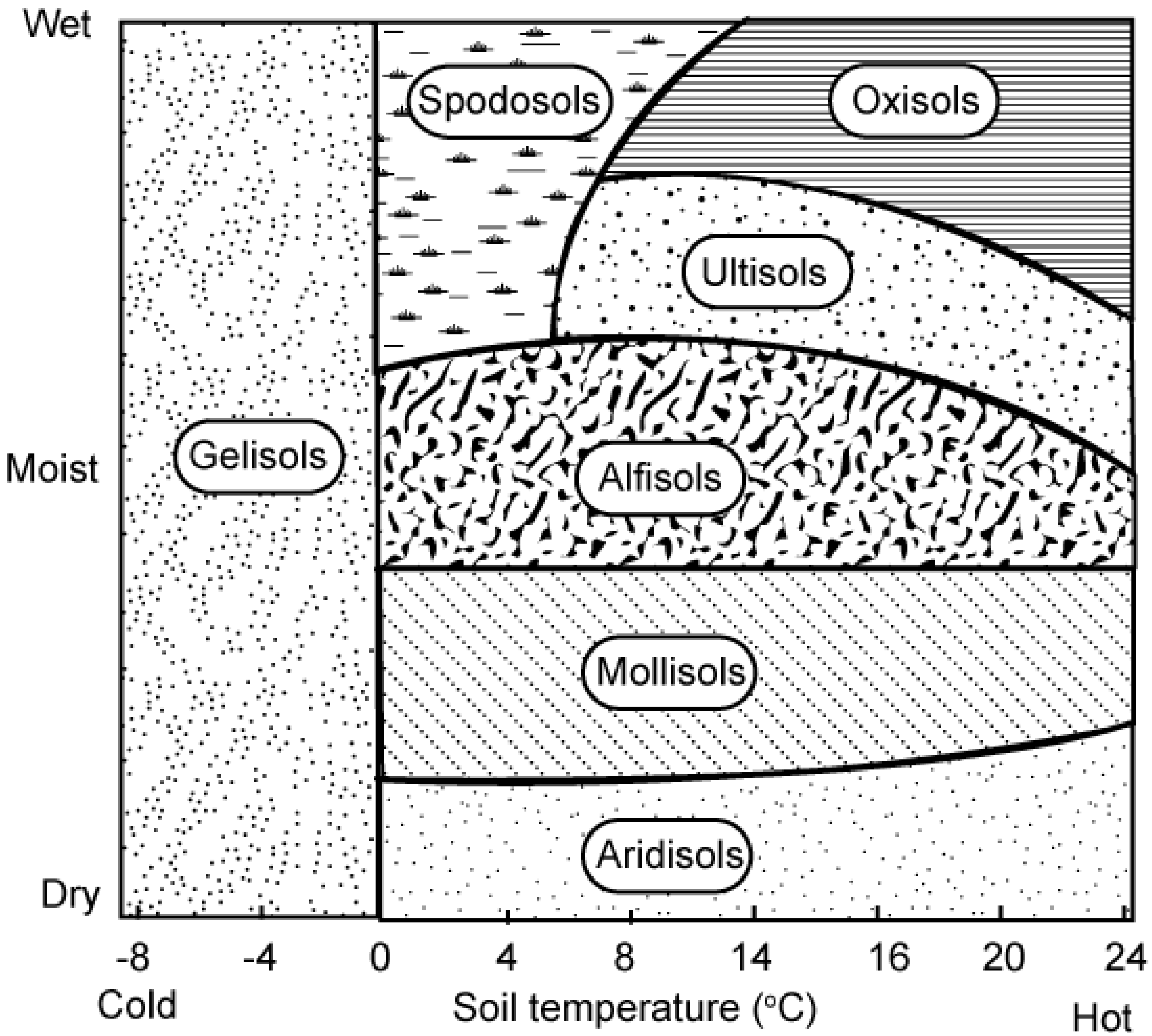
Annual Total Precipitation



Average Annual Temperature

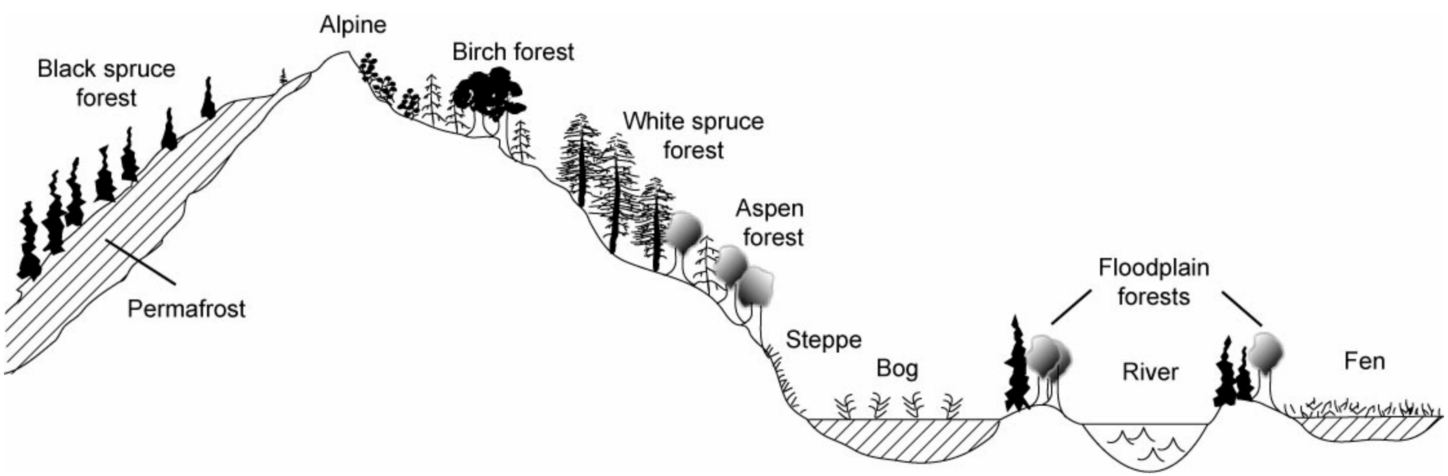


Climate


Wet
Moist
Dry
Spodosols
Oxisols
Ultisols
Gelisols
Alfisols
Mollisols
Aridisols
-8
-4
0
4
8
14
16
20
24
Cold
Soil temperature (°C)
Hot

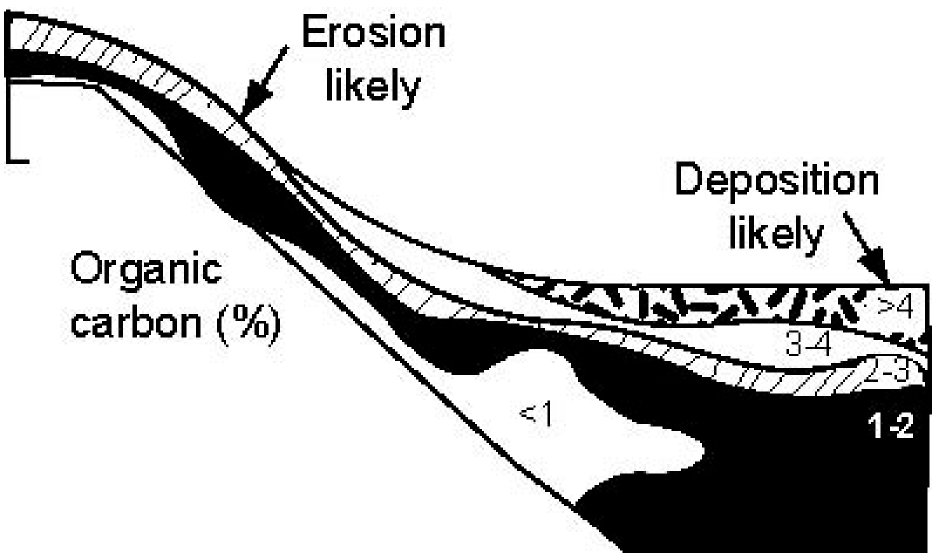
Topography

- 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)
  - $H_2O + CO_2 \leftrightarrow H^+ + HCO_3^- \leftrightarrow H_2CO_3$
- Primary production → 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 → organic acid → 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 > SO_4 > 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[a]

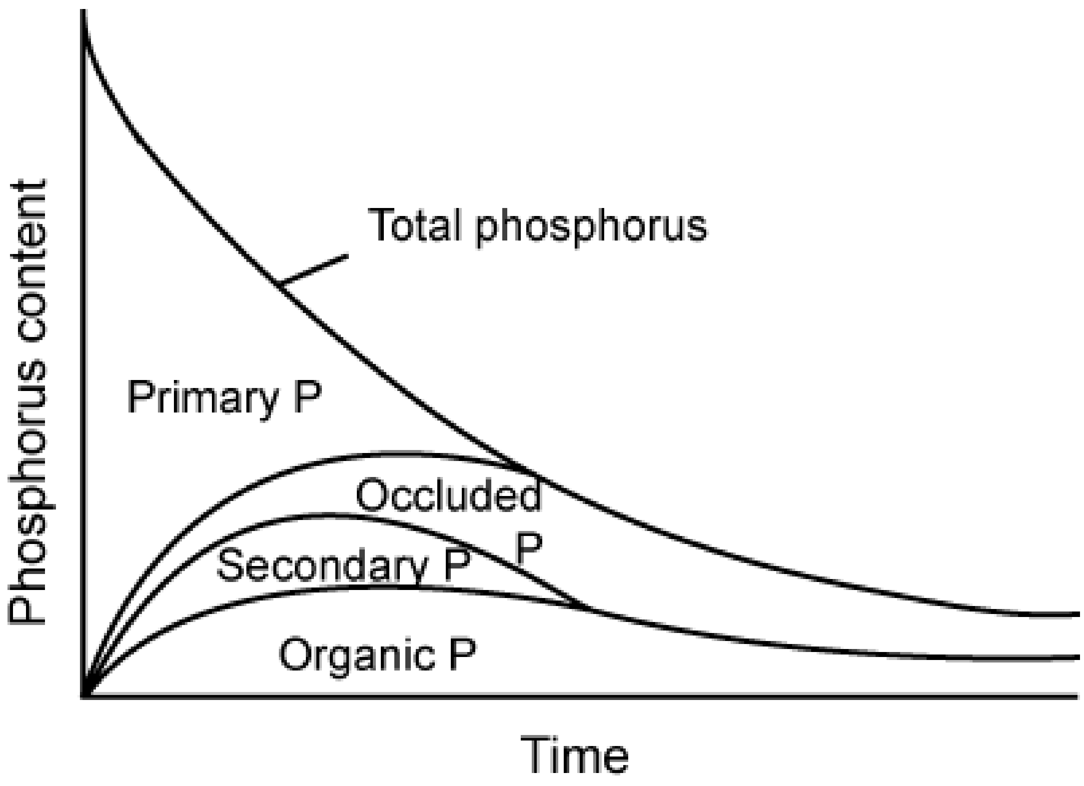
Constituent	Percentage composition
Si	28.8
Al	7.96
Fe	4.32
Ca	3.85
Na	2.36
Mg	2.20
K	2.14
Ti	0.40
P	0.076
Mn	0.072
S	0.070

[a] Data from Wedepohl (1995).

Schlesinger (1997)

Time

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



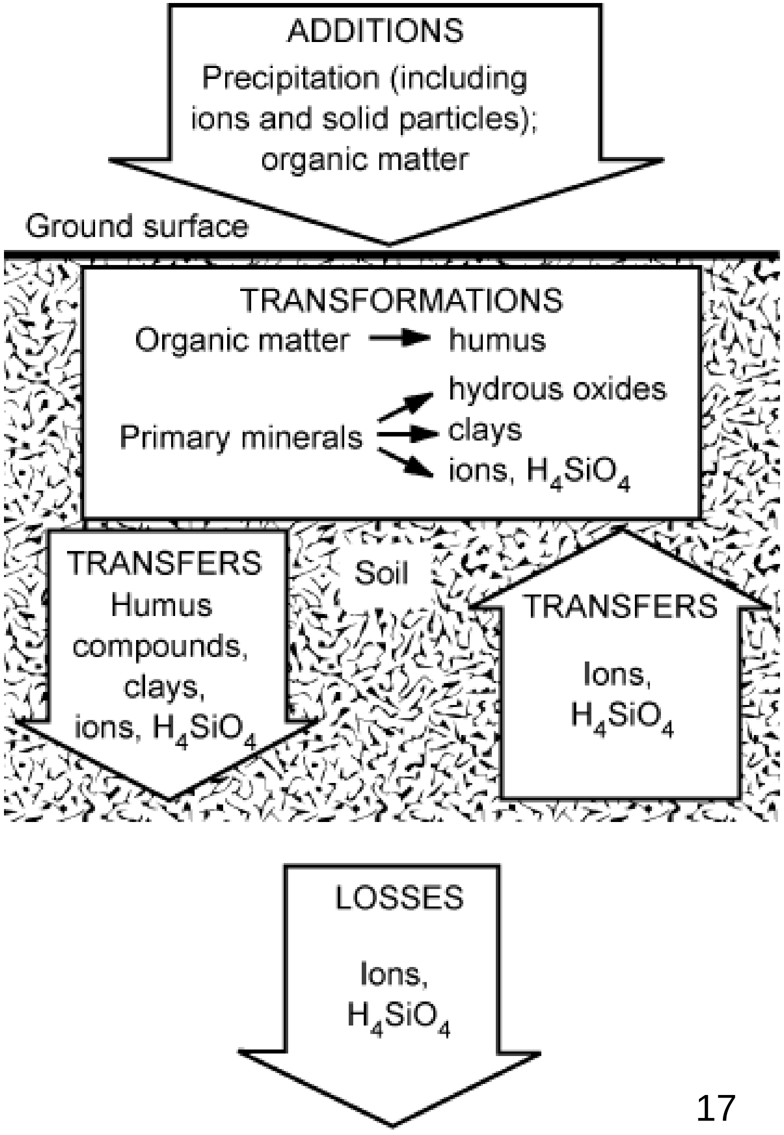
Walker and Syers (1976)

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_20)
   – Monovalent cations (Na^+, K^+) and anions (Cl^-, $NO3^-$) 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

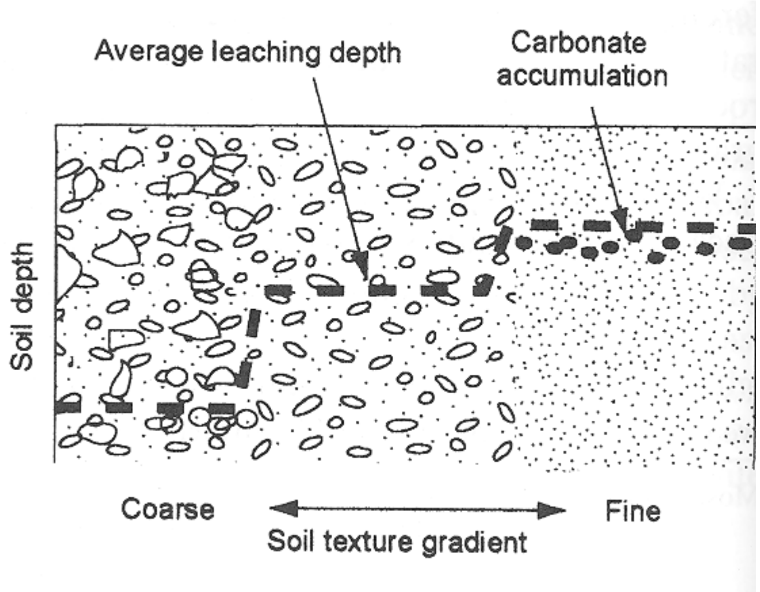
- Predominate in severe environments
- Cracks (e.g., roots) or abrasion (e.g., glaciers)
- No chemical change
- Produces coarse textured soils
- Importance lies in creation of new surfaces for chemical weathering
  - Increases surface area : volume ratio

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?

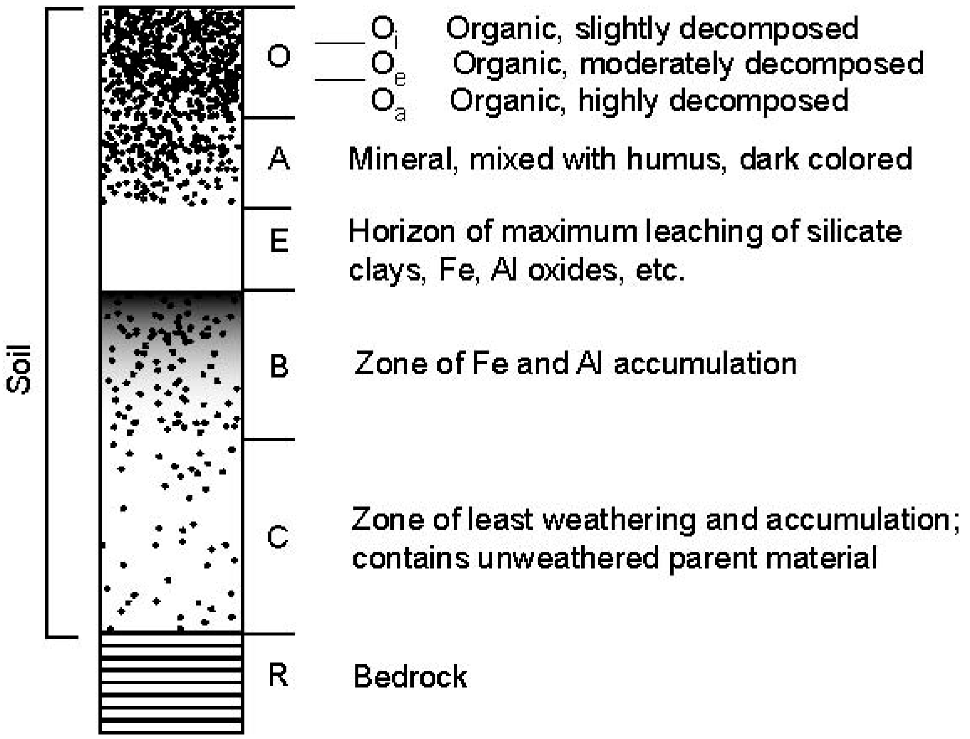
Soil transfers

- 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



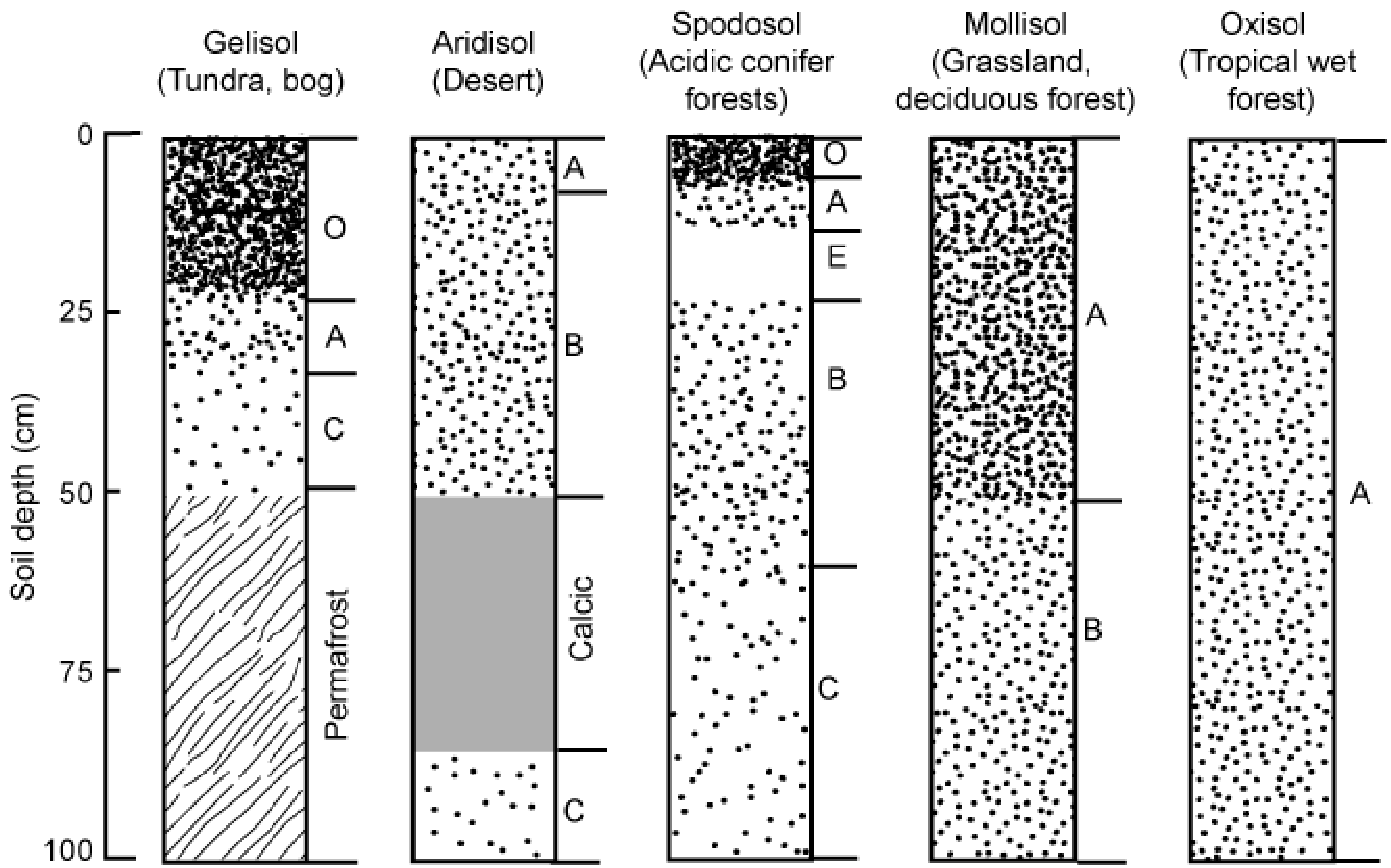
Typical Soil Profile

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



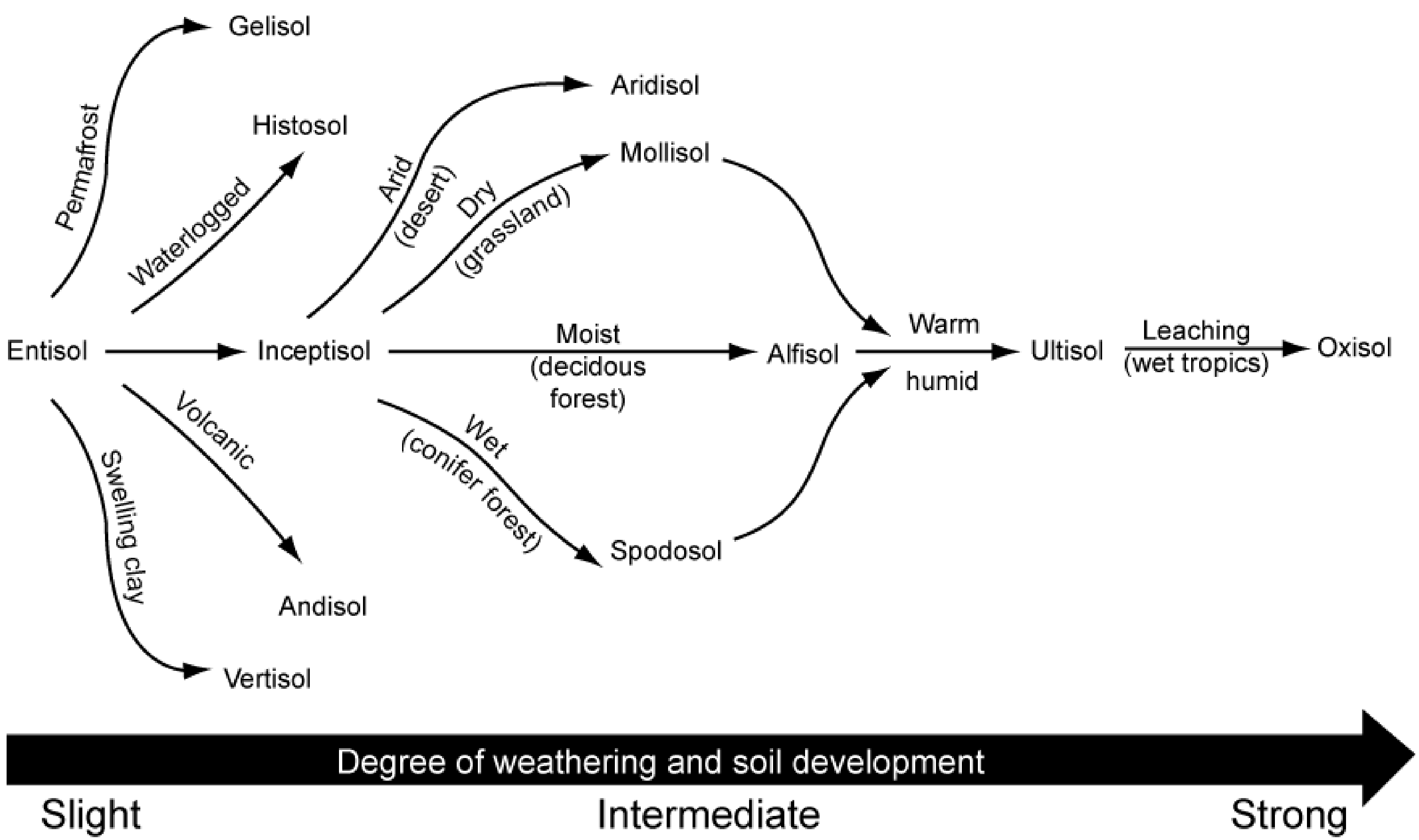
Typical Soil Profile

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

Soil order	Area (% of ice-free land)	Major characteristics	Typical occurrence
Rock and sand	14.1		
Entisols	16.3	No well-developed horizons	Sand deposits, plowed fields
Inceptisols	9.9	Weakly developed soils	Young or eroded soils
Histosols	1.2	Highly organic; low oxygen	Peatland, bog
Gelisol	8.6	Presence of permafrost	Tundra, boreal forest
Andisols	0.7	From volcanic ejecta; moderately developed horizons	Recent volcanic areas
Aridisols	12.1	Dry soils with little leaching	Arid areas
Mollisols	6.9	Deep, dark-colored A horizon with >50% base saturation	Grasslands, some deciduous forests
Vertisols	2.4	High content (>30%) of swelling clays; crack deeply when dry	Grassland with distinct wet and dry seasons
Alfisols	9.7	Enough precipitation to leach clays into a B horizon; >50% base saturation	Moist forests; shrublands
Spodosols	2.6	Sandy leached (E) horizon; acidic B horizon; surface organic accumulation	Cold, wet climates, usually beneath conifer forests
Ultisols	8.5	Clay-rich B horizon, low base saturation	Wet tropical/subtropical climate; forest or savanna
Oxisols	7.6	Highly leached horizon on old landforms	Hot, humid tropics beneath forests

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)

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

Soil order	Area (% of ice-free land)	Major characteristics	Typical occurrence
Rock and sand	14.1		
Entisols	16.3	No well-developed horizons	Sand deposits, plowed fields
Inceptisols	9.9	Weakly developed soils	Young or eroded soils
Histosols	1.2	Highly organic; low oxygen	Peatland, bog
Gelisol	8.6	Presence of permafrost	Tundra, boreal forest
Andisols	0.7	From volcanic ejecta; moderately developed horizons	Recent volcanic areas
Aridisols	12.1	Dry soils with little leaching	Arid areas
Mollisols	6.9	Deep, dark-colored A horizon with >50% base saturation	Grasslands, some deciduous forests
Vertisols	2.4	High content (>30%) of swelling clays; crack deeply when dry	Grassland with distinct wet and dry seasons
Alfisols	9.7	Enough precipitation to leach clays into a B horizon; >50% base saturation	Moist forests; shrublands
Spodosols	2.6	Sandy leached (E) horizon; acidic B horizon; surface organic accumulation	Cold, wet climates, usually beneath conifer forests
Ultisols	8.5	Clay-rich B horizon, low base saturation	Wet tropical/subtropical climate; forest or savanna
Oxisols	7.6	Highly leached horizon on old landforms	Hot, humid tropics beneath forests

Data from Miller and Donahue (1990) and Brady and Weil (2008)

UH–CTAHR Soils of Hawai'i SCM-20 — Sept. 2007

Table 1. The areas (in acres) of soil orders on the six main Hawaiian Islands.

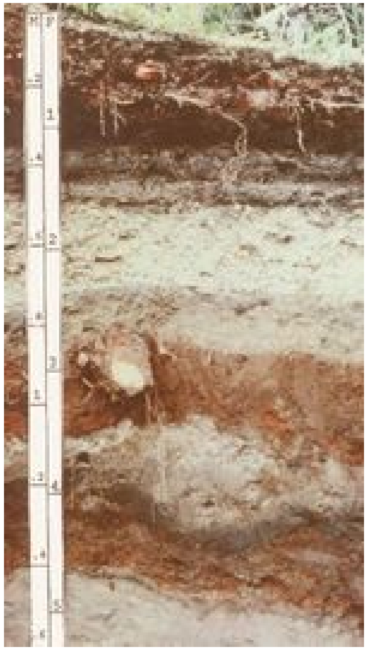
Soil order	*Kaua'i*	*O'ahu*	*Moloka'i*	*Lāna'i*	*Maui*	*Hawai'i*	*Total*
Andisol	14,499	3794	5555	0	99,245 [a]	695,381	818,474
Aridisol	4,616	7431	1588	0	14,204	41,126	68,965
Entisol	4,093	5438	4545	1247	8352	14,998	38,673
Histosol	6095	172	0	0	5762	527,890	539,919
Inceptisol	21,307	16,791	12,227	53	21,805	51,046	122,513
Mollisol	24,867	38,466	8794	11,791	66,917	13,018	163,853
Oxisol	76,638	83,079	27,941	16,703	12,156	0	216,517
Spodosol	4105	0	1892	0	0	0	5997
Ultisol	14,381	45,861 [b]	6387	1129	21,854	0	89,612
Vertisol	3,069	25,096	2283	3650	0	0	34,098

[a] This acreage of Andisols on Maui includes 45,836 acres mapped to a mixture of Andisols and Histosols and 12,351 acres mapped to a mixture of Andisols and Spodosols.
[b] This acreage of Ultisols on O'ahu includes 13,442 acres mapped to a mixture of Ultisols and Inceptisols.

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 adsorbtion)

Histosols

>50% OM

Low BD, High WHC

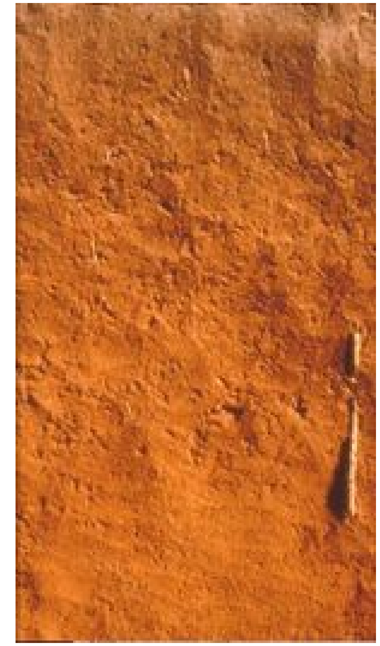
Prod > Decomp

Atypical in Hawaii

Little horizon dev.

Fertile

Oxisols



Highly weathered

Very little OM

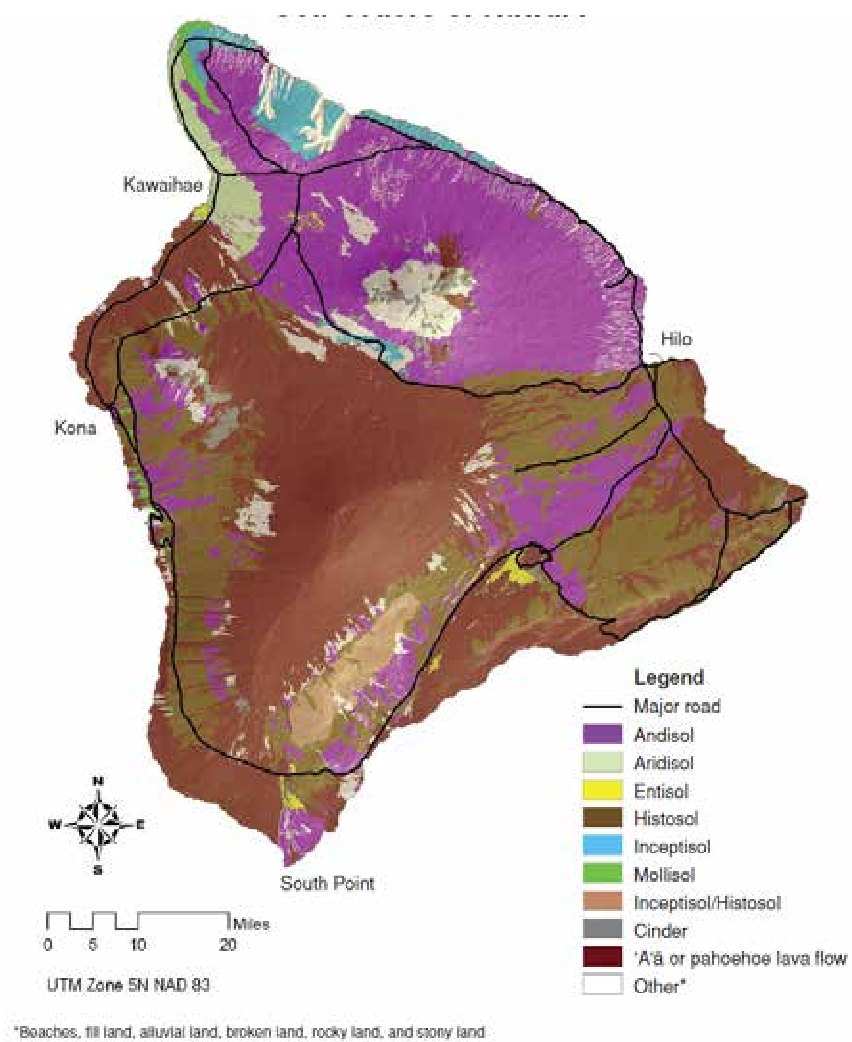
Well drained

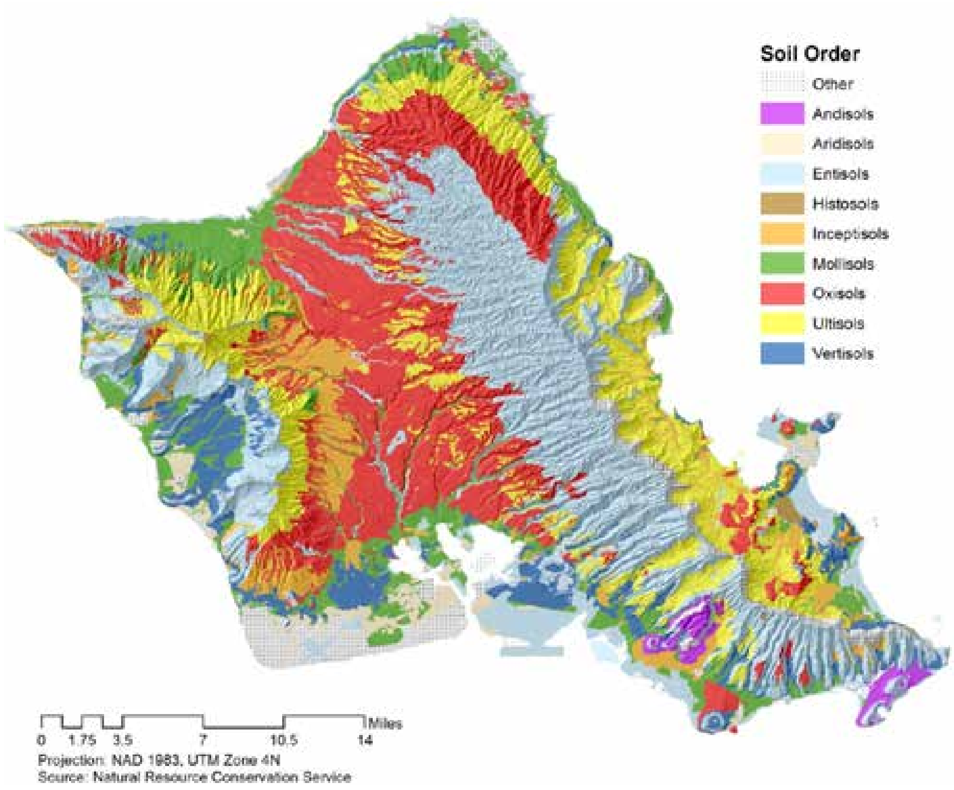
Little horizon dev.

Very infertile, but good physical prop.

Common in tropics

Young Island | Old Island



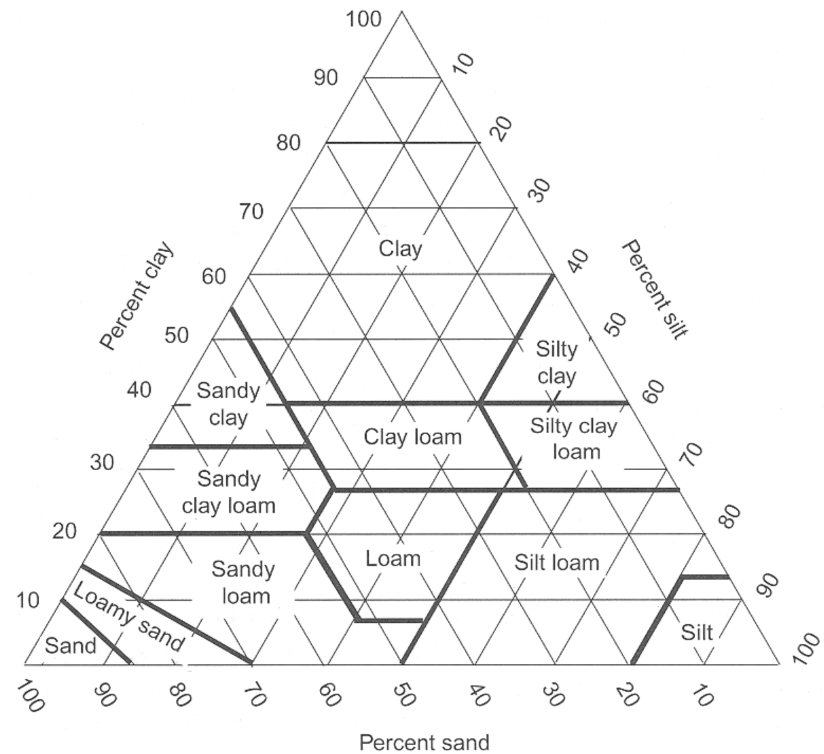


Soil physical properties

- Physical properties → availability and cycling of H_2O and nutrients
  - Texture
  - Structure
  - Bulk density
  - Water-holding capacity

Soil physical properties

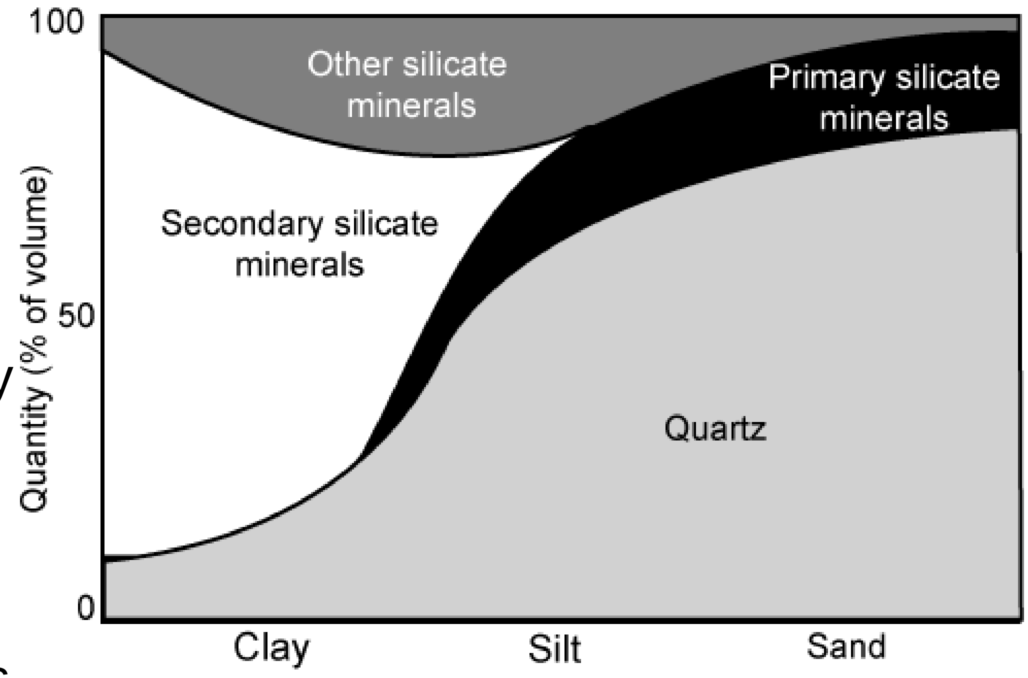
- Texture
  - %sand, silt, and clay
    - Sand and silt mainly unweathered primary minerals
    - Clay mainly secondary minerals
  - Surface area / unit volume
    - Small particles → high SA/V → high WHC



Clay: <0.002mm
Silt : 0.002 – 0.05mm
Sand: 0.05 – 2.0mm

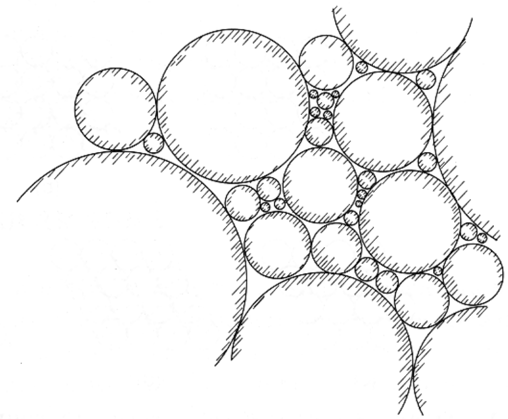
Soil physical properties

- 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



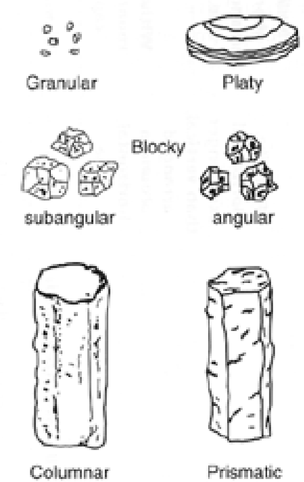


Fig. 5.5. Observable forms of soil aggregation.

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_2O filtration, nutrient content (% conc. X B.D.)
  - Influenced by: mineralogy, chemical composition, compaction, soil animals

Soil physical properties

- Water holding capacity (WHC)

  WHC = Field Capacity (FC) - 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

  – $\Psi_{soil} = \Psi_{grav} + \Psi_{osmotic} + \Psi_{matrix}$

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
  - $Al^{3+} > H^{+} > Ca^{2+} > Mg^{2+} > K^{+} \approx NH_4^{+} > Na^{+}$
    - 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 Al^{3+} or 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
  - $PO_4^{3-} > SO_4^{3-} > Cl^- > NO_3^-$
    - Can be altered by large quantities of a weaker anions
    - Results in leaching of nitrate (NO_3^-)

Soil biological properties

- Biological properties → 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